Report to the Thirty-Third Legislature
2026 Regular Session

Pūpūkea Marine Life Conservation District
Act 31 (2022)
Carrying Capacity Program
Final Report

Prepared by the

State of Hawaii
Department of Land and Natural Resources
Division of Aquatic Resources

In response to Act 31 (2022)

December 2025

Pūpūkea Marine Life Conservation District
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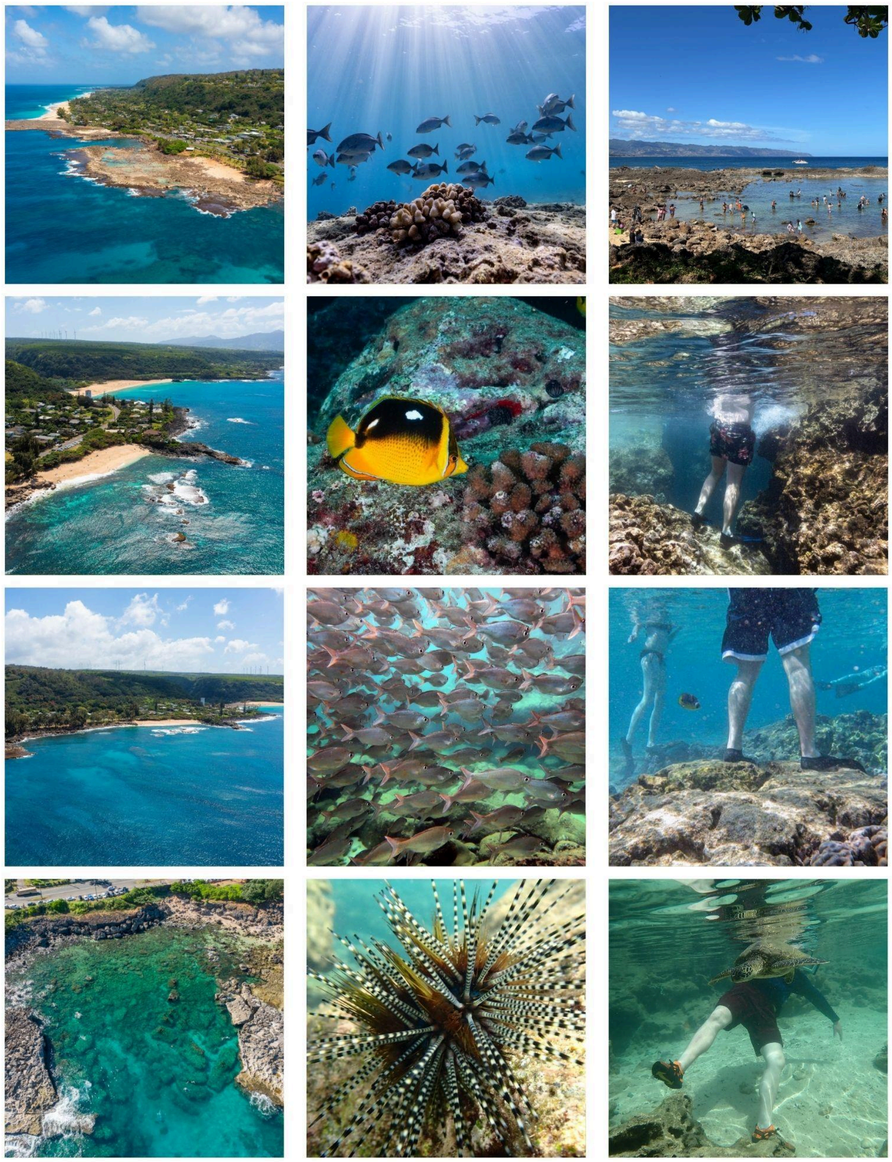

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for the Hawaiʻi State Department of Land and Natural Resources
Division of Aquatic Resources
and the Hawaiʻi State Legislature
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I. Executive Summary

Mālama Pūpukea-Waimea (MPW) submits this Final Report to the State of Hawai‘i Department of Land and Natural Resources (DLNR) Division of Aquatic Resources (DAR) and the State Legislature pursuant to Act 31 (2022, S.B. 3330) under Contract No. 71474.

The purpose of Act 31 was "to assess the carrying capacity of certain areas in the Pūpūkea marine life conservation district in light of threats to marine life from human use; monitor, document, and assess the effectiveness of mandatory and voluntary kapu, or closures, of high-traffic areas in the Pūpūkea marine life conservation district and other restrictions on access to these areas, including the imposition of fees; and propose long-term management options to reduce the impact of humans on the health and abundance of marine life in the sensitive areas of the Pūpūkea marine life conservation district" (Appendix A - Act 31, §1, p. 6).

Established in 1983 by DLNR through Hawai‘i Administrative Rules (HAR) § 13-34, the Pūpūkea Marine Life Conservation District (MLCD) (Figure 1) has the highest level of state marine protected area designation in order to protect the unique diversity of marine organisms and important nearshore habitat along this iconic coastline of the North Shore of O‘ahu.

Pūpūkea is one of eleven MLCDs in Hawai‘i. Only three MLCDs are designated on O‘ahu: Pūpūkea, Hanauma Bay, and Waikīkī. In 2002, the Pūpukea MLCD was expanded to 180 marine acres, stretching from Wānanapaoa Islets on the southern boundary of Waimea Bay through Kalua o Maua (Three Tables) and Kapo‘o (Sharks Cove) to the northern boundary of Kulalua Point. (Appendix B - DLNR DAR, Pūpūkea MLCD Management Plan, 2024.)

In 2021, DLNR amended the administrative rules specifically to include the Kapo‘o "Tidepools" within the boundaries of the Pūpūkea MLCD. The rule amendment followed from the 2008 Executive Order, initiated by then-DLNR Director Laura Thielen, that transferred the jurisdiction of the Tidepools back to the State from the City and County of Honolulu (City) to ensure its protection as part of the marine reserve. A former quarry site from the 1930s, the Tidepools had evolved into essential protected habitat for marine life with its numerous connections to the contiguous "Cove" and other waters of the MLCD. The area had been designated as part of Pūpūkea Beach Park in 1965, about twenty years prior to the establishment of the state-level MLCD.

Figure 1 - Map of the Pūpūkea MLCD

Figure 1: Map of the Pūpūkea MLCD, including the three main sections: Pūpūkea Kapoʻo, Kalua O Māua and Waimea Bay.

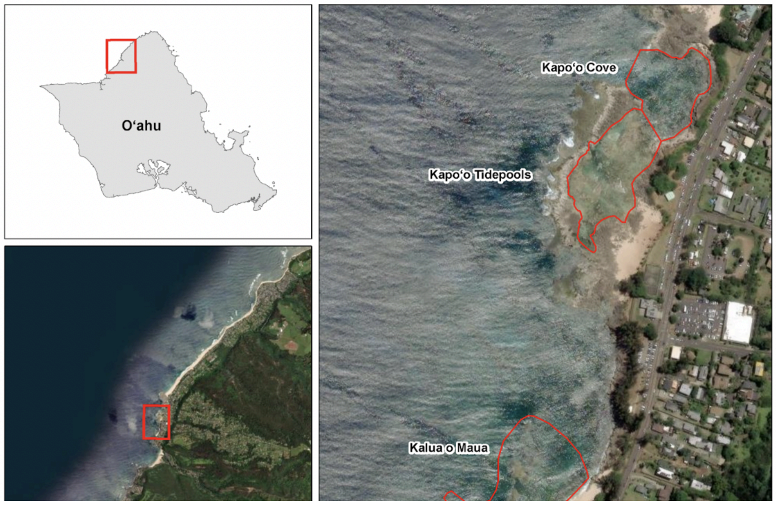
Source: DLNR-DAR, Pūpūkea MLCD Management Plan (2024)

Since its founding in 2005, MPW has focused its non-profit work on stewardship of the Pūpūkea MLCD (Appendix C - MPW, 20-Year Impact Report) in partnership with DLNR, the City, the National Oceanic and Atmospheric Administration (NOAA), and the community.

One year after Governor Ige signed Act 31 on World Ocean Day on June 8, 2022, DLNR awarded the contract to MPW in June 2023 pursuant to a Request for Proposal (DAR-RFP-202302), with a budget allocation of $269,990 from the State Legislature. MPW received the Notice to Proceed in August 2023.

In summer 2023, under the Act 31 contract, MPW commenced an extensive "biological carrying capacity" research program in the heavily visited sensitive shallow water habitat of Kapoʻo (Sharks Cove) Tidepools and Cove, focusing on the threats to marine life of increased human use. Surveys were extended to Kalua o Maua in summer 2025. (Figure 2.)

Figure 2 - Map of Act 31 Study Area: Kapoʻo Tidepools, Cove, and Kalua O Maua



Source: Summers et al., Pūpūkea Marine Life Conservation District
2025 Biological Monitoring and Carrying Capacity Assessment

The marine team's Pūpūkea Marine Life Conservation District 2025 Biological Monitoring and Carrying Capacity Assessment ("Year 3 Report") is attached as an integral part of this Final Report (and also as Appendix E.4). The Year 3 Report is the culmination of the extensive research and analysis of over ten marine researchers during the Act 31 period and includes a package of recommendations to DLNR, discussed below.

As the marine research studies commenced in summer 2023, MPW also began assessment of the impacts of human use in the terrestrial environment, focused on the City's Pūpūkea Beach Park, which adjoins Kapoʻo, working with planning and technical consultants SSFM International and, on the shared-use path project, the North Shore Community Land Trust.

MPW also began numerous projects to better understand the impacts of human use and management options through social science surveys, advisory board consultation, community engagement, collaboration with City and DLNR partners, law and policy research, educational outreach, and program evaluation.

MPW continued frequent detailed reports and invoices to DAR (Appendix D.1) and successfully secured several grants and donations to support its Act 31 work. MPW's match in grant/donation support and staff/volunteer time over the three-year period ultimately contributed $125,093 in cash and $124,800 in-kind for a total match of $249,893, nearly doubling the DLNR contract award (Appendix D.2).

Recommendations to DLNR, the City, and the Legislature resulting from this integrated makai and mauka-focused work, essential for protection of the marine life of Kapo’o and Kalua o Maua and the entire MLCD, are presented below.

II. Recommendations

MPW provides the following “up front” recommendations to DLNR, the City, and the Legislature to facilitate a focused review of the need for urgent and long-term action.

Taken together and implemented effectively, this package of recommendations to DLNR, the City, and the State Legislature would restore and protect the heavily visited sensitive areas of the Pūpūkea MLCD and help sustain the entire marine reserve at its intended status - the highest level of marine protected area in Hawaiʻi where marine life thrives, spillover is abundant to adjacent coastal areas, recreational use and tourism is well managed, and Hawaiʻi residents are encouraged to come back to enjoy and kōkua an area that they love for their families and future generations.

Without implementation of these recommendations, or with half-hearted, under-funded, or delayed management measures, these areas of the Pūpūkea MLCD will continue to deteriorate rapidly despite the decades of grassroots efforts of community organizations like MPW. After the end of the Act 31 contract in 2025 and looking into 2026, MPW faces significant funding and staffing limitations that will impair its programs; like other non-profits, MPW has experienced loss and delay of several critical federal and other grants. Despite these challenges, MPW will continue to pursue the Act 31 objectives and recommendations, and funding options, as much as feasible.

For convenience, the entire section explaining the six recommendations of the marine team (see Section IV, Recommendations, Year 3 BCC Assessment) is replicated here:

The following next steps and recommendations from the Act 31 marine team are grounded in the findings of the 2023–2025 Biological Monitoring and Carrying Capacity Assessments for the Pūpūkea Marine Life Conservation District (MLCD), many years of prior scientific studies by numerous researchers, and decades of human use counts by MPW.

These recommendations focus on the science-based management actions necessary to address the documented ecological degradation associated with excessive and prolonged human use at Kapoʻo (Sharks Cove) Tidepools and Cove, and should also be considered for Kalua o Maua over time based on additional monitoring.

Taken together, these measures represent an initial phase of adaptive management to be evaluated and refined through continued monitoring and stakeholder collaboration. In the view of the marine team, the scientific foundation provided by the Act 31 program strongly supports the following recommendations for DLNR action during 2026–2027 and beyond.

A. Recommendations to DLNR

1. Establish a Visitor Access and Fee System for Kapoʻo Tidepools and Kalua o Maua

Recommendation: Establish a structured Visitor Access and Fee Program (VAFP) for Kapoʻo Tidepools and Kalua o Maua to manage visitor capacity limits and generate sustainable funding for site management, ecological monitoring, restoration, and visitor safety. The access system should include online reservations, capacity limits (see 4 below), and daily enforcement at access points. Fees should apply to all non-resident visitors, not to Hawaiʻi residents. Closure or rest days, like at Hanauma Bay, should be at least two days a week, with an additional day designated for residents only (e.g., Sundays). Rest days not only protect marine life but allow marine research and park maintenance to occur, and reduce wear and tear on public infrastructure.

Rationale: Visitor access and fee programs are well-established management tools used globally to mitigate tourism impacts, fund conservation, and regulate access at sensitive marine ecosystems. Hanauma Bay Nature Preserve, a City Beach Park adjacent to and surrounding the State-designated Hanauma Bay MLCD, provides a successful local precedent: following implementation of an entrance fee and reservation system for non-resident visitors, the site experienced reduced daily visitation, improved water quality, and measurable biological recovery. Similar fee models at high-use reef systems in Thailand, Palau, the Seychelles, and Ningaloo Marine Park demonstrate that regulated access combined with conservation financing increases compliance, reduces trampling and anchor damage, and supports monitoring and enforcement capacity.

Given the biological sensitivity of Kapoʻo and Kalua o Maua—and the demonstrated link between human density and declines in fish abundance, species richness, and coral health—and based on community consultation and adaptive management approaches, the VAFP program offers an equitable mechanism for reducing overcrowding while funding essential management interventions, and protects resident access to and enjoyment of the area.

Supporting Evidence: Act 31 monitoring shows strong evidence of declining ecosystem conditions associated with high visitor use. Non-schooling fish abundance declined by more than 50% across the study period at heavily visited sites, species richness decreased significantly, and coral damage was positively associated with human density. At peak periods, Kapoʻo Tidepools supported visitation exceeding 100+ individuals in water simultaneously, creating sustained ecological pressure that exceeds documented recovery thresholds in comparable systems.

Hanauma Bay provides a relevant management precedent: implementation of a visitor access system , a parking and entry fee (currently $25 for non-residents and $0 for residents), mandatory education program, reservation system to even out crowds throughout the day with limited open hours for non-residents, and daily caps (currently capped at 1400 visitors daily) (see below) resulted in increases in coral cover, improved water clarity, and 40–70% increases in key fish groups (Madin et al. 2024; Graham 2024). Globally, user-fee systems—such as the Palau Green Fee, Bonaire Marine Park Tag, and Phi Phi Islands Marine Visitor Fee—successfully fund reef monitoring, restoration, safety personnel, and waste infrastructure. These examples demonstrate that well-designed access management and fee systems reduce uncontrolled visitation while improving funding reliability for conservation actions.

A comparable program at Kapoʻo and Kalua o Maua would address chronic underfunding of enforcement and site maintenance while simultaneously reducing daily visitation to ecologically sustainable levels. Revenue could support lifeguard or safety officers, sustained marine science and enhanced data collection, education and outreach, erosion-control infrastructure, and community stewardship programs like MPW's effective Ocean Education Ambassador (OEA) program.

2. Establish a Permanent, Integrated, and Community-Based Marine Science, Monitoring, and Data Program for the Pūpūkea MLCD

Recommendation: Use visitor fees (see above), Ocean Stewardship User Fee funds, or other sources to establish a permanent, integrated, community-based marine science, monitoring, and data program for the Pūpūkea MLCD. The program should include biological monitoring of the entire MLCD, nearby "spillover" and control areas, and partnerships for additional research.

The monitoring program should integrate all available biological, physical, and human-use data across all zones using standardized methods and annual public reporting. Implementation should occur in collaboration with MPW, building on Act 31 research methods, and include expanded studies on carrying capacity, socio-ecological dynamics, and adaptive management. The program should maintain at least twice-monthly fish and mobile invertebrate surveys expanded to include all zones within the MLCD (adjusted for swell during winter months), annual benthic photo-quadrats, human use and visitor impact surveys, and annual broad-scale coral impact surveys.

The marine science program should facilitate partnerships to pursue focused applied-research initiatives in collaboration with MPW, DLNR, and academic partners to inform science-based management. All current methods should continue and additional areas of research should include:

- *Wastewater source and impact assessment*, including a dye study to trace and quantify wastewater flow from the septic systems of the comfort stations; and dye or other methods to trace flow and impacts of showers, water fountains, parking lot run-off, storm drain run-off, and surrounding infrastructure into nearshore waters of the MLCD.

- *Population-genetic and spawning studies* of Āholehole and ʻAmaʻama to evaluate connectivity, spillover, and local spawning timing. Reports from Moʻomomi (Molokaʻi) indicate winter spawning peaks, while other parts of Oʻahu exhibit year-round activity with greater frequency in winter. Determining the spawning seasonality at Pūpūkea could inform the design and timing of seasonal closures. Monitoring limu and herbivore seasonal relationships would also be useful.
- *Carrying-capacity assessments* for additional MLCD zones beyond Kapoʻo, including building on the baseline study of Kalua o Maua and extending surveys to Waimea Bay, to identify sustainable visitor thresholds and detect and manage user translocation.
- *Collaborative research partnerships* to expand socio-ecological and ecosystem connectivity studies that directly inform adaptive management.

Rationale: A permanent, integrated (meaning with shared information and collaboration among MPW, DLNR, and NOAA) marine monitoring program is essential to maintain the scientific foundation for adaptive management, policy evaluation, and long-term reef resilience of the Pūpūkea MLCD. The Act 31 program demonstrated both the feasibility and value of consistent, community-based data collection. A sustained program will preserve methodological integrity, prevent data loss during funding gaps, and ensure that local knowledge continues to inform DLNR decision-making. Integrating ecological metrics (fish, coral, and benthos) with visitor-use data (counts, drone imagery, and VIS surveys) provides a comprehensive understanding of the coupled human–natural system, enabling early detection of degradation, evaluation of management outcomes, and data-driven policy adjustments.

Continued monitoring across all zones will be essential to detect human translocation effects, evaluate management effectiveness, and track overall reef recovery. A permanent community-based program, led collaboratively by MPW, DLNR-DAR, and partners, will preserve methodological continuity, expand monitoring throughout the MLCD, and produce annual *Pūpūkea MLCD Monitoring Reports* summarizing ecosystem condition and visitor-use trends to guide future adaptive management. Annual public reporting will strengthen transparency, coordination, and accountability under the Ocean Stewardship User Fee program.

These additional scientific studies will address key knowledge gaps identified through Act 31 monitoring. Understanding water quality, population connectivity, recruitment dynamics, and spatial variation in human-use impacts will strengthen the scientific basis for future rulemaking and community co-management. Expanding research across zones ensures that adaptive management measures remain data-driven, equitable, and responsive to the evolving ecological conditions of the Pūpūkea MLCD.

Supporting Evidence: The Act 31 program provided an extensive biological dataset for the sensitive, most visitor-impacted areas of the MLCD, including a total of 108 survey days, 920 hours in the water, and 1,617 transect and radial surveys. These data established multi-year baselines for fish abundance, richness, biomass, benthic cover, coral health, and water quality. Integration of human-use counts, drone mapping, and Visitor Impact Surveys revealed strong correlations between visitor density and ecological condition.

New baseline values from Kalua o Maua also now serve as a critical control for evaluating ecological change and assessing whether visitor pressure shifts over time.

3. Enact Seasonal Closures of Kapoʻo Tidepools and Cove during Winter Months

Recommendation: Commence an annual closure of the Kapoʻo Tidepools and Cove for five months (November – March).

Rationale: Provide a seasonal rest period for marine life to recover from chronic disturbance and reduce shoreline degradation during high-surf months when public-safety risk is elevated.

Supporting Evidence: Act 31 Year 3 data showed a 53% cumulative decline in non-schooling fish abundance (2022–2024), a 42% decline in species richness, and minimal calcifier recovery (CCA = 2.30%). Peak human densities averaged 115 ± 17.4 individuals in-water at 3 p.m., indicating sustained biological stress.

Additionally, kilo from community members during the Covid-19 anthropause (Rutz et al., 2020) suggested that a rest period from humans dramatically increased limu and juvenile fish production (Yagodich, Personal Communications). Similar findings were reported at Hanuama Bay (Madin et al., 2025; Graham 2024).

4. Set Visitor Caps for Kapoʻo Tidepools

Recommendation: Implement quantitative, science-based "visitor" (non-Hawaiʻi resident) caps or number thresholds derived from Act 31 data using an hourly reservation system and daily limits.

Rationale: Unregulated visitation has resulted in sustained biological stress and measurable ecological degradation across Kapoʻo. Continuous daily use, often exceeding 100 individuals simultaneously in the water in a single zone, has reduced fish abundance and richness, diminished calcifier cover, and altered coral and benthic structure. Setting an explicit visitor hourly or point-in-time and daily cap for the Tidepools will allow the reef to recover from chronic disturbance, provide real-time evaluation of carrying-capacity limits, and restore equitable resident access that has been displaced by over-tourism. Such measures mirror the proven success of time-based access management used at Hanauma Bay, where controlled visitation significantly improved coral and fish recovery.

Supporting Evidence: Act 31 Year 3 monitoring demonstrated a significant negative correlation between human presence and non-schooling fish abundance (trend = –0.12 ± 0.04 SE, p = 0.005). Mean weekday in-water counts ranged from 59 to 76 individuals, which are well above ecological tolerance thresholds identified through generalized linear mixed-model analyses.

This study identified a threshold of **1 human within a 10 m radius circle** expanding from the center of a transect. This threshold is equivalent to 31.8 humans per hectare. This value was then multiplied by measures of the Tidepools area in hectares to calculate carrying capacity limits (Stamoulis 2023).

1. The area at low tide was 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.
2. The area with the majority (90%) of humans based on the human density surface derived from the 2025 drone surveys, as a subset of the area at low tide described above.

This analysis yielded a carrying capacity range of 27 - 31 humans in the Tidepools at any given time. Selecting from within this range, **the study recommends implementing a limit of 30 visitors in the Tidepools at any given time**. Since the data from the 2023 visitor impact survey (see Coberly et al., 2024 for methods) displayed an average use of 49 minutes in the Tidepools across 77 follows (and 43 minutes overall across 151 follows, with similar findings in 2023), **the marine science team also recommends 30 people as a number to be used for reservations per hour**. These limits could be implemented through an online reservation system (similar to the system used for Hanauma Bay).

A daily cap on visitors, similar to management of Hanauma Bay, can be determined by scaling the hourly recommendation by the trend in hourly use (Figure 41) and the hour with the maximum mean number of visitors can be determined. Setting the usage during this peak hour equal to a factor of 1, the relative usage factor for every other hour compared to this peak hour (e.g., if a non-peak hour has half the visitors, its factor is 0.5) can be determined. Summing all these hourly factors yields Z, which represents the total proportional units or reservations per day. This scaling factor (Z) can then be multiplied by the recommended hourly use (X) to generate (A) total permits per day.

5. Initiate Rulemaking To Implement Long-Term Management Measures

Recommendation: Use results from pilot closures to commence formal rulemaking to authorize and implement the management measures outlined above within the Pūpūkea MLCD.

Rationale: Establish a legal framework that allows DLNR, the City, MPW, and partners, to implement data-driven adjustments in response to quantified ecological thresholds and human-use impacts.

Supporting Evidence: Three years of Act 31 studies documented > 40 % declines in fish richness, rugosity reductions of 0.2 – 0.3 m, and fluctuating CCA cover (9.7 – 16.4 %), among other effects, under sustained high human use in the Tidepools. Permanent regulatory changes will be necessary to protect the marine life of the sensitive areas of the MLCD.

6. Establish a Permanent Community-Based Ocean Education Ambassador Program

Recommendation: The human use counts taken by MPW over the years through the Makai Watch partnership with DLNR and its Ocean Education Ambassadors (OEA) program provide an essential data set that supports and integrates with the marine transect and ecological conditions data and analysis. The OEA program also provides critical direct educational and management capacity to protect marine life on a daily basis. Establishing a permanent OEA program for the Pūpūkea MLCD in collaboration with MPW that can cover the existing study zones as well as expand to Waimea Bay in the future is an important next step to complement the science-based management recommendations stated above. At Hanauma Bay, Sea Grant currently provides the educational and outreach staff, along with City management staff, to operate the park and support infrastructure, using the fees from the reservation system for non-residents. On-the-beach staffing is essential to the success of access management for a marine life protection district.

Rationale: The effectiveness of future management measures at the Pūpūkea MLCD depend not only on a continued excellent marine science program but also on consistent and robust human use counts.

Supporting Evidence: The MPW OEA Report for 2025 (provided as Appendix F.1 to the Act 31 Final Report) provides data that show the effectiveness of the currently small program – part-time contractors, and volunteers conduct 3- to 4-hour field shifts five days a week at the Kapoʻo Tidepools and Cove, and at Kalua o Maua, within the Pūpūkea MLCD and Pūpūkea Beach Park.

OEA Metric	**2025**
People Educated	4,002
Educational Interventions	1,289
Pounds of Trash Removed	2,343
Hours Contributed (Makai Watch/OEA)	815

7. Initiate Discussions of Transfer of Jurisdiction of Pūpūkea Beach Park to DLNR

(Note: Recommendation 7 comes from MPW and was not part of the Year 3 Report; it is also included below in the recommendations to the City, below.)

As discussed with DLNR and the City in meetings subsequent to adoption of the Pūpūkea MLCD Management Plan, MPW urges the City and DLNR to initiate a Memorandum of Understanding (MOA) process to analyze the options for transfer of jurisdiction of Pūpūkea Beach Park, and potentially Waimea Beach Park, to the State of Hawaiʻi to facilitate a holistic approach to management and protection of the Pūpūkea MLCD.

B. Recommendations to the City

As stated in the Year 3 Assessment, the marine team supports the MPW Final Report recommendations to the City regarding new management measures at Pūpūkea Beach Park.

Those recommendations, to be integrated with those above to DLNR, are as follows:

1. Initiate Discussions of Transfer of Jurisdiction of Pūpūkea Beach Park to DLNR

As discussed with DLNR and the City in meetings subsequent to adoption of the Pūpūkea MLCD Management Plan, MPW urges the City and DLNR to initiate a Memorandum of Understanding (MOA) process to analyze the options for transfer of jurisdiction of Pūpūkea Beach Park, and potentially Waimea Beach Park, to the State of Hawaiʻi to facilitate a holistic approach to management and protection of the Pūpūkea MLCD.

2. Create Parking Lot Management System

In alignment with the recommendations above, and in collaboration with MPW and the community, create a parking lot management system for Pūpūkea Beach Park and Waimea Beach Park to support the protection of Kapoʻo, Kalua o Maua, and Waimea Bay.

Implement a parking system with fees for non-residents that are 100% reinvested into maintenance of the beach park and Pūpūkea MLCD science, education, and human use monitoring programs.

Reserve 50% of parking spaces for Hawaiʻi residents with no parking fee. Designate ample first responder, maintenance, loading zones, ADA parking, and future shuttle stop. Hire local residents as parking lot attendants (as with the Hāʻena model, this approach promotes employment, local knowledge, better visitor experience, collaboration with Lifeguards and OEA programs, HPD, HFD, DOCARE). Reinvest in management and education programs under co-management and revenue-sharing agreement with community organizations like MPW or North Shore Transportation Alternatives (NSTA).

Through an agreement with DOT, limit highway shoulder parking in area and ensure first responder access routes especially during traffic congestion. Restrict parking on residential streets within .25 miles of MLCD to residents. Plan for eventual North Shore Shuttle system to manage visitor access and "regenerative" tourism experience.

3. Extend Ke Ala Pūpūkea Shared Path through Kapoʻo

Adopt MPW-SSFM-NSCLT plan for extension of shared pedestrian-bike path through Kapoʻo Parking Lot with makai alignment. Integrate with new parking management system (above). Design and implement through DTS with continued community collaboration. Complete the project in 2026. Begin collaboration with DOT and others re further extensions of Path to Waimea Bay.

4. Re-landscape and Manage Pathways and Access to Kapoʻo

Collaborate with MPW on design, materials, installation, monitoring of new landscaping plan and managed pathways and access points for Kapoʻo and then Kalua o Maua. Add/revise State-City signage for Pūpūkea Beach Park at Kapoʻo to Kalua o Maua. Include boardwalks and overlooks, and wave-resilient stairs to steep areas. Add "big brown" park/MLCD signs to visible and entry locations. Consolidate all signage and reduce sign clutter. Extend project to Kalua o Maua.

5. Redesign Infrastructure To Prevent Wastewater Contamination

Remediate wastewater from septic system based on findings from future MPW Dye Study. Remediate shower run-off based on findings from MPW shower study. Remediate drinking fountain run-off (Fire Station parking lot); no further study required. Assess run-off from Waimea Bay Beach Park showers and fountains, and remediate.

C. Recommendations to the State Legislature

The marine team supports the MPW Final Report recommendations to the State Legislature regarding statutory changes that will further the protection of Pūpūkea and all MLCDs statewide. Those recommendations are as follows:

1. Authorize DLNR Co-Management Agreements

Adopt legislation to authorize DLNR to enter into co-management agreements with qualified community stewardship non-profits, like MPW, that have demonstrated track records of mālama ʻāina and agency partnership work, including mauka and/or makai organizations, building on the current request by Hui Maka'ainana o Makana for improved partnership agreements with DLNR.

2. Provide Permanent Funding for DAR MLCD Science and Management

Authorize and fund Marine Research, Ocean Education Ambassadors, Makai Watch and Visitor Access Programs focused on managing and minimizing human use impacts. Amend the Adaptive Management statute to expand expedited rules authority to include visitor impact management purposes. Establish Ocean Education Ambassador programs for all MLCDs. Expand funding for Makai Watch communities statewide. Establish Parking and Access Management programs for all MLCDs.

3. Mandate Visitor Management Systems for MLCDs Statewide

Assess visitor impacts (especially non-resident tourism) at all MLCDs and related beach parks. Authorize and mandate visitor management systems to avoid degradation. Reinvest parking revenue through cooperative agreements with counties into the park and marine reserves. Establish co-management agreements with qualified community non-profits for long-term stewardship of the area.

III. Additional Act 31 Projects and High Human Use at Kapoʻo and Kalua o Maua

In addition to the extensive research conducted by the Act 31 marine teams that is conveyed in the cumulative Year 3 Report, MPW initiated a wide range of research projects focused on the impacts of human use of Pūpūkea Beach Park, which adjoins the Kapoʻo and Kalua o Maua marine areas of the MLCD, and potential management options.

The status and scope of these numerous projects, many of which are more connected to MPW's recommendations to the City than those in the Year 3 report, which are directed to DLNR, are described in detailed reports in the Appendices.

To underline the findings in the Year 3 Report and this Final Report, recent data obtained from City Ocean Safety Lifeguard counts of human use at Kapoʻo (including Kalua o Maua) are presented here to supplement the analysis and recommendations regarding high levels of human use.

Figure 3 below shows monthly visitor totals demonstrating that Kapoʻo experiences sustained human use at levels comparable to, and often exceeding that of, Waimea Bay, one of Oʻahu's most heavily visited beaches. As the chart shows, **Kapoʻo visitation outpaced Waimea in four of the ten monitored months** and closely matched visitation during peak summer and shoulder-season periods.

Kapo'o received over 603,708 visitors in 10 months, over 2,000 each day on average, representing only a 7% difference from Waimea's visitation in the same timeframe. These findings highlight the exceptional intensity of use occurring at Kapo'o and underscore a level of human pressure inconsistent with its current management and carrying capacity.

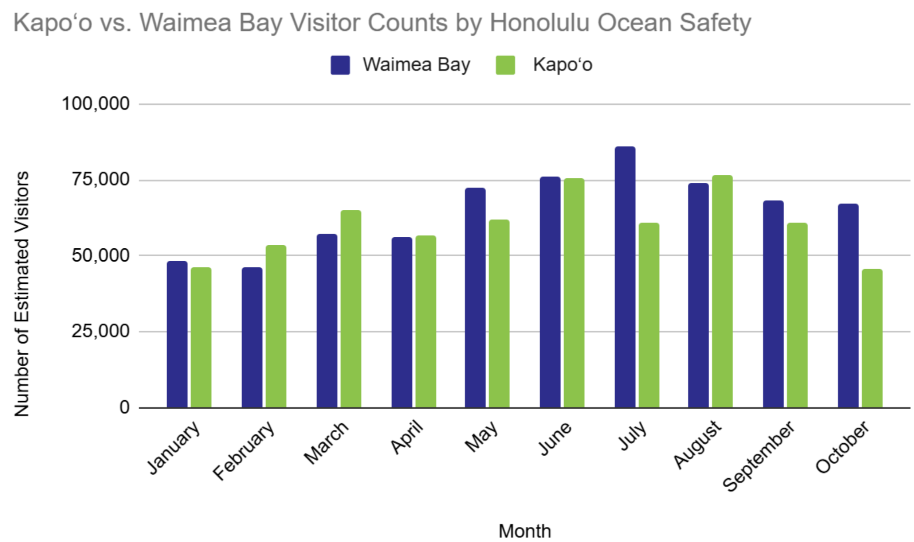


Figure 3: Total Daily Visitor Counts at Kapo'o v. Waimea Bay - City and County of Honolulu Ocean Safety Data

Based on MPW's kilo and Ocean Education Ambassador program data, approximately 95-55% of these visitors are non-Hawai'i residents, underscoring the displacement of local residents' use of these areas, particularly since COVID and in the last decade, and emphasizing the urgent need for management measures that prioritize and bring back residents to use, enjoy, and protect the MLCD.

IV. Conclusion

To underscore the urgency of the analysis and recommendations in the Year 3 BCC Assessment and this report, and the revelations in the recent Ocean Safety data presented in Section V, MPW concludes the Final Report with a photo from yesterday, November 25, 2025, showing the extraordinarily high number of visitors - 158 total counted by MPW - just at one point-in-time in the Tidepools at Kapo'o.

MPW is grateful to have had the opportunity to conduct the Act 31 Carrying Capacity Program for the Pūpūkea MLCD, has been deeply honored to work with dedicated and top-notch teams of scientists, consultants, advisors, staff, and community and agency partners on this project, and stands ready to work with DLNR, the City, the Legislature, elected officials, partners, and our amazing North Shore community on reviewing, refining, and implementing the important and urgent package of recommendations presented in this Final Report.

V. Appendices

The following studies and reports are located in a google folder.

A. Act 31 (SB 3330, 2022)
B. DLNR DAR, Pūpūkea MLCD Management Plan (2024)
C. MPW 20-year Impact Report
D. Act 31 Contract with MPW
    1. Reports and Invoices to DAR
    2. MPW Cash and In-Kind Match Report
E. Biological Carrying Capacity Reports
    1. 2022 - Year 0
    2. 2023 - Year 1
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Pūpūkea Marine Life Conservation District 2025 Biological Monitoring and Carrying Capacity Assessment

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- Emily Summers

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I. Executive Summary

Pursuant to Act 31, passed by the Hawaiʻi State Legislature in 2022, the Department of Land and Natural Resources (DLNR) Division of Aquatic Resources (DAR) contracted non-profit Mālama Pūpūkea-Waimea (MPW) to implement a three-year "carrying capacity" program. This program includes biological studies as well as the development of pilot measures and longer-term management strategies to protect the marine resources of the Pūpūkea Marine Life Conservation District (MLCD) on the North Shore of Oʻahu.

The goal of the Act 31 Year 3 Biological Carrying Capacity (BCC) study conducted from April through August 2025 was to build on the Year 1 study (Coberly et al., 2024), Year 2 study (Tomoda-Bannert et al., 2025), as well as the Year 0 study pre-Act 31 transect and coral surveys (Jones and Stamoulis, 2022), to determine the ranges, types, and potential thresholds of human use impacts to inform better management and protection of marine life in the sensitive Kapoʻo (Sharks Cove) and Kalua o Maua (Three Tables) areas of the Pūpūkea MLCD. The 2025 study continued to assess how visitor numbers, and spatial and temporal patterns of visitor use, correspond to marine organism distribution and health.

As with Years 1 and 2, Year 3 consisted of marine surveys and biological assessments of fish and mobile invertebrate abundance and richness, coral health, and benthic assemblages. The study refined Years 1 and 2 analysis of human or environmental factors that drive patterns in organism abundance and richness, while expanding methods to include an additional sensitive area, Kalua o Maua (Three Tables), and collected biomass data to assess implications of human impacts for different life stages of fishes. The 2025 Year 3 study extended the methodologies developed for fish and benthic assemblage monitoring first adopted in 2022 by MPW Marine Science Coordinator Ellie Jones and Marine Research Advisor Dr. Kosta Stamoulis (Stamoulis, 2023).

The areas of geographic focus of Act 31 and this biological carrying capacity study continued to be the Kapoʻo "Tidepools" and "Cove" because the marine life within these areas are susceptible to the high concentrations of human use and impacts due to the accessibility of the shallower water and popularity of the area for tourists. The Year 3 study expanded surveys to the Kalua o Maua (Three Tables) area to gain a better understanding of human impact within this adjacent area of the MLCD that has also experienced increased human use. This addition provided a baseline understanding of current visitor use of and impacts on Kalua o Maua ecology and supports analysis of future management options of Kapoʻo that could translocate visitors to this popular nearby beach.

The surveys were conducted in the Kapoʻo Tidepools, the Kapoʻo Cove, and at Kalua o Maua in 2025 by the MPW Act 31 Marine Science Team, led by in-water researcher and team coordinator Emily Summers under the supervision of Callie Stephenson M.Sc., Sarah Severino M.Sc., and Dr. Kosta Stamoulis. This report builds on the research by MPW's previous Marine Science Coordinators and research partners starting in 2012 who also focused their surveys on Kapoʻo including: Stamoulis and Friedlander 2012, Rosinski 2012, Barcina 2020, Mislinski 2021, Jones 2022, Stamoulis 2023, Coberly 2023, and Tomoda-Bannert 2024.

Over the Act 31 period, the marine teams conducted a total of 108 survey days, 920 hours in the water, and 1,617 transect and radial surveys. In 2025, Year 3, the marine team work comprised 36 survey days with roughly 349 working hours in the water, with 319 fish and benthic transect surveys, 48 coral transect surveys, and 43 radial coral impact surveys, compared to Year 1 that had 31 survey days, 240 hours in the water, and 544 transects, and Year 2 with 41 days of surveys of the Kapoʻo Tidepools and adjacent Cove, representing 331 hours in the water, with a total of 663 transect surveys, including winter survey dates.

This report continues the Years 1 and 2 analysis of the environmental and human-induced changes to the Kapoʻo ecosystem, as well as now including metrics for Kalua o Maua, and serves as a biological baseline for further research.

Year 3 did not include a pilot closure of Kapoʻo; however, based on findings from Act 31 monitoring, which documented the ecological impacts of human use and the effectiveness of site-specific management measures, this report recommends implementing pilot closure measures at Kapoʻo in future management actions.

Observed trends and ecological monitoring indicate that such measures, including visitor capacity limits and temporary closures, would help reduce human impacts on sensitive habitats and support ecosystem resilience. This recommendation is further supported by studies at Hanauma Bay Marine Life Conservation District, where periodic closures and controlled visitor access of the Hanuama Bay Nature Preserve, managed by the City and County of Honolulu (City), have facilitated habitat recovery and informed adaptive management strategies (Madin et al., 2025). Implementing access management measures suited to the unique geographic, community, and management setting at Kapoʻo and potentially Kalua o Maua would align with the long-term objectives of the Pūpūkea MLCD Management Plan. Under the collaborative guidance of DAR, the City, MPW, and other agency and community partners, these management measures would help balance conservation goals and sustainable recreational use.

To determine thresholds of acceptable human presence and impacts on the Kapoʻo and Kalua o Maua ecosystems, the Marine Team's biweekly surveys from April to August 2025 documented the abundance, species, size, and distribution of fish, mobile invertebrates, and coral; monitored coral health; recorded in-water human presence within the Kapoʻo Tidepools and Cove and Kalua o Maua; and monitored environmental variables that impact marine organism health. Surveys were conducted only when ocean conditions allowed, as the later season winter swell often made safe access to the water or certain transects challenging.

Year 3 expanded study methods to include recording the total length of fish within transect surveys, which was used along with established length–weight relationships to calculate biomass. Biomass, the estimated weight of fish in an area, provides a key indicator of ecosystem health and can be used to compare the productivity and resilience of the different areas surveyed, evaluate potential impacts from human activity, and assess whether certain areas function as important nursery grounds based on the relative abundance of smaller size classes (Karachle and Stergiou, 2012).

The Year 3 study also continued in-water human presence counts by the Marine Team along the transects, mapping by Shoreline Conservation Initiative of human presence areas using a drone, broad-scale coral impact surveys, and "Visitor Impact Surveys" (VIS) by students under the supervision of Dr. Heather Page, Sea Education Association (SEA), Woods Hole, Massachusetts. SEA tracked the type and frequency of substrate contact by visitors in the water at Kalua o Maua and Tidepools (building on MPW's 2023 and 2022 VIS study and adapting the methods of Meyer and Holland, 2008).

The primary findings of this Year 3 BCC study under Act 31 are as follows:

1. **Biodiversity:** The Kapoʻo Tidepools and Cove, as well Kalua o Maua, continue to provide essential habitat for a diverse assemblage of marine organisms.

    a. **Fish**: The biweekly transect data recorded fish abundance (total number of fish present), richness (the type and number of fish species present), and this year also included biomass (the estimated total weight of fish based on total length measurements).

    Significant declines in fish abundance and richness were observed across both the Tidepools and Cove since 2022, particularly for non-schooling species. Schooling species have also become less frequently encountered in the Tidepools and Cove.

    The 2025 Kalua o Maua baseline data establishes an important reference point for future ecosystem assessments.

    Non-schooling species abundance was highest in Year 1 across both Tidepools and Cove before declining substantially in subsequent years. In the Tidepools, non-schooling fish abundance decreased by 37% from 2022 to 2023 and by another 26% by 2024 (a total 53% decline), before a modest 15% rebound in 2025. In the Cove, abundance remained stable from 2022 to 2023 but fell sharply (46%) in 2024, with no significant change in 2025.

    Schooling species also exhibited decreasing trends in occurrence. The probability of encountering a school declined consistently from 2022 onward, with significant reductions between 2023 and 2024 in both the Tidepools and Cove. By 2025, schools were 30–60% less likely to be observed than in 2022. When present, schools showed increasing abundance from 2022-2024, with a drop in 2025. Despite this statistical variability, local kilo observations indicate that large schools of *Kuhlia sandvicensis/xenura*[1] (āholehole) in the Tidepools may have continued to increase.

    Fish species richness declined steadily across all years in both zones. In the Tidepools, richness was highest in 2022 and decreased by 42% by 2024, with no significant change

[1] This report uses the species name *Kuhlia sp.* in reference to āholehole (Reticulated Flagtail). Observations in 2025 were confirmed to be *Kuhlia xenura*; however, prior year species identification were recorded as *Kuhlia sandvicensis,* though these likely were also *Kuhlia xenura.* Figures primarily use *K. sandvicensis* for consistency with prior reports.

in 2025. In the Cove, richness declined significantly each year, with a total reduction of 41% from 2022 to 2025, equivalent to approximately 5.7 fewer species per 40 m^2 transect.

Shifts in species composition indicate potential community restructuring, with about 35 species disappearing or newly appearing between years. In the Tidepools, total abundance (including schooling species) was driven primarily by *Kuhlia sp.*, with *Thalassoma duperrey* (saddle wrasse) and *Acanthurus nigrofuscus* (maʻiʻi) as leading non-schooling contributors. In the Cove, *Acanthurus nigrofuscus* was most abundant, followed by *Kuhlia sp.* and *Acanthurus leucopareius* (maikoiko). Kalua o Maua, surveyed for the first time in 2025, exhibited a community dominated by *Acanthurus nigrofuscus* and *Thalassoma duperrey*, and surveys provided a new ecological baseline for comparison in future years.

Schooling fish abundance has declined overall, although species-specific patterns varied. *Acanthurus triostegus* (manini) and *Neomyxus leuciscus* (uouoa) both decreased sharply, with large schools no longer observed after 2023. In contrast, *Kuhlia sp.* schools in the Tidepools appeared to increase through 2024 before a slight decrease in 2025, maintaining higher abundance and richness than in the Cove.

Biomass estimates show that the Kapoʻo Tidepools had intermediate non-schooling fish biomass (670–1480 g/40 m^2), while the Kapoʻo Cove exhibited the highest biomass (1049–2201 g/40 m^2), approximately 48% greater than at Kalua o Maua (520–1180 g/40 m^2, $p = 0.012$).

b. **Benthic Composition**: Benthic composition in 2025 varied distinctly among zones, shaped by differences in wave exposure, sedimentation, and visitor pressure.

The Tidepools remained dominated by unconsolidated substrate and turf algae as in previous years, with sand (38.73%) and turf (33.19%) comprising most of the cover, followed by silt (13.14%) and bare substrate (10.91%). CCA remained low (2.30%). These results reaffirm the Tidepools as a soft-bottom, high-disturbance environment where limited water flow and frequent trampling restrict the establishment of calcifiers.

The Cove and Kalua o Maua exhibited greater substrate stability and higher proportions of calcified cover. In the Cove, turf algae dominated (53.37%), followed by silt (28.18%) and CCA (16.42%), reflecting more favorable conditions for encrusting algae and substrate consolidation.

Kalua o Maua displayed the most structural complexity, with turf (47.2%), moderate silt (7.42%), sand (9.06%), and CCA (16.1%).

Across zones, CCA trends show clear interannual variability. In the Tidepools, cover declined from 11.1% in 2022 to 2.4% in 2023, stabilizing at 2.30% in 2025, while in the Cove, CCA decreased from 33.7% in 2022 to 9.7% in 2024, then rebounded to 16.42% in

2025. These patterns suggest localized recovery of calcified substrate in the Cove, while the Tidepools remain constrained by sedimentation and high visitor disturbance.

c. **Coral Health**: In 2025, coral communities across all zones showed high percent live tissue cover and moderate stress.

The Tidepools coral community was dominated by *Montipora capitata* and *Porites lobata*, with the lowest mean live tissue per colony (82.0%) and highest paleness (14.6%) compared to the other surveyed zones.

Multiple coral heads in the Tidepools exhibited physical damage, including breakage, smothering by debris, and abrasion consistent with trampling, indicating ongoing mechanical disturbance in this shallow zone, in addition to having the highest signs of other physiological stress resulting in paleness and death.

The Cove coral community was dominated by *Pocillopora meandrina* and *Montipora capitata*. Mean live coral was 85.3%, with 2.6% pale, 2.0% bleached, and 3.5% dead, and new colonies were observed at previously coral-free transects, suggesting localized recruitment.

Kalua o Maua exhibited the highest coral cover, richness, and structural complexity, dominated by *Porites lobata* and *Pocillapora meandrina*. Live coral reached 87.0%, with minimal bleaching (1.0%) and moderate mortality (7.2%), partly due to natural senescence of *P. meandrina*.

Disease cases, including Multifocal and Focal White Syndrome and *Porites* trematodiasis, were observed at Kalua o Maua and the Tidepools.

d. **Invertebrates**: In 2025, mobile invertebrate communities across all zones were dominated by urchins, particularly *Echinometra mathaei*.

In the Tidepools, 22 invertebrate species were recorded, although *Echinometra mathaei* remained overwhelmingly dominant (35.64 individuals per 20 m² transect, 95.38% of total abundance). Other species such as *Echinometra oblonga*, *Diadema paucispinum*, and sea cucumbers occurred in lower but regular numbers.

The Cove had 15 invertebrate species recorded on transects and was similarly dominated by *E. mathaei* (37.2 per 20 m² transect, 87.24%) and *E. oblonga* (0.78 per 20 m² transect, 11.56%). Brittle stars were documented as an independent group for the first time and ranked among the most abundant taxa. Several invertebrate species absent in 2024 reappeared in 2025.

Kalua o Maua showed the highest invertebrate abundance and structural complexity. *E. mathaei* dominated (45.85 per 20 m² transect, 76.78%), followed by brittle stars (9.88 per 20 m² transect, 11.51%) and *E. oblonga* (5.15 per 20 m² transect, 2.42%).

2. **Environmental Components**

   a. **Temperature:** The Tidepools temperatures in 2025 showed higher extremes than the Cove, with similar mean conditions across sensors (26.61–26.64°C, SE = 0.012–0.028°C) but substantially elevated maximums at Tidepools transect 4 (T4) (35.50°C) and T8 (34.52°C).

      Threshold exceedances accumulated at these two transects over the course of the summer and early fall, with the logger on Tidepools transect 4 (T4) recording 52 readings above 29°C (with 9 continuous events, meaning consecutive hourly exceedance readings) and TP8 recording 119 readings (with 24 continuous events), totaling approximately 52–119 hours above threshold.

      The Cove remained cooler and more stable (25.40–28.15°C; mean 26.58°C, SE = 0.01°C), did not exceed the bleaching threshold, and showed no cumulative thermal stress over the monitoring period.

   b. **Water clarity**: In 2025, correlations between water clarity and depth weakened across all zones, showing a modest positive relationship in the Tidepools (r = 0.350), little to no correlation in the Cove (r = 0.147), and a modest relationship at Kalua o Maua (r = 0.342). These results contrast with the stronger and more consistent positive correlations recorded in 2023–2024.

   c. **Rugosity:** In 2025, rugosity measurements revealed continued variability in substrate complexity across all zones, reflecting the effects of seasonal wave energy and sediment redistribution.

      Baseline rugosity measurements from 2022 in the Tidepools ranged from 11.37-13.27 m (mean= 12.01 m), and in the Cove ranged from 11.47-15.37 m (mean= 13.34 m).

      In the Tidepools, changes in rugosity compared to measurements from prior summer months ranged from –1.90 m to +1.55 m, while the Cove varied from –3.10 m to +3.30 m, indicating alternating erosion and recovery at different transects. On average, both zones showed slight decreases in rugosity (Tidepools –0.20 m; Cove –0.30 m) compared to Years 0-2, consistent with shifting sand and hydrodynamic forces.

      Baseline rugosity measurements at Kalua o Maua in 20225 ranged from 10.50–16.30 m (mean = 12.45 m) and established a new reference for future monitoring of structural complexity.

3. **Human Presence**

a. **Human counts on transects -** based on marine team counts**:** Human presence tracked by the marine team within 10 m of transects increased substantially in 2025, with counts of the same relative area showing more than double 2024 levels.

   In 2025 in the Tidepools, counts averaged 2.92 ± 0.31 SE people within 10 m of each transect, with a transformed maximum of 20.16—the highest Tidepools value since monitoring began. This represents a 37% increase from 2024 (2.14 ± 0.15 SE) and a 214% increase from the 2022 baseline.

   In the Cove, human counts averaged 1.64 ± 0.16 SE, with a maximum of 7.94, marking an 89% increase from 2024 (0.87 ± 0.09 SE) but below 2023 levels (2.98 ± 0.29 SE). Compared to 2022 (1.15 ± 0.15 SE), the 2025 average represents a 43% increase.

   Kalua o Maua transects showed the lowest human presence along the transects.

   Overall, four years of monitoring humans along transects reveals a clear and persistent rise in human pressure, especially in the Tidepools, highlighting the need for continued tracking and targeted management.

   Combined across the Tidepools and Cove, the 2025 mean human count was approximately 2.43 people within a 10 m radius of the transect, more than double the 2024 mean, consistent with long-term patterns of increasing human presence.

b. **Point-in-time human use counts** - based on MPW Makai Watch human use counts:

   i. **Hourly Use**: In 2025, the counts showed a sustained, high visitation across all zones of the Pūpūkea MLCD, particularly within the Kapoʻo Tidepools.

      Hourly patterns showed a consistent rise in in-water users beginning around 8 a.m., peaking between 11 a.m. and 3 p.m., and tapering toward sunset.

      The Tidepools reached the highest densities, averaging 115 ± 17.4 SE individuals at 3 p.m., while the Cove peaked near 65 ± 5.4 SE individuals at midday and Kalua o Maua averaged 66.9 ± 22.5 SE at its 1 p.m. peak.

      These hourly patterns mirror previous years, demonstrating that elevated recreational pressure during mid-day hours has become an entrenched trend.

   ii. **Weekly Use**: Visitation remained uniformly high throughout the week, with little distinction between weekdays and weekends.

      The Tidepools continued to attract the most consistent year-round use, averaging 59–76 people at a single time each weekday, similar to 2024 levels, and reflecting the substantial increases first recorded in 2023.

In contrast, the Cove showed renewed growth, with weekday averages rising to 40–67 individuals, surpassing 2023–2024 levels and approaching the higher counts recorded in 2022. Kalua o Maua followed a similar daily pattern with lower overall use.

iii. **Monthly Use**: Seasonally, human presence remained high through summer months across all zones, but persistent high use continued in the Tidepools into winter months despite hazardous surf conditions.

The Tidepools in particular had mean winter counts of 40–60 individuals, reflecting that this area was perceived to be a sheltered refuge for visitor recreation when surrounding beaches were closed or not swimmable.

These data confirm that visitor use across the MLCD has reached historically high levels, with the Tidepools experiencing the most persistent and concentrated in-water activity. These high visitor counts underscore the ongoing need for adaptive management and safety measures.

c. **Drone Mapping of Human Use:** Drone surveys from 2022–2025 showed consistent concentration of visitors around main access points, with overall human density and areas of use increasing over time.

In the Tidepools, a persistent high-use corridor from the sandy entrance to the exposed seaward end – known as the "Crack"-- expanded in width through 2024–2025, aligning with deeper water and higher coral and āholehole presence.

In the Cove, the entrance hotspot gradually shifted offshore by 2024, while use increased near Keiki/Baby Beach, indicating a shift toward shallow, family-friendly areas. While spatial patterns stayed similar, visitor density grew within these preferred zones.

At Kalua o Maua, 2025 drone flights identified a single hotspot at the south end where access was easiest. Use elsewhere was low and consisted mostly of swimmers.

4. **Human Impacts on Biodiversity:** The 2025 study focused on several indicators of the impacts of human presence on biodiversity: (a) fish abundance and richness, (b) benthic impacts, and (c) coral size and damage.

a. **Fish**: In 2025, non-schooling fish abundance and richness showed modest but zone-specific responses to human presence, with the most pronounced effects observed in the heavily visited Kapoʻo Tidepools. Non-schooling fish biomass showed no significant relationship with visitor counts.

Over four years of study, both non-schooling fish abundance and species richness were negatively related to human presence at both the Kapoʻo Tidepools and Cove in 2022, and showed weaker but still significant declines with higher visitor numbers at the

Tidepools in 2024 and 2025. This pattern suggests that localized human disturbance continues to influence non-schooling fish communities in the Kapoʻo Tidepools despite some interannual variability in sampling conditions.

b. **Benthic**

i. **Coral size**: The 2025 broad-scale coral impact surveys documented recent damage, including breaks, scrapes, partial mortality, paleness, and bleaching across all zones.

The highest proportions occurred near major access points at Kalua o Maua, Kapoʻo Cove, and the Tidepools high-use corridors between the sandy entrances and the seaward points, all areas with elevated visitor density.

Statistical modeling confirmed that coral damage increased significantly with human density ($\beta = 0.34 \pm 0.16$ SE, $p = 0.035$), while depth and colony size were not significant predictors.

Human use ranged from near-zero to over 150 persons ha^{-1}; predicted damage probabilities rose from ~15–20% in low-use areas to over 40% in the most heavily visited sections.

By focusing on recent damage rather than long-term conditions (e.g., disease, algal overgrowth), the analysis directly linked short-term physical and stress-related coral injuries to chronic human presence.

Although other environmental factors also influence coral condition, these results show a strong spatial alignment between visitor hotspots and coral damage, indicating that reducing or redistributing human use could lessen direct impacts and support reef resilience.

ii. **Visitor Impacts**: In 2025, Visitor Impact Surveys (VIS) tracked the first 10 minutes of in-water behavior for 52 visitors at Kapoʻo Tidepools and Kalua o Maua, focusing on substrate contact rather than GPS-mapped movement.

Footwear played a major role in how often and what types of substrate visitors contacted when in the MLCD. Shoes (including reef shoes, street shoes, and tabis) resulted in the highest overall number of substrate contacts per person within 10 minutes (6.50), followed by fins (4.85), while bare feet produced the fewest (2.86).

Substrate-specific patterns also differed: fin users made the most contact with coral (6) and frequently contacted turf/colonized rock (4.38), barefoot visitors had relatively little coral contact (1) and moderate limu contact (1.2), and shoe-wearing visitors most often contacted turf/rock (5.38) while contacting coral and limu less frequently.

These patterns indicate that footwear elevates both the frequency and ecological impact of contact through standing, walking, or unintended fin strikes, whereas barefoot visitors cause the least disturbance.

5. **Biological Carrying Capacity**

   a. Based on analysis of the relationships between human visitation and multiple biological indicators, the most dynamic (across the range of human density) and persistent effect (across study years) of human presence was on non-schooling fish abundance in the Kapo'o Tidepools. For this reason, the analysis focused on this relationship to identify a specific threshold of human use to apply for management.

   b. Threshold analysis showed that fish abundance is maximized when human presence is at zero and reaches a local minima at a little over 1 human per 10m radius. Thus, a proposed threshold of 1 human per 10m radius provides a conservative estimate for a biological carrying capacity for the Kapoʻo Tidepools.

   c. By extrapolating to two calculations of the area of the Tidepools, the study identifies a carrying capacity range of 27 - 31 humans in the Tidepools at any given time.

These findings from the 2025 Year 3 Biological Carrying Capacity (BCC) study under Act 31 highlight the continued need for proactive management of in-water human activity and sustained scientific monitoring to evaluate long-term ecological responses within the sensitive areas of the Pūpūkea MLCD.

Elevated and persistent human use, particularly in the Kapoʻo Tidepools and increasingly in the Cove, underscores the importance of implementing targeted management measures to mitigate visitor impacts and support reef resilience while allowing responsible recreational use.

The analyses and supporting data are presented in detail below, and the recommendations for future research and adaptive management for ensuring the longevity of this resource are outlined in the "Recommendations" section.

II. Introduction

This introduction largely repeats the background information provided in the Year 1 and 2 reports in order to provide the same foundation for the reader to interpret the following Year 3 analysis below. This Year 3 report also includes data from prior years for comparison. The current report also has expanded the scope from previous years, including the addition of a new site within the MLCD (Kalua o Maua) and the evaluation of fish size distribution and biomass.

Nearshore marine environments in Hawaiʻi are threatened by concerted local and global stressors that decrease the functionality of biological systems. Global threats include increased sea surface temperatures, ocean acidification, and extreme weather events that can cause large-scale ecological changes. Chronic local stressors that can exacerbate regional or global threats include sedimentation, nutrient runoff, plastic pollution, resource depletion such as overfishing, and excessive human influence through recreational or extractive activities and tourism. The State of Hawaiʻi Department of Land and Natural Resources (DLNR) has authority under H.R.S. Chapter 190 to establish and manage Marine Life Conservation Districts (MLCDs) in order to conserve and replenish Hawaiʻi's marine resources, which can be an effective strategy to mitigate these global and local stressors.

In Hawaiʻi, MLCDs are the highest level of state marine managed areas where most "take" of marine life is prohibited. These protected areas are typically designated and managed to protect and enhance the abundance and richness of marine life in a particular area and to support spillover into adjacent areas where take (e.g., fishing) is allowed (Stamoulis and Friedlander, 2013). MLCDs also contribute to the protection of coral reefs in the long-term by reestablishing populations of herbivores that reduce macroalgal competition with coral colonies. MLCDs are popular tourist destinations for marine recreational activities such as snorkeling, SCUBA diving, and swimming. MLCDs also contribute to the ecological, social, and economic value of Hawaiʻi's reefs statewide. Healthy marine protected areas in Hawaiʻi have an estimated annual value of $34 billion (Bishop, 2011) and coral reefs generally provide an estimated $836 million value annually in averted damages to property and economic activity to the Hawaiian islands (Storlazzi et al., 2019).

Figure 1. Map of Pūpūkea Marine Life Conservation District. Source: Pūpūkea MLCD Management Plan (DLNR).

The Pūpūkea MLCD on the North Shore of O‘ahu (Figure 1) was established by the State of Hawai‘i in 1983 after its selection as one of two potential sites for a marine conservation district (Kimmerer and Durbin, 1975) and expanded in 2002-2003 to include Waimea Bay through community stakeholder consultation led by DLNR. In 2021, the MLCD rules were amended by DLNR, in response to a request by Mālāma Pūpūkea-Waimea (MPW), to include the Kapo‘o Tidepools due to their ecological importance, constant and high levels of human use for recreation and tourism, and numerous poaching violations (Hawai‘i Department of Land and Natural Resources 2021).

The Pūpūkea MLCD is a no-take marine reserve, with the exceptions of commercial fishing of two fish species (akule and ‘ōpelu) during seasonal periods in Waimea Bay only, restricted line fishing from shore in Waimea Bay only, and hand harvesting of limited amounts of two species of limu (macroalgae) - limu kohu (*Asparagopsis taxiformis*) and limu lipe‘epe‘e (*Laurencia sp.*).

The Pūpūkea MLCD is one of the most popular spots on Oʻahu for recreational snorkeling and diving (Friedlander et al., 2005). The popularity of this North Shore marine reserve is largely due to the large proportion of endemic biodiversity, the unique geological and oceanographic conditions of the area, and the relative ease of beach access and facilities.

One purpose of MPAs is to restore fish stocks in an area in order to create a spillover effect into nearby water (Stamoulis and Friedlander, 2013). Preventing or limiting fishing allows fish populations to rebound in the restricted area. Friedlander et al. (2007) found more robust fish assemblages in MPAs around the state of Hawaiʻi. At the Pūpūkea MLCD, Stamoulis and Friedlander (2013) found 2.5 times higher resource fish biomass inside of the Pūpūkea MLCD compared to adjacent non-protected areas. In Kāneʻohe Bay on the windward side of Oʻahu, herbivore biomass was higher inside of the MPA (Moku o Loʻe Hawai'i Marine Laboratory Refuge) than in surrounding fished areas (Stamoulis et al., 2017). MPAs additionally can prevent the loss of coral cover in the long-term (Selig and Bruno, 2010) through the establishment of a trophic cascade by protecting and replenishing grazer populations and limiting macroalgal competition (Mumby et al., 2007).

Fish are an important component of healthy marine ecosystems and when fish stocks are depleted, the ecosystem can become degraded. This degradation of the habitat and the fish populations can be exaggerated by the impacts of chronic local stressors (Gissi et al., 2021). Land-based nutrient and sediment run-off to ocean waters through large storm events and groundwater lead to declines in coral cover, fish biomass, and trophic integrity, while overfishing leads to declines in fish biomass (Weijerman et al., 2018). These local stressors work additively with global stressors, such as ocean heating and ocean acidification (Pandolfi et al., 2011), to contribute to functional collapse in nearshore coral reef ecosystems. Therefore, it is important to monitor how managed areas are faring under the environmental conditions with the added stressor of high human presence.

The Pūpūkea Marine Life Conservation District (MLCD) spans the ahupuaʻa of Pūpūkea and Waimea, areas rich with ancestral place names that reflect both cultural and ecological significance (Stephenson, 2025). The name Pūpūkea has been translated in ʻōlelo Hawaiʻi to mean “a stone used as an octopus lure” or “white shell,” each interpretation highlighting traditional subsistence practices, particularly heʻe (octopus) fishing, and the intimate ecological knowledge held by generations of coastal stewards.

Within Pūpūkea, Kapoʻo, popularly known today as “Sharks Cove” for reasons unrelated to the traditional name, derives from the word for “loud echoing sound . . . as of waves booming,” describing the powerful swells characteristic of the area (Mālama Pūpūkea-Waimea, n.d.). Kalua o Maua, called “Three Tables” for its flat reef outcroppings, is associated with a moʻolelo about a wahine named Maua, sometimes depicted as a skilled fisher who disappeared one night and was later found transformed into a stone on the reef. The reefs expose freshwater seeps, or punawai, that local communities historically used for freshwater collection during droughts (Mālama Pūpūkea-Waimea, n.d). Together, these ancestral names and stories embed ecological knowledge, subsistence practices, and a deep cultural connection to the land and sea, reinforcing the biocultural significance of the MLCD and guiding contemporary conservation and stewardship efforts.

The Kapoʻo "Tidepools" are a unique nearly 3-acre marine ecosystem comprised of shallow water, rocky areas, tidal ocean influx, and groundwater discharge sites that is protected from the open ocean by a rocky limestone "wall" and "papa," or flat reefs, on the outside of the wall. The area was created in the 1930s from commercial quarrying of the then hard rock and coral rubble for road building materials. The area is technically not a "tidepool" because it has many connections to the larger ocean area, particularly through a large opening (called "the Crack") in the west-facing wall and through a wide rocky channel on the North end connected to the adjacent Cove. Other submerged smaller channels and tunnels in the border-wall allow for additional ocean water exchange and support constant flushing of new ocean water except at the lowest tides.

The adjacent "Cove" features large boulders, arches, shelves and submarine caves in deeper water that opens up into the surrounding MLCD. This area is in continuous connection with the open ocean and subject to the seasonal changes that occur, such as the large waves and strong currents in the winter.

Nearby Kalua o Maua contains similar papa formations, or "the tables," that stretch in a row across the entrance of the shallow cove. On its western side, an extended rocky wall defines the cove's edge. The area is characterized by large boulders, coral reefs, submarine arches and valleys, along with submarine groundwater discharge (SGD) vents where freshwater enters the ocean. A sandy beach stretches its length and includes a sandy access point to the water. The accessibility coupled with the relatively high coral cover make it a popular location for recreation including snorkeling, SCUBA, and swimming.

These areas are subject to the same dramatic seasonal changes; in the summer, Kalua o Maua and the Kapoʻo Tidepools and Cove (commonly referred to as "Sharks Cove" or "Pūpūkea Cove") are characterized by "flat" conditions – weak currents and small waves. These conditions attract constant recreational use for snorkeling, swimming, and SCUBA, including a high number of visitors with less experience in the ocean. In the winter, large North Shore waves make the Cove and Kalua o Maua dangerous and unusable for recreational use.

However, the Tidepools continue to be heavily used in the winter and under all surf conditions because they are usually protected from the large swells by the outer rock wall and are easily accessible from Pūpūkea Beach Park. While the Tidepools offer more shelter compared to the Cove, recreational users still face significant risks, especially during periods of high surf when waves overtopping the rock wall can sweep at high speed and volume through the Tidepools and pull unsuspecting visitors into the even more dangerous Cove. This high human use and dangerous winter conditions at Kapoʻo have prompted the City Department of Ocean Safety to plan for installing a new lifeguard tower at the Tidepools in Spring 2026.

The ecological and social importance of Kapoʻo, coupled with the potential for environmental degradation resulting from human use, highlights the need for effective biological monitoring and management and was a major impetus for the Legislature's passage of Act 31.

Act 31 is a three-year study that aims to inform management and protection of marine life in the "sensitive areas of the Pūpūkea marine life conservation district" (S.B. 3330, 2022). This type of monitoring and action is needed due to the high numbers of visitors this MLCD receives and the degradation that occurs as a result of unmanaged visitor activities, pollution, and wildlife disturbance (Lin et al., 2023, Sunlu, 2003). Visitor activities such as sportfishing, swimming, snorkeling, and SCUBA diving (Hall, 2001) can directly and indirectly cause damage to the biological resources (Hall 2001, Zakai and Chadwick-Furman, 2002). The physical presence of people, even when they do not come into physical contact with the marine life or reef can indirectly alter fish behavior and decrease biomass (Weng et al., 2023, Watson and Harvey, 2007).

The objective of the Act 31 marine studies has been to scientifically examine biological carrying capacity by assessing effects of human use to inform visitor management recommendations for the Pūpūkea MLCD. The Year 3 findings presented in this report are the ongoing and cumulative results from this multi-year investigation.

III. Methods

Year 3 field surveys were conducted from April 22, 2025 through August 26, 2025 within the Kapoʻo Tidepools, adjacent Cove, and Kalua o Maua within the Pūpūkea Marine Life Conservation District (MLCD). The methods used in field surveys were largely the same as in the Year 2 study, including: fixed transects navigated by using GPS, fish and mobile invertebrate surveys with human presence counts, water clarity measurements, coral bleaching surveys, benthic community analysis, temperature monitoring, human use counts, drone human use surveys, and visitor impact surveys. Additionally, Year 3 included recording of the total length of fish within transect surveys, which was used along with established length–weight relationships to calculate biomass.

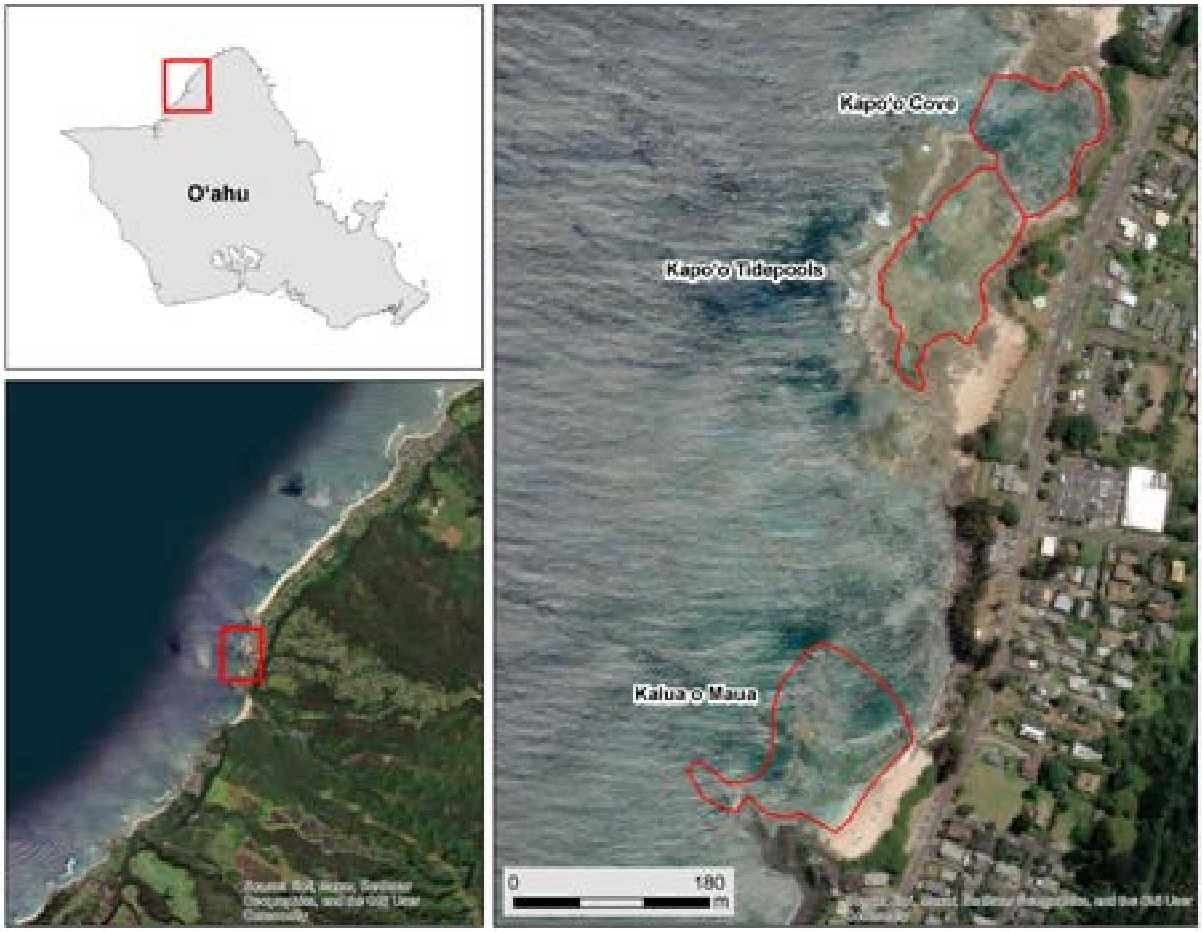


Figure 2. Overview of Pūpūkea MLCD Act 31 study sites.

Over the Act 31 period, the MPW marine teams conducted a total of 108 survey days, 920 hours in the water, and 1,617 transect and radial surveys. In 2025, Year 3, the marine team work comprised 36 survey days with roughly 349 working hours in the water, with 319 fish and benthic transect surveys, 48 coral transect surveys, and 43 radial coral impact surveys, compared to Year 1 that had 31 survey days, 240 hours in the water, and 544 transects, and Year 2 with 41 days of surveys of the Kapoʻo Tidepools and adjacent Cove, representing 331 hours in the water, with a total of 663 transect surveys, including winter survey dates. Detailed procedures can be found in the "Marine Science Coordinator Protocols" and in Appendix C that outlines all procedures for in-water surveys and analysis of data.

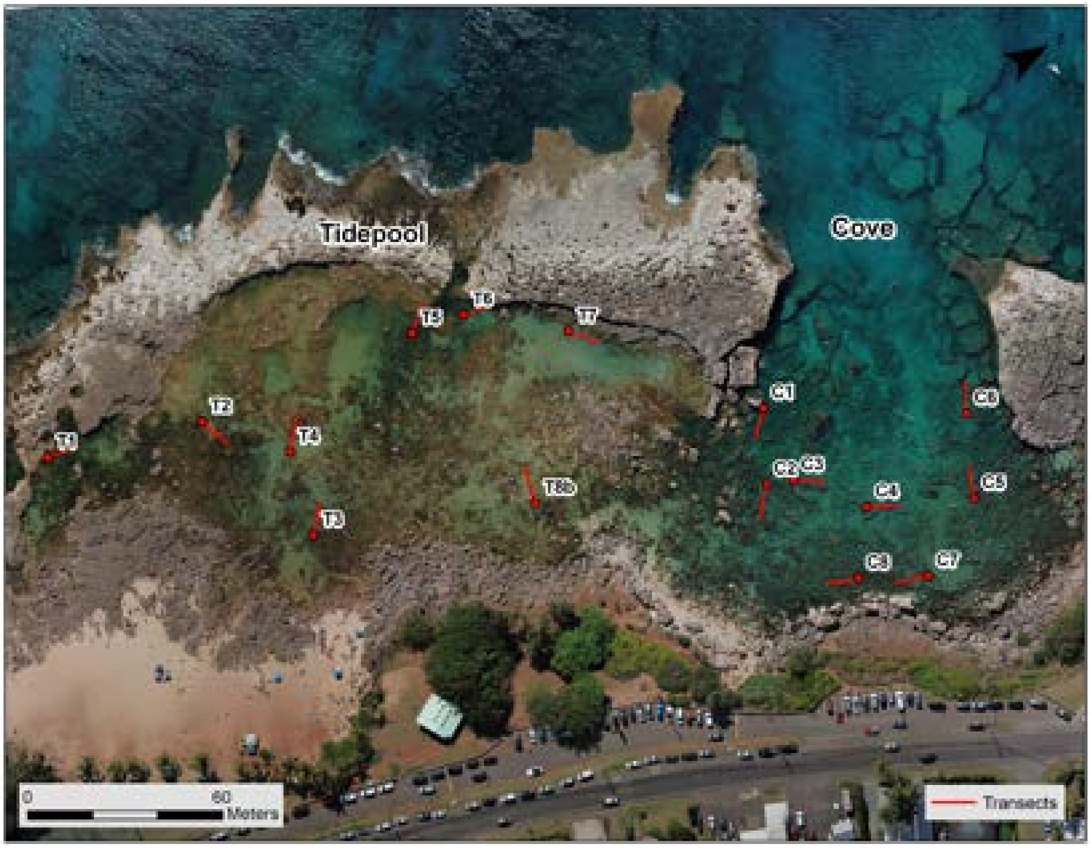


Figure 3. Map of survey areas and fixed transect locations
within the Kapo‘o Tidepools and Cove.

Figure 4. Map of survey areas and fixed transect locations within Kalua o Maua

A. Fish and Mobile Invertebrate Transects with Human Use Count

Following the Years 1 and 2 methods, fish and mobile invertebrate richness and abundance, human presence, and water clarity surveys were quantified through biweekly visual transects for the duration of the study period. Year 3 expanded methods to include recording the total length of fish within transect surveys, which was used along with established length–weight relationships to calculate biomass. Biomass, the estimated weight of fish in an area, provides a key indicator of ecosystem health and can be used to compare the productivity and resilience of the different areas surveyed, evaluate potential impacts from human activity, and assess whether certain areas function as important nursery grounds based on the relative abundance of smaller size classes (Karachle and Stergiou, 2012).

Sixteen transects established by the 2022 Marine Science Coordinator Ellie Jones and Advisor Kosta Stamoulis in consultation with MPW were determined and regularly surveyed within the study area: eight in the Tidepools and eight in the Cove. Transect location criteria included a ten-meter by four-meter area with greater than 50% hard bottom habitat in generally heavily-visited portions of the surveyed area. In Year 3, Transect 8 in the Tidepools was shifted to nearby “T8B,” due to changing benthic composition and an inundation of sand and boulders that left a portion of the original transect out of the water (Figure 3). Additionally in Year 3, a new set of eight transects was established in the Kalua o Maua study area by Emily Summers, Kosta Stamoulis, and Callie Stephenson, with input from MPW, following the same criteria for establishment as the Kapoʻo transects (Figure 4). All transects were repeated year-after-year using GPS and by matching exact benthic features of permanent structures that did not change over time, without the use of installed rebar pins.

The marine research team counted and identified fish within two meters on either side of the ten-meter transect line (40m^2) and mobile invertebrates within one-meter to either side of the transect (20m^2). Water clarity was then measured with a 2.5-inch diameter secchi disk at each transect (Figure 5), which provides a measurement of visual distance underwater and is used as a proxy for water clarity. (See Appendix C for standard operating procedures.)

During each survey, humans within 10 m of the transect were counted. The way humans were counted changed between 2023 and 2024 (Figure 5); in 2022-2023, humans were counted within a 10 m radius from the center of the transect, but in 2024-2025, the method changed to anywhere within 10 m of the entire transect. This area change was accounted for during analysis and data have been transformed to account for the survey area increase in 2024-2025.

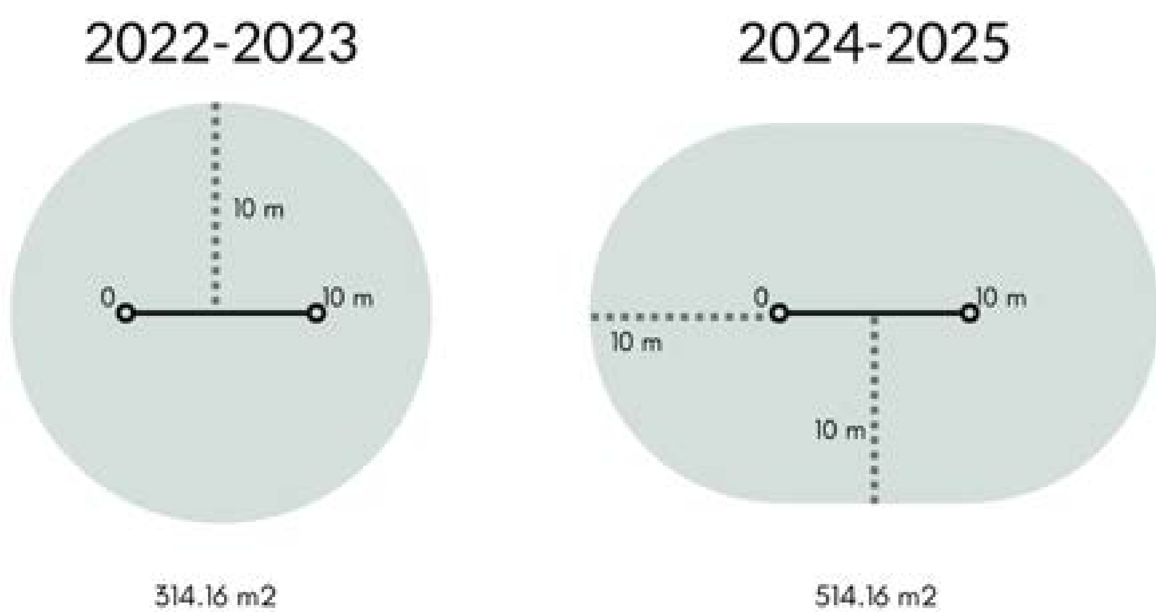


Figure 5. Demonstrates the method for counting humans within 10 m of the transect, and the shift in area size that occurred between 2023 and 2024 that is accounted for in the analysis.

B. Coral Health Surveys

Coral health surveys were conducted to assess bleaching and monitor the health of coral colonies in Kapoʻo and at Kalua o Maua at the beginning and end of the Year 3 survey season. In Years 1 and 2, surveys were conducted monthly over the course of the study period, but due to the addition of eight transects at Kalua o Maua and their associated higher coral cover, surveys were done with less frequency in Year 3.

These surveys monitored every coral larger than 10 cm in maximum diameter within one meter of either side of the transect line, recording their lowest taxonomic identification, longest diameter (cm), health as associated with color using the Koʻa Card (Bahr et al., 2020), and any signs of fish bites or damage (Figure 6).

The researchers used the Koʻa Card, a coral health assessment tool that utilizes different colors as a tool to assess health. Because coral color is largely determined by the concentration of symbionts in the coral tissue, typically, the darker the color, the better the function of a coral's metabolism (photosynthesis and calcification).

Additionally, a broad-scale coral impact study, previously referred to as the "roving coral survey," was conducted at each zone. This survey intended to more holistically document and gauge impacts to corals across a broader spatial scale for comparison with drone-derived patterns of human distributions. Every coral above 10 cm was photographed, identified to the lowest taxonomic level, and measured at its longest diameter. Any observed damage was documented, including the type and size of the damage.

In Year 3, the methods for this survey changed to accommodate the addition of Kalua o Maua, which added more transects as well as higher coral cover. Points were distributed in a grid laid over each survey area in GIS and navigated using a GPS in the field. Two transects were laid down perpendicular to each other at the selected point and each coral within a two meter radius was surveyed. (See Appendix C for descriptions of methods and step-by-step procedures.)

Figure 6. Health assessment using a Ko‘a Card (photo from 2024).

C. Benthic Composition Photoquadrats

Benthic cover was assessed along the 24 transects within the Tidepools, Cove, and Kalua o Maua using the same methodology for photo quadrats as in Years 1 and 2. In Year 3, benthic cover was assessed in June 2025, as opposed to September 2023 and early February 2024 in Year 1.

Digital images were captured along each 10-meter transect using an Olympus Tough TG-6 digital camera mounted on an aluminum monopod frame (Figure 7). The camera was positioned 0.5 m above the substrate, allowing for a 50 cm × 67 cm image, with the exception of T6 and T7. For these transects, the benthos are predominantly sand. For this reason, photo-quadrats were taken on the adjacent wall of the transect at the midpoint. Photos were taken at one-meter intervals along each transect.

Each photo was analyzed using CoralNet (UCSD), a tool for benthic image analysis, to quantify percent cover of relevant benthic habitat categories. The semi-automated tool allows easy classification of organisms and substrates. Additionally, the tool generates percent cover calculations. Using CoralNet methods, fifty random points were distributed on each of the benthic quadrats. The benthic substrate was classified under each point to the lowest taxonomic level possible, then analyzed for percent cover and benthic community composition.

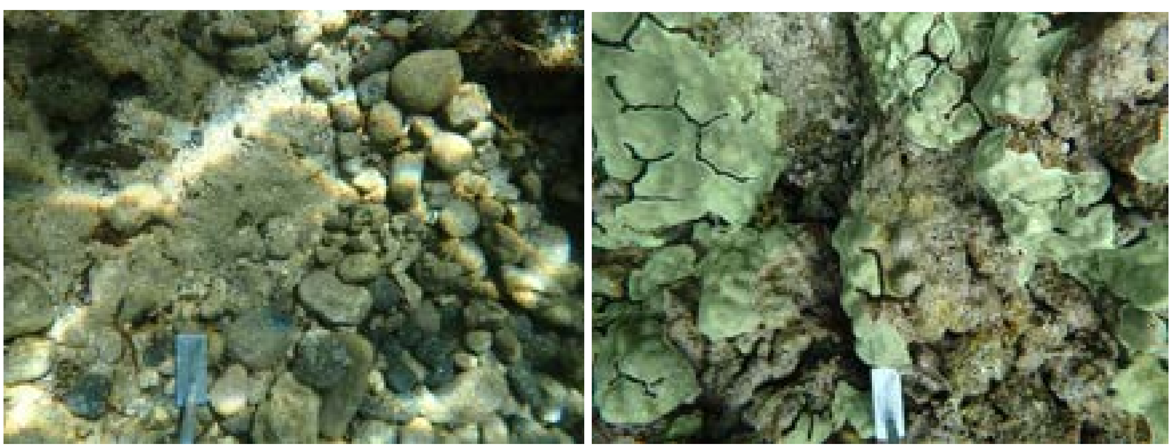


Figure 7. Example of Year 3 benthic photo-quadrat from A) Tidepools and B) Kalua o Maua.

D. Rugosity

As in Years 1 and 2, in Year 3, rugosity measurements were conducted at each transect at all sites using a chain with a 1.3 cm link length (Figure 8). To account for observation error, three measurements were taken at each transect and averaged to determine the mean rugosity. A 10-meter transect tape was positioned along each transect, after which the chain was unspooled and laid along the tape, following the natural contours of the reef. The length of the chain was then compared to the transect length to calculate the rugosity ratio by dividing the chain length by the transect length. For example, a 10 m transect with a

10 m rugosity chain gives a ratio of 1, indicating low rugosity, while a 10 m transect with a 20 m chain gives a ratio of 2, indicating higher rugosity.

Figure 8. Laying down a rugosity chain along a transect at Kalua o Maua.

E. Water Temperature

As in Years 1 and 2, Year 3 water temperature at Kapoʻo was monitored using a layout of Onset© HOBO water temperature Pro V2 data loggers with an accuracy of +/- 0.53°C and range of -20° C to 70°C. Kalua o Maua did not have temperature loggers deployed in Year 3.

Loggers were calibrated prior to placement by immersion in water baths at 0°C and 30°C using a certified thermometer and water bath. Loggers were then attached to inconspicuous concrete encasements embellished by shells taken from outside the MLCD, affectionately named "HOBO Houses" (Figure 9) and deployed in the water following the specifications of DAR Special Activity Permit DAR SAP 2026-12 and OCCL SPA OA 24-07.

Loggers were programmed to record water temperature at 1-hour intervals. On June 19, 2025, a logger was deployed at transects 1 and 4 in the Tidepools and at 1 and 4 in the Cove (Figure 10). On July 17, 2025, seven more loggers were deployed at transects 2, 6, 7 and 8B in the Tidepools, and at transects 3, 6 and 8 in the Cove.

The loggers were removed from the Cove on October 2, 2025 before large winter swells arrived, but kept in the Tidepools to record possible predicted temperatures that would lead to thermal coral bleaching, then removed on October 30, 2025. The logger at Tidepools transect T8B was paused and then redeployed after 3 days due to being removed from the water by a visitor.

Figure 9. Deployed temperature logger at Transect 2 in HOBO House in the Tidepools.

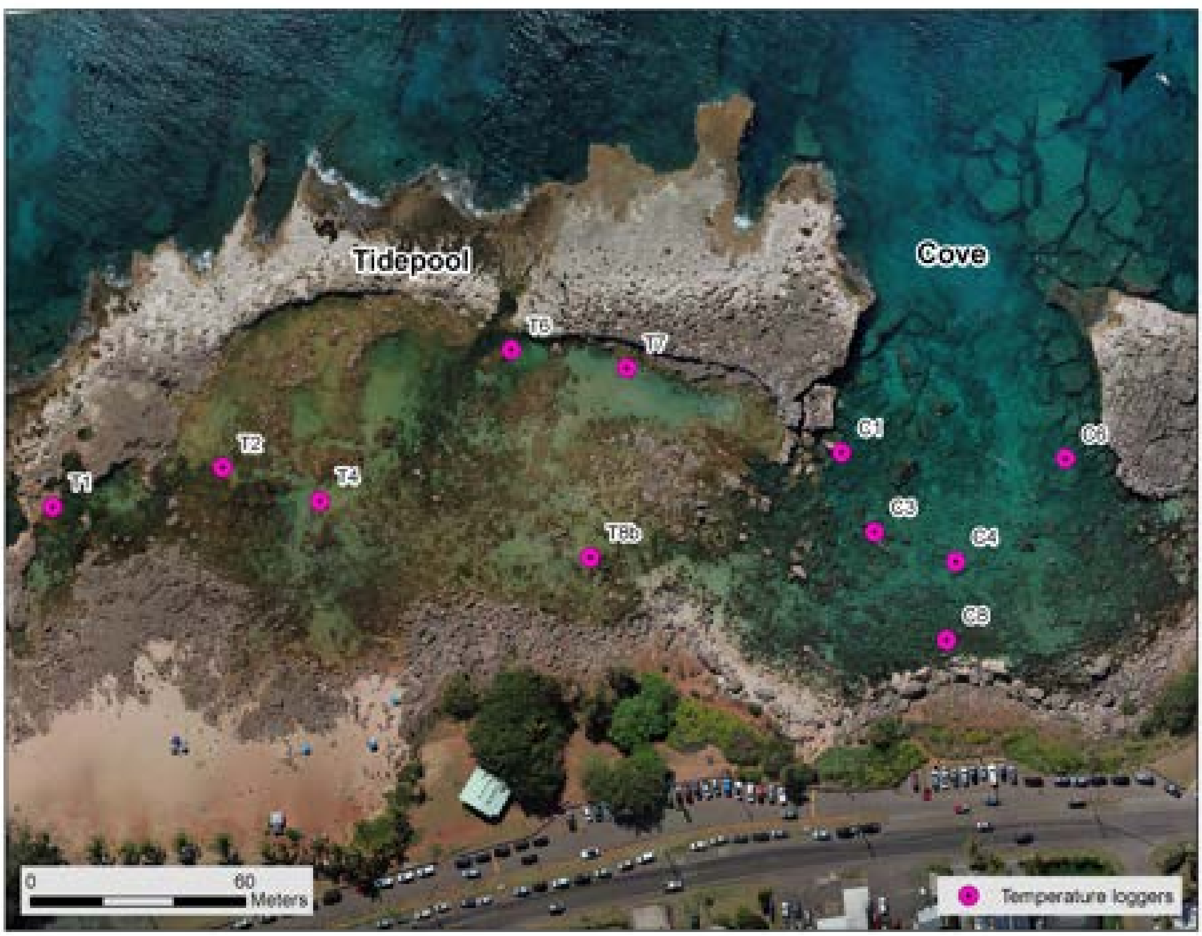


Figure 10. Locations of temperature loggers in the Kapo‘o Tidepools and Cove

during June-October 2025.

F. Human Use Counts

Human use counts of all users were obtained through MPW's long-standing Makai Watch Program and consisted of categorizing and counting visitors in the different sections of the Kapoʻo area of the MLCD. Survey zones included the Tidepools, the Cove, and Kalua o Maua. Users were classified as swimmers, snorkelers, SCUBA, rock walkers, reef waders, paddlers, kayakers, or other. In 2024, categories were refined to combine swimming and snorkeling into "swimmers/snorkelers in water (not standing)" and "people standing in water (on sand or reef/rocks)." The number of people observed participating in each activity in each area was recorded by MPW staff and volunteers with the date, time, moon phase, weather, wind, and surf conditions. This study reports on in-water human use numbers most relevant to marine organisms, which comprise swim, snorkel, and SCUBA uses.

Additionally, as explained above, data were taken along each fish and benthic transect to record the number of humans within 10 m of each transect at the time of the survey.

G. Drone Surveys

Similar to Years 1 and 2, as part of the Year 3 Act 31 study, four unmanned aerial vehicle (UAV) surveys were conducted by Shoreline Conservation Initiative to map human use patterns at Kapoʻo and in 2025, Kalua o Maua was included.

Each UAV flight was conducted during high-use times from 10 am - 5 pm and alternated between high and low tide conditions to account for variation in human use based on water depth.

Human use was characterized using QGIS software after flight images were compiled into an orthomosaic. 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. 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 four kernel density rasters were then averaged to derive the final human density surface used for analysis.

H. Visitor Impact Survey

In Year 3, MPW, in collaboration with a visiting group of students under the supervision of Dr. Heather Page from the Sea Education Association (SEA), Woods Hole, Massachusetts, continued its Visitor Impact Survey (VIS) program to monitor human interactions with the nearshore marine environment. Building on surveys conducted in 2022-2024, the 2025 VIS study expanded to include Kalua o Maua in addition to Kapoʻo. SEA's "secret snorkelers" discreetly observed visitors for the first 10 minutes of their in-water activities, recording movement patterns, activity type (snorkeling or swimming), footwear, and all substrate contacts. Each contact was categorized by substrate type, such as live coral, turf-covered rock, crustose coralline algae, or macroalgae, with notes taken if visible damage occurred.

Unlike previous years, Year 3 surveys did not incorporate GPS tracking of visitor movements, placing greater emphasis instead on the frequency, type, and potential ecological consequences of substrate contact. The inclusion of data on footwear (fins, booties/reef shoes, or none) aimed to expand the understanding of these different types of visitor impacts.

I. Additional Environmental Data

Other environmental datasets were again acquired from online databases. The distance of each transect from shore was obtained using the measurement tool on QGIS. Tide height was collected using the Haleiwa, Waialua Bay gauge on the "Tides" app (7th Gear). The tidal coefficient from each day was obtained through Tides4Fishing (Tides4Fishing.com/us/hawaii/haleiwa-waialua-bay). Wave height and wind speed and direction were obtained from the National Data Buoy Center (NDBC) and the Pacific Islands Ocean Observing System (PacIOOS) Waimea Bay buoy.

J. Statistical Analysis

Data Accessibility: Many of the same statistical methods used in Year 1 were utilized in Year 3. All statistical models were run using R 4.5.1 (R Core Team (2024). All code and data for analyses are stored in a GitHub repository, with access available upon request to MPW. Details about each model are described below.

Biodiversity of fishes: Changes in the background abundance and species richness of fishes over time (i.e. the fish community when humans were not present) was evaluated using generalized linear mixed models (GLMMS) fitted with the glmmTMB and validated using diagnostics from the DHARMa package. For non-schooling species, the study evaluated changes in abundance using a zero-inflated poisson GLMM with a year by zone interaction and a random effect of transect.

For schooling species, due to the potential for structural zeros, a hurdle poisson model was used to evaluate both the difference in the probability of observing schooling species over time and the abundance of schooling species when present. The two-step model used a binomial distribution to evaluate presence and a truncated negative binomial distribution to evaluate the abundance of schooling fish when present through a year by zone interaction and a random effect of transect.

Schools were defined as observations of at least five fish of a schooling species. Schooling species included manini (*Acanthurus triostegus*, Convict Tang), ʻiao (*Atherinomorus insularum*, Hawaiian Silverside), āholehole (*Kuhlia sp.*, Reticulated Flagtail), ʻamaʻama (*Mugil cephalus*, striped mullet), and uouoa (*Neomyxus leuciscus*, sharpnose mullet) (due to their similar appearance, those two species of mullet were combined for analyses).

In all cases, model fit was evaluated for under/overdispersion, zero-inflation, and outliers. Fish species richness was evaluated relative to the total fish species richness, including both schooling and non-schooling species, using a generalized poisson model with an interaction of year and zone and a random effect of transect.

For 2025 data, the change in biomass between zones was evaluated using GLMMS fitted with the glmmTMB package. Since the biomass observations were continuous data always greater than 0, a gamma distribution with a log link function was used with a fixed effect of zone and a random intercept by transect. Model fit was evaluated for under/overdispersion, zero-inflation, and outliers using the DHARMa package. To address residual heterogeneity the model was refitted to explicitly allow the dispersion parameter to vary by zone.

Human Impacts on Fish Biodiversity: This study examined the relationship between non-schooling fish abundance and human presence across the three monitoring zones using GLMMs with a negative binomial error distribution to account for overdispersed count data. The model included standardized human counts recorded within a 10 m radius, zone, and their interaction as fixed effects, along with water clarity and depth as covariates.

Transect identity was included as a random intercept to account for repeated sampling and spatial dependence among observations. Model residuals were assessed for overdispersion and zero inflation using simulation-based diagnostics, and overall model performance was evaluated using marginal and conditional R^2 values. Zone-specific slopes for the effect of human presence were estimated using marginal trends from the fitted model, holding water clarity and depth at their mean values. Predicted values were visualized for each zone to facilitate comparison among zones. Non-schooling species richness was modeled with a poisson distribution, and biomass with a Gamma distribution and log link to account for the continuous, positive nature of the data, with otherwise identical model structure. To compare results across sampling years, only the summer data for 2024 were used to be comparable to previous sampling efforts (i.e. data from winter months was excluded). In the models incorporating both years of data, both non-schooling fish abundance and biomass were modeled with negative binomial GLMMs.

The study employed a non-parametric approach to evaluate the relationship between fish community composition and human presence by applying the envfit function in R (using the vegan package). The species data were first transformed into a Bray-Curtis dissimilarity matrix to obtain ordination scores, which were then fitted with the environmental variable (human presence). The analysis was run including all observations and restricting the species data to those present in 5% of observations. Statistical significance for species and habitat vectors was assessed using permutation tests with $p < 0.05$ as the threshold and significant vectors were visualized.

Human Impacts on Benthic Biodiversity: To evaluate the relationship between human use and coral condition, the study modeled the probability of recent coral damage using a generalized linear mixed-effects model (GLMM). The response variable was a binary indicator of recent damage, defined as the presence of breaks, scrapes, partial tissue loss, paleness, or bleaching. The study used a binomial error distribution with a logit link to estimate the likelihood of damage as a function of three fixed effects: human density, colony depth, and colony diameter. Human density was derived from drone-based surveys and standardized prior to analysis. Because multiple coral colonies were surveyed within the same locations, and sites differed in baseline levels of damage, the study included a random intercept for location to account for spatial clustering and unmeasured ecological differences among sites.

Human counts from the drone orthomosaic images were obtained using QGIS Version 3.34.2-Prizren. Makai Watch human use counts were analyzed in Microsoft Excel Version 16.48, and figures visualizing the human use data were also generated in Microsoft Excel.

IV. Results and Discussion

A. Biodiversity

1. Fishes

A. Fish Abundance by Year

Fish abundance in Kapo‘o showed notable fluctuations between 2022-2025 with non-schooling species highest in 2022 before declining sharply in the Tidepools in 2023 and 2024, and showing a slight increase in 2025. Schooling species also experienced significant changes, with a decreasing likelihood of encountering schools over time, especially in the Cove.

Fish abundance of non-schooling species in Kapo‘o was highest in 2022 compared to all other surveyed years, with a mean of 24.0 ± 13.9 fish per 40m^2 transect in the Tidepools and 40.7 ± 15.6 fish per 40m^2 transect in the Cove, indicating a peak in population during that period.

Following 2022, observed abundance of non-schooling species in the Tidepools across all surveys declined by 60.5% in 2023 (mean abundance of 14.9 ± 11.8 per 40m^2) and by another 37% between 2023 and 2024 (mean abundance of 10.8 ± 9.7 per 40m^2), a dramatic reduction in non-schooling fish presence. In 2025, the abundance of non-schooling species rose by 15% (mean abundance of 12.8 ± 12.7 per 40m^2).

Because of concurrent changes in human density, the study attempted to understand the background change in the abundance of fishes by evaluating fish abundance on transects without any humans nearby. For these transects, the data continued to show a decrease in non-schooling fish abundance in the Tidepools (Figure 11). Models of this data were done using lognormally transformed fish abundance data with a random effect of transect and fixed effects of depth and water quality. The model estimated a 52% decrease between 2022 (estimated abundance 24.3 ± 4.3 per 40m^2) and 2023 (estimated abundance 11.5 ± 2.1 per 40m^2), with a further decrease of 24.1% in 2024 (estimated abundance 8.7 ± 1.6 per 40m^2), and an insignificant decrease of 0.6% in 2025 (estimated abundance 8.7 ± 1.7 per 40m^2).

In the Cove, abundance of non-schooling species was not significantly different ($p = 0.15$) between 2022 (95% CI: 30.7 - 53.4 per 40m^2) and 2023 (95% CI: 29.6 - 51.5 per 40m^2); however, the abundance of non-schooling species dropped significantly in 2024 (46% decline, 95% CI for 2024: 16.1 - 28.1, $p < 0.001$). In 2025, the abundance of non-schooling fish in the Cove slightly decreased (95% CI for 2025: 15.7 - 27.5 per 40m^2), but was not significantly different from 2024 ($p = 0.86$).

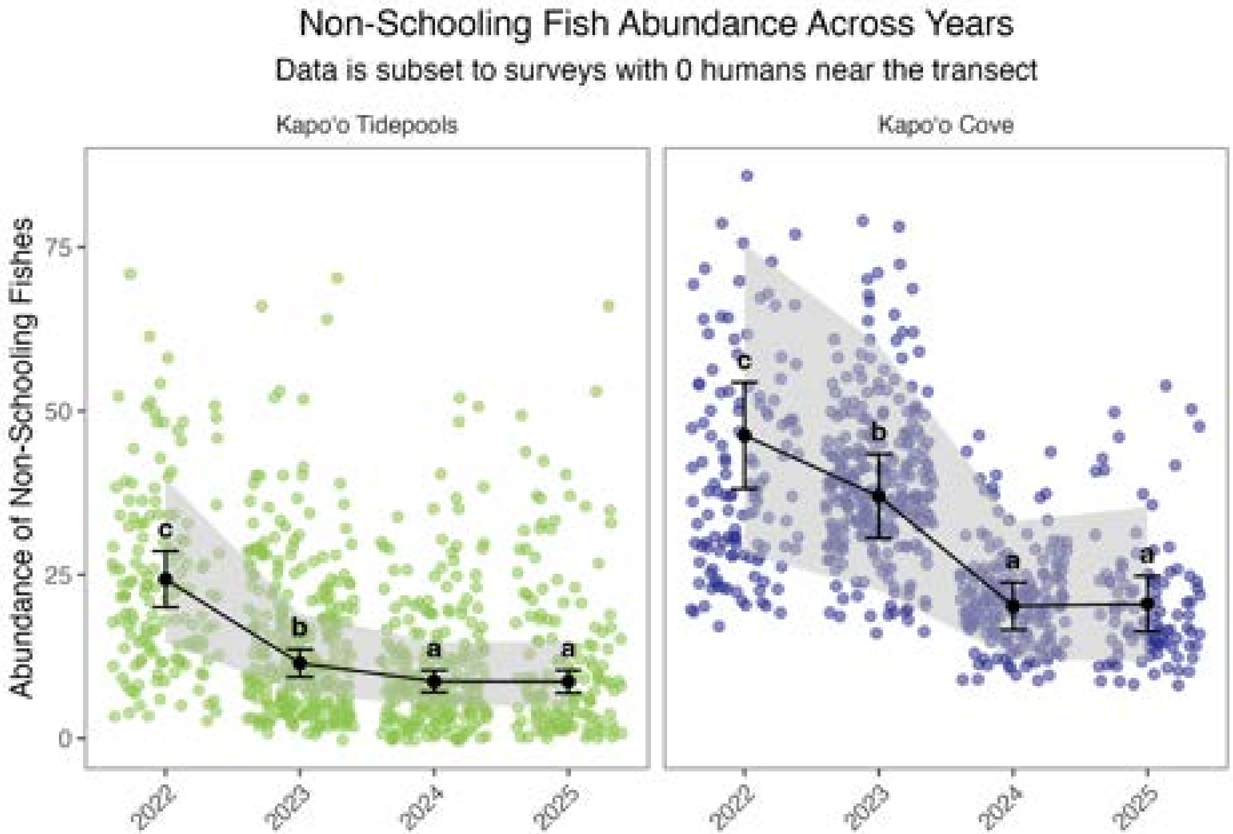


Figure 11. Abundance of non-schooling fish in the Tidepools and Cove from 2022-2025 per 40m^2. Data are represented as jittered points by year, with model-predicted values in black, with standard errors black bars and a gray ribbon for the upper and lower 95% confidence interval.
Letters represent statistical significance between years; years with different letters are significantly different from each other.

Abundance of schooling species was evaluated to test both the abundance of schooling species when present (Figure 12A) and the probability of encountering a school (Figure 12B).

In the Tidepools, the probability of encountering a school showed a declining trend year after year; however, this decline was not significant between 2022 (95% CI: 67.3% - 87.8%) and 2023 (95% CI: 58.5% - 79.9%, $p = 0.44$). This decline was significant between 2023 and 2024 (95% CI: 41.0% - 68.7%, $p < 0.01$), representing a 21.35% drop in probability between 2023 and 2024, and a 30.4 % decrease from 2022 to 2024. This probability continued to decline as well, but was not significantly different between 2024 and 2025 (.95% CI: 30.0% - 67.8%, $p = 0.91$).

Overall, schooling fish are less likely to be present in the Cove than in the Tidepools. The probability of encountering schools of fish in the Cove was highest in 2022 (95% CI: 23.2% - 51.9 %). This probability fell by 81.5% from 2022 to 2023 (95% CI: 2.7% - 16.1%, $p < 0.01$), and remained around this level through 2024 (95% CI: 0.8% - 12.6%; $p = 0.69$), increasing in 2025 (95% CI: 6.5% - 54.0 %; $p = 0.83$).

For the observed schools of fish, the analysis also modeled whether the size of these schools changed over time within each zone.

In the Tidepools, abundance of schooling fish was lowest in 2022 (95% CI: 10.4 - 26.6), increasing by 102.8% in 2023 (95% CI: 20.0 - 56.7, $p = 0.02$), then again by 86.5% in 2024 (95% CI: 37.0 - 106.4, $p < 0.001$). This trend was reversed in 2025, where schooling species abundance declined by 25.9% (95% CI for 2025: 23.9 - 90.6, $p < 0.001$).

Schooling species are notoriously difficult to count *in-situ*, and therefore difficult to model. As such, these results should be interpreted with caution. Local knowledge from community members has suggested that the large school of āholehole (*Kuhlia sandwicensis*, reticulated flagtail) in the Kapoʻo Tidepools has continued to increase.

The mean abundance of schooling species within the Cove has fluctuated over time. Similar to the Tidepools, schooling species abundance in the Cove was lowest in 2022 (95% CI: 5.5 - 20.3). This abundance increased by 214.3% to its peak in 2023 (95% CI: 11.8 - 94.1; $p < 0.001$), significantly falling 57.0% in 2024 (95% CI: 3.5 - 58.7; $p < 0.001$), and significantly increasing again by 48.6% in 2025 (95% CI: 6.6 - 69.2; $p < 0.001$). Given the lack of occurrence of these schools within transect counts, it is probable that these fluctuations are due to stochastic processes intrinsic to the survey methodology and observer bias when estimating school size.

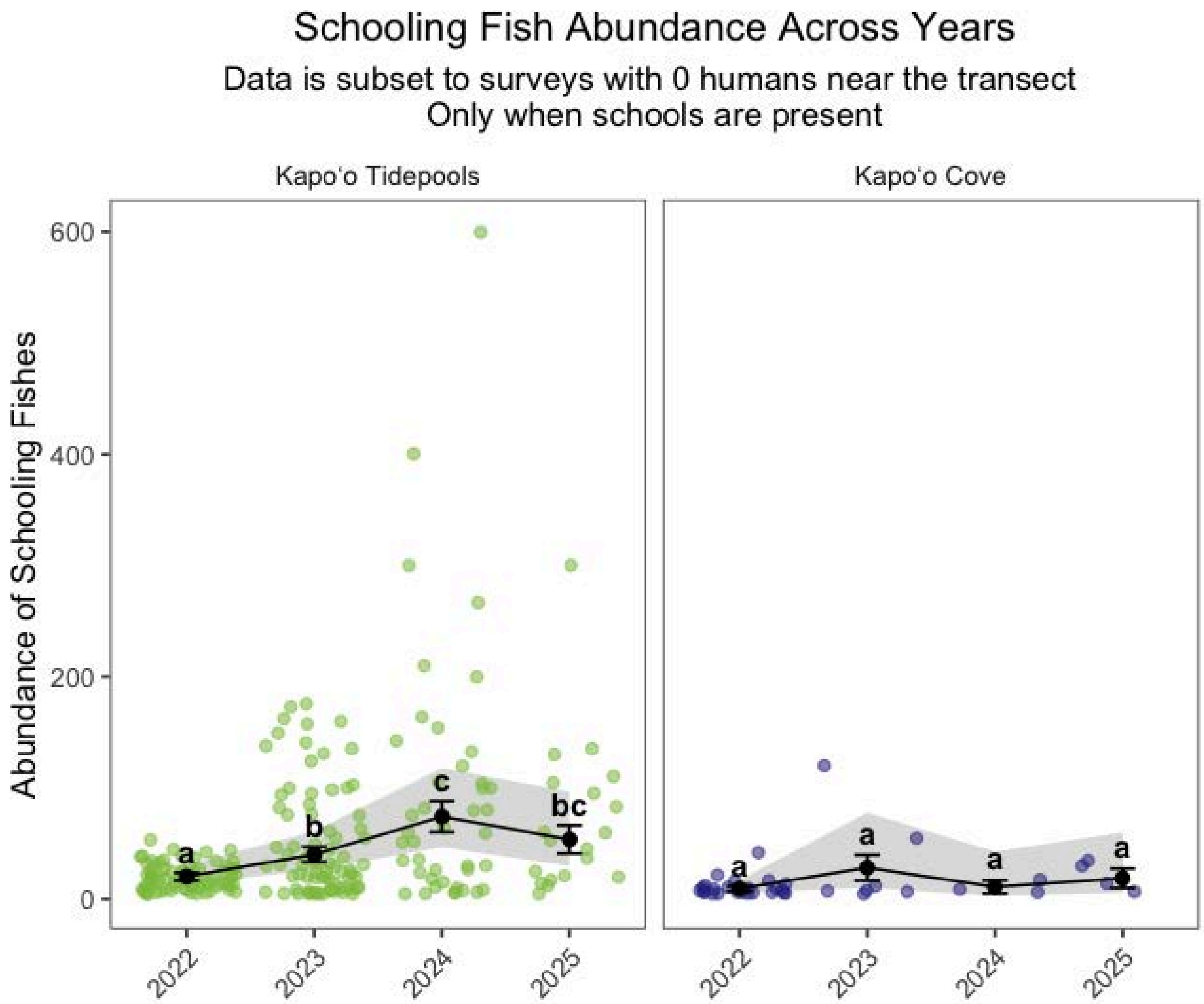


Figure 12A. Abundance of schooling fish in the Tidepools and Cove from 2022-2025. Data are represented as jittered points. Model-predicted values are represented as black dots with standard error bars and a gray ribbon for the upper and lower 95% confidence interval. Letters represent statistical significance between years; years with different letters are significantly different from each other.

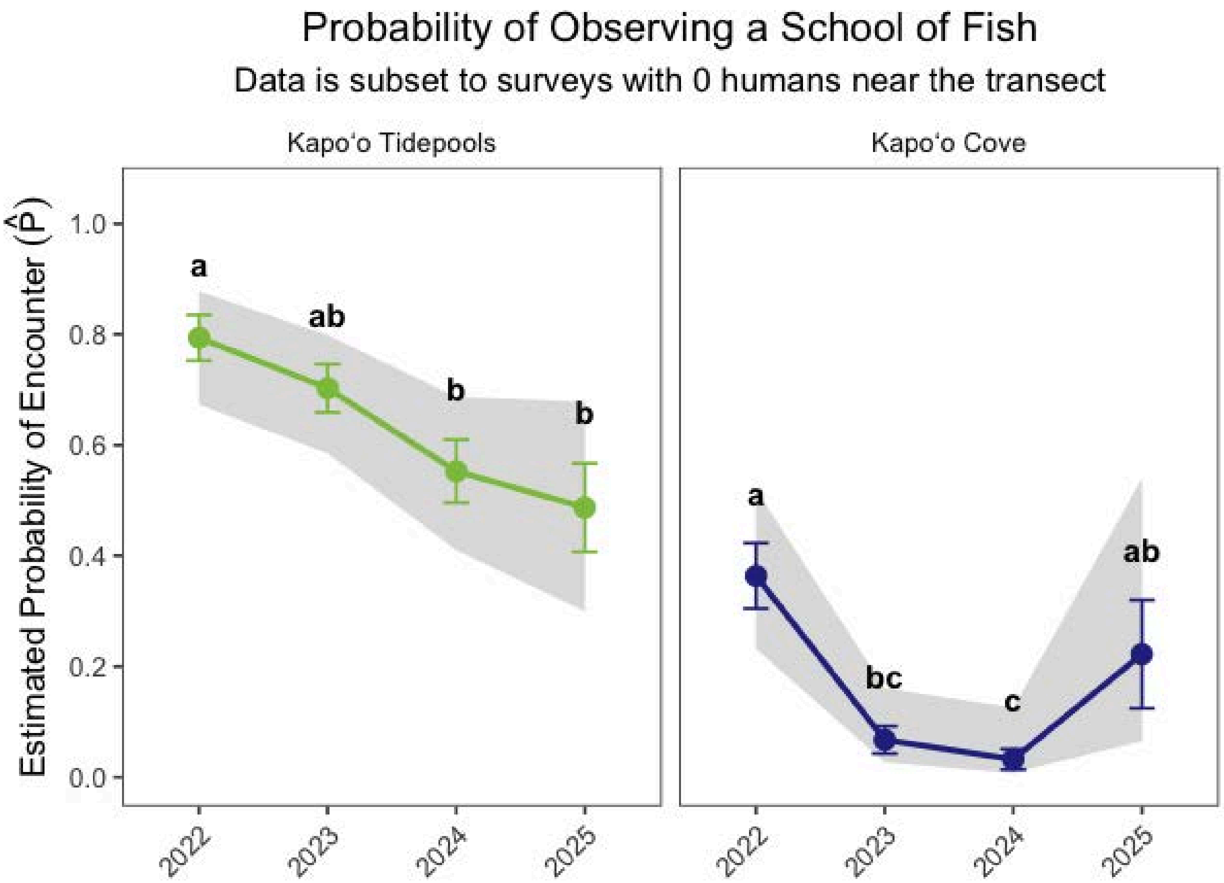


Figure 12B. Probability of observing a school of fish in the Kapo‘o Tidepools and Cove across years.Model-predicted values are represented as black dots with standard error bars and a gray ribbon for the upper and lower 95% confidence interval. Letters denote significantly different groupings of values. Multiple letters represent groups that cannot be distinguished statistically from other groups with the same letter.

B. Fish Richness by Year

The analysis of fish species richness when humans are not present in Kapo‘o reveals a general decline over the years, with both the Tidepools and Cove showing reduced diversity, particularly in non-schooling species.

Fish species richness was modeled with both schooling and non-schooling species included using a generalized poisson model to account for underdispersion.

Fish species richness in Kapo‘o showed a general decline across years in both zones (Figure 13).

In the Tidepools, species richness of non-schooling species was significantly highest in 2022 (95% CI: 8.0 - 11.9, $p < 0.001$), decreasing 22.1% in 2023 (95% CI: 6.2 - 9.3, $p < 0.001$) and further decreasing 25.3% in 2024 (41.7% total decline, 95% CI: 4.6 - 7.0, $p < 0.001$); however, there was no significant difference between species richness in the Tidepools between 2024 and 2025 (95% CI: 4.7 - 7.0, $p = 1.0$).

In contrast, the Cove showed a significant decline in fish species richness each year surveyed. From 2022 (95% CI: 11.6 - 16.9) to 2023 (95% CI: 10.57 - 15.33), fish species richness declined 9.1% ($p < 0.001$), representing the loss of approximately one species observation per 40 m^2 transect surveyed. Richness continued to decline 27.8% in 2024 (34.4% total change, 95% CI for 2024: 7.62 - 11.09, $p < 0.001$), and a further 9.7% in 2025 (95% CI: 6.9 - 10.0, $p = 0.0188$), representing a total decline of an estimated 5.7 fish species observed on each transect, a 40.7% decline in fish species richness from 2022.

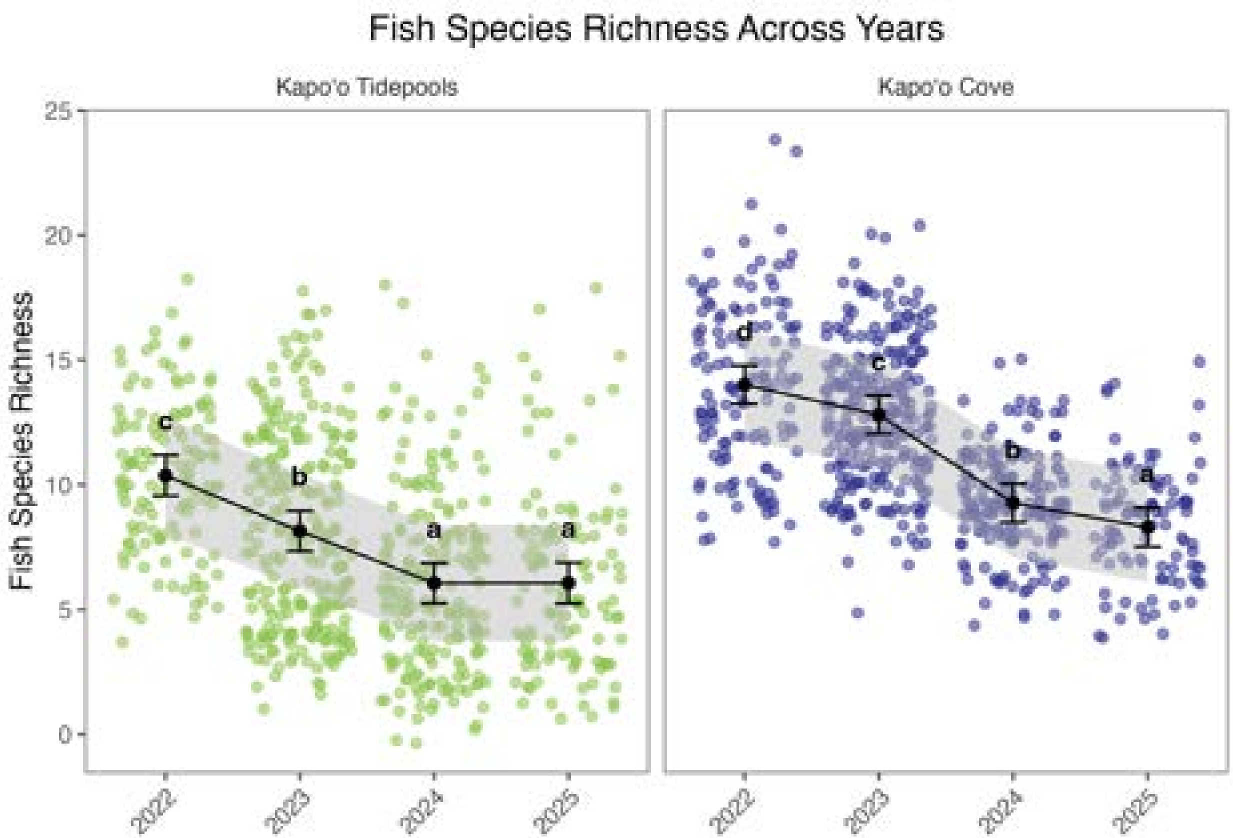


Figure 13. Fish Species Richness between 2022-2025 in both the Tidepools and Cove. Values of fish species richness include both schooling and non-schooling species, and are displayed as estimated values with estimated standard error.
The lettered labels denote significant differences in groups.

The data found a likely assemblage change due to some species being observed in 2022 and 2023 and not 2025, and vice versa. About 35 species were at some point no longer observed between years in the dataset. This gap will be further described below in sections on Fish Abundance by Species, Fish Community Ordination, and Trophic Abundance. Species varied in their detection each year (Figure 14).

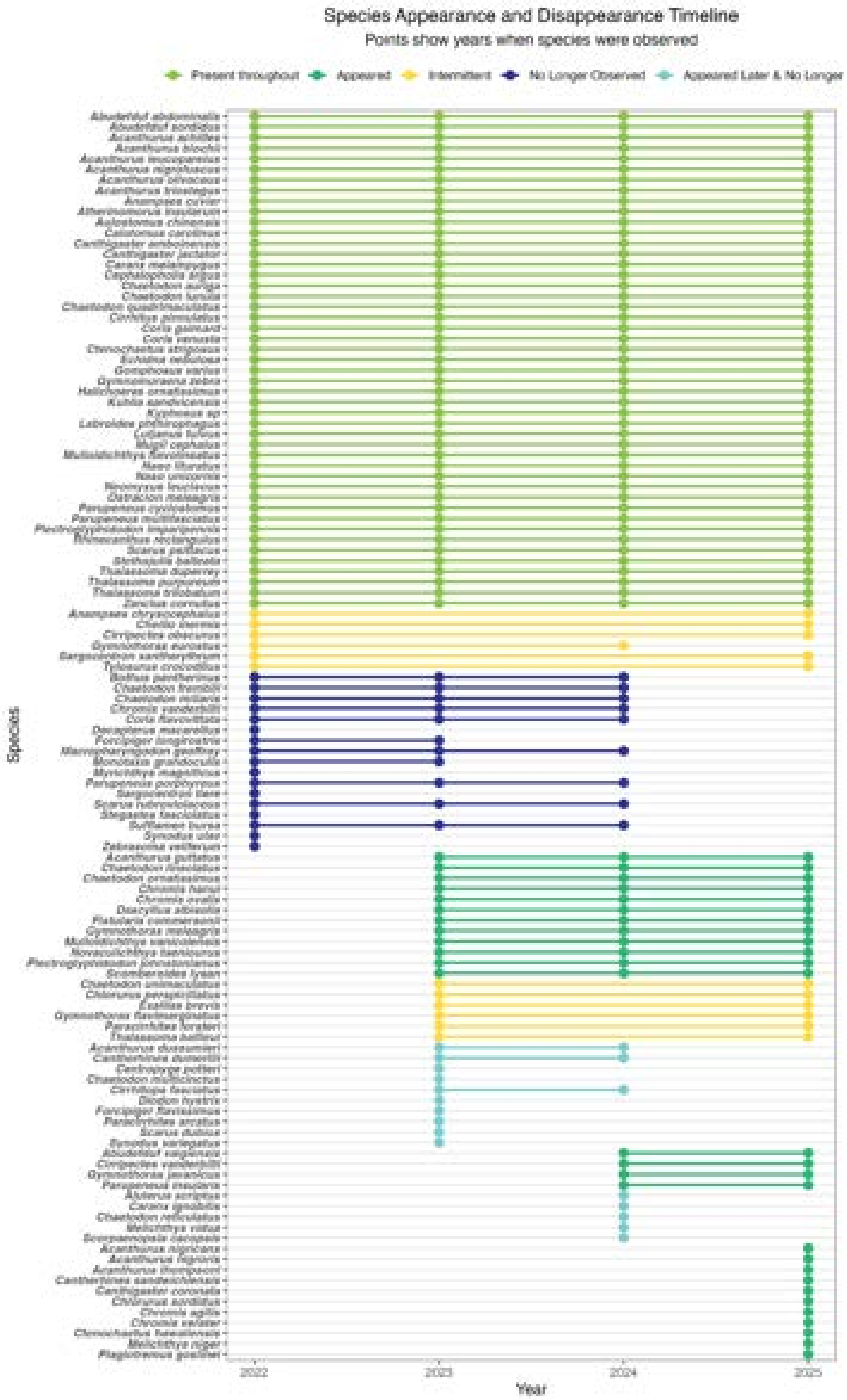


Figure 14. Timeline of species appearance/disappearance over time in the Kapo'o Tidepools and Cove.

C. *Fish Abundance by Species*

i. Tidepools

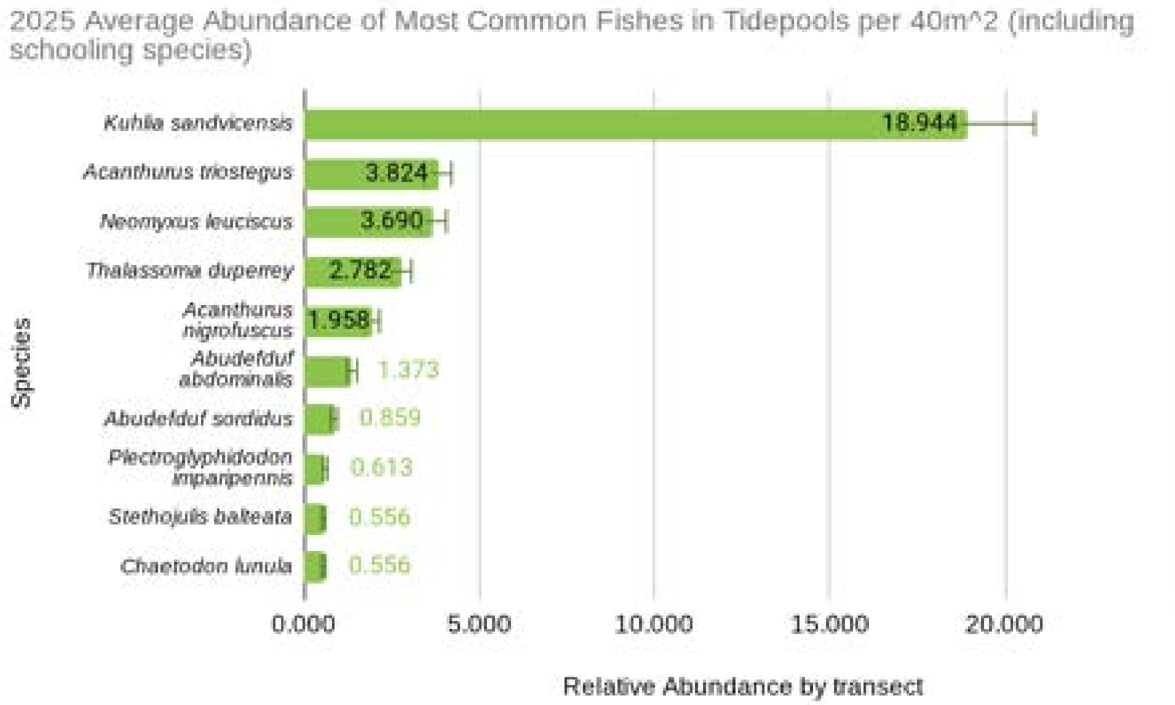


Figure 15**.** Top 10 fish species contributing to fish abundance in the Tidepools in 2025, including schooling species.

The species abundance in the Tidepools during Year 3 (2025) was dominated by *Kuhlia sp.* (āholehole), with a relative abundance of 18.944/40 m² when schooling species were included (Figure 15).

Other important abundant species were *Acanthurus triostegus* (manini*,* 3.824/40 m²); *Neomyxus leuciscus* (‘uouoa, 3.690/40 m²); *Thalassoma duperrey* (Saddle Wrasse, 2.782/40 m²); *Acanthurus nigrofuscus* (ma‘i‘i‘i, 1.958/40 m²); *Abudefduf abdominalis* (māopū, 1.373/40 m²); *Abudefduf sordidus* (kūpīpī, 0.859/40 m²); *Plectroglyphidodon imparipennis* (Brighteye Damselfish, 0.613/40 m²); *Stethojulis balteata* (‘ōmaka, 0.556/40 m²); and *Chaetodon lunula* (Rasphead Butterflyfish, 0.556/40 m²).

The high abundance of āholehole reflects its schooling behavior, which strongly influences the overall relative abundance in the Tidepools.

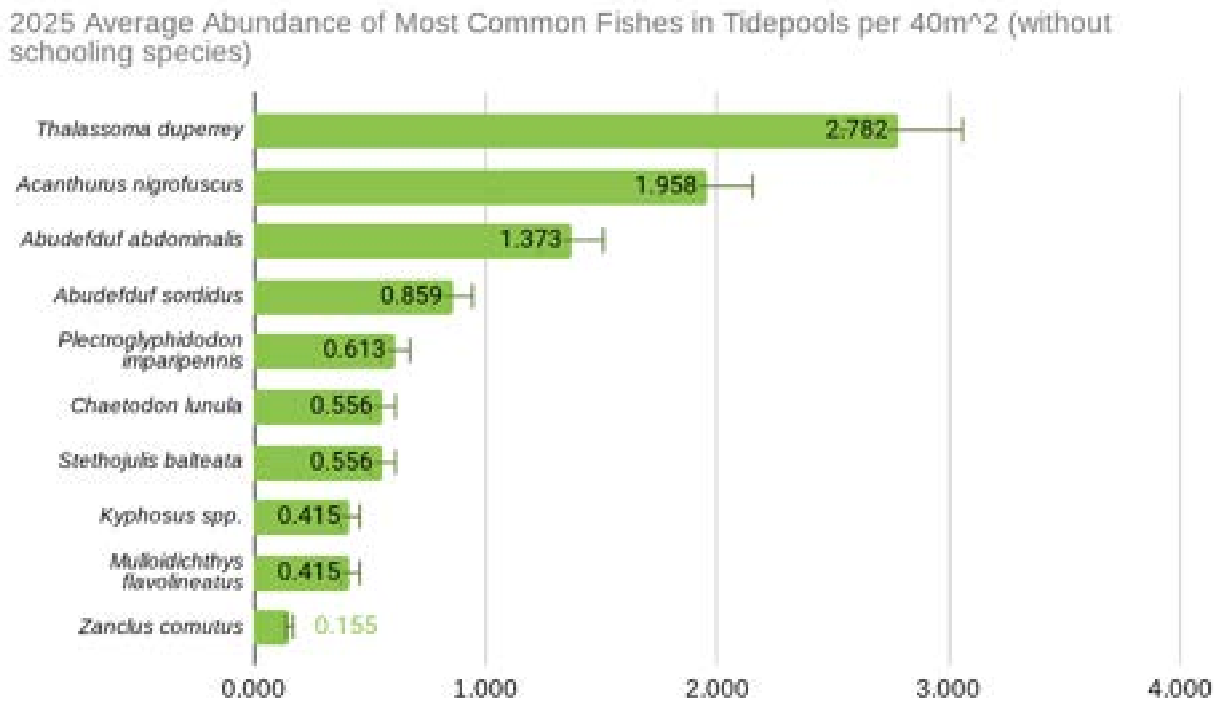


Figure 16. Top 10 fish species contributing to overall abundance in the Tidepools, without schooling species (see Species List in Appendix A for designations).

The species abundance in the Tidepools during Year 3 (2025), excluding schooling species, was dominated by *Thalassoma duperrey* (saddle wrasse), a species endemic to Hawai‘i, with a relative abundance of 2.782/40 m² (Figure 16).

Other important abundant species included *Acanthurus nigrofuscus* (ma‘i‘i‘i, 1.958/40 m²); *Abudefduf abdominalis* (māopū, 1.373/40 m²); *Abudefduf sordidus* (kūpīpī, 0.859/40 m²); *Plectroglyphidodon imparipennis* (brighteye damselfish, 0.613/40 m²); *Stethojulis balteata* (‘ōmaka, 0.556/40 m²); *Chaetodon lunula* (rasphead butterflyfish, 0.556/40 m²); and *Mulloidichthys flavolineatus* (weke ‘a, 0.415/40 m²).

Excluding schooling species reduces the influence of *Kuhlia sp.* (āholehole) on observed relative abundances and highlights the contributions of non-schooling species. These data provide a critical baseline for monitoring fish community structure at Kapo‘o and will support future evaluations of changes in relative abundance and species composition over time.

ii. Cove

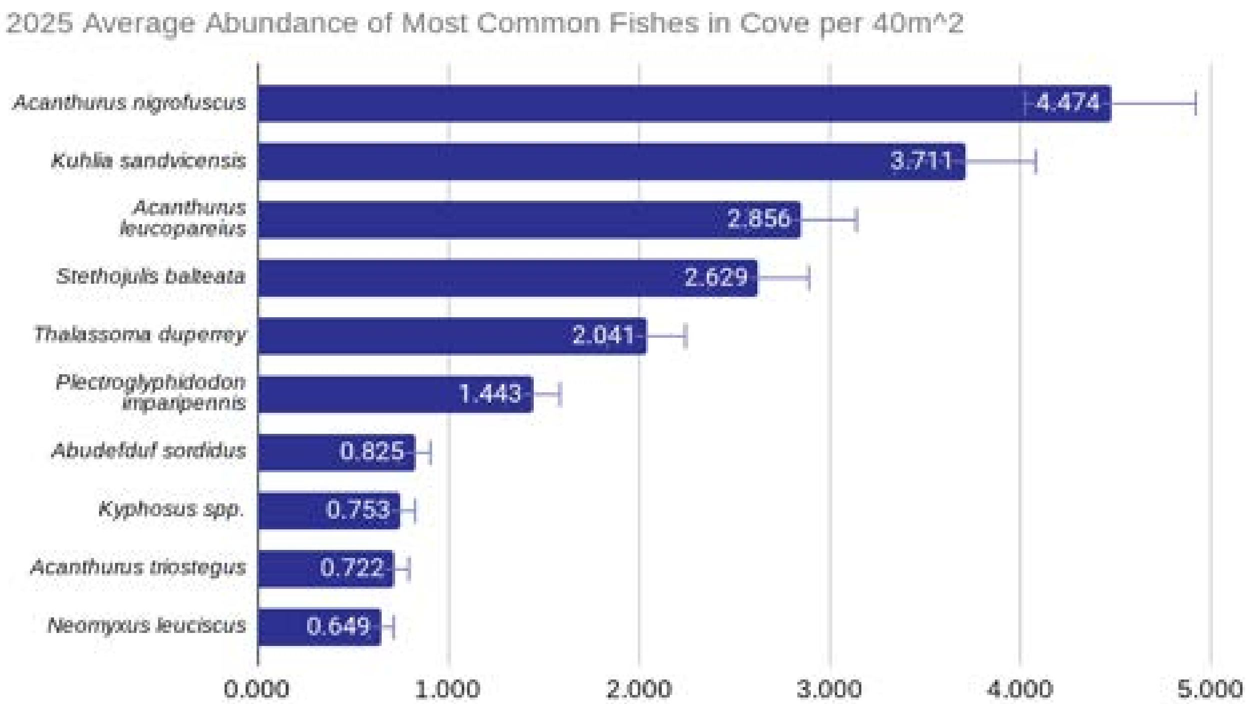


Figure 17. Top 10 fish species contributing to fish abundance in the Cove in 2025.

The species abundance in the Cove during Year 3 (2025) was dominated by *Acanthurus nigrofuscus* (maʻiʻi), with a mean abundance of 4.47/40m². The second most abundant species was *Kuhlia sp.* (āholehole), at 3.71/40m².

Other species contributing to overall abundance included *Acanthurus leucopareius* (maikoiko) at 2.86/40m²; *Stethojulis balteata* (ʻōmaka) at 2.63/40m²; and *Thalassoma duperrey* (saddle wrasse) at 2.04/40m². Additional abundant species were *Plectroglyphidodon imparipennis* (brighteye damselfish) at 1.44/40m²; *Abudefduf sordidus* (*kūpīpī*) at 0.83/40m²; *Kyphosus* spp. (nenue) at 0.75/40m²; *Acanthurus triostegus* (manini) at 0.72/40m²; and *Neomyxus leuciscus* (ʻaua) at 0.65/40m² (Figure 17).

Across all transects in the Cove, the mean total fish abundance in 2025 was 24.93 individuals per 40m². The increase in āholehole*,* along with shifts in maikoiko and ʻōmaka rankings, highlights changes in community composition.

iii. Kalua o Maua

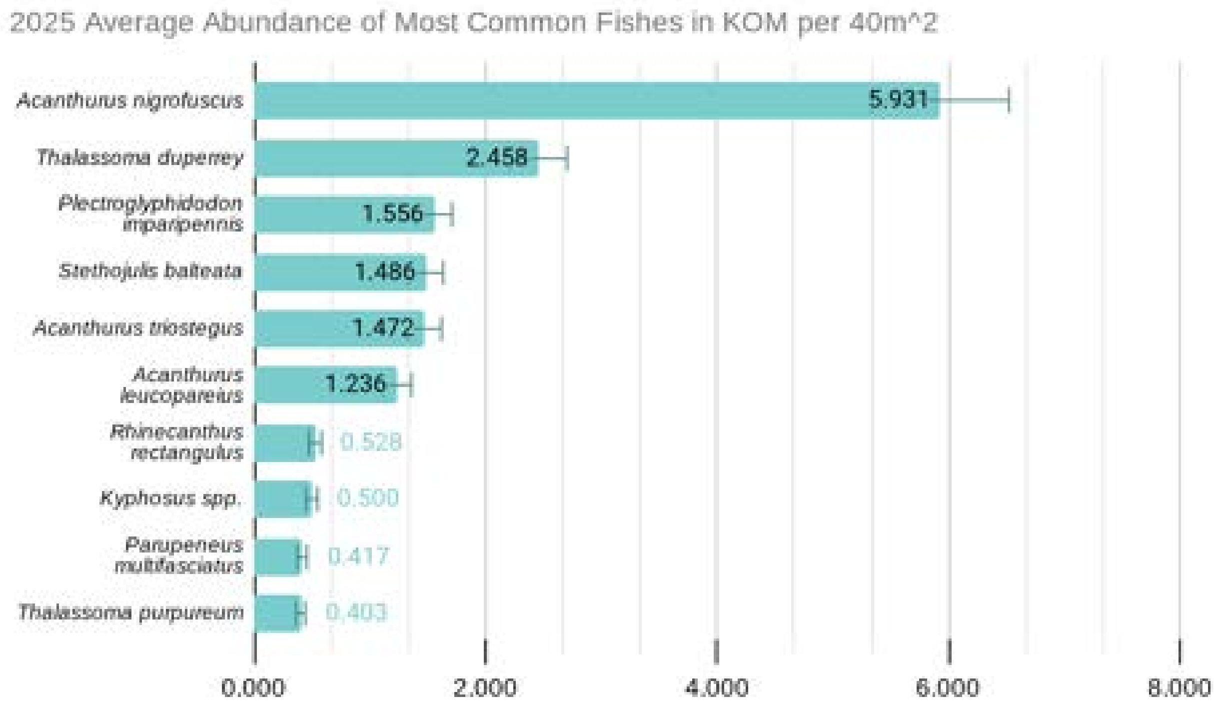


Figure 18. Top 10 fish species contributing to fish abundance in Kalua o Maua in 2025.

Year 3 (2025) is the first year that the marine team conducted fish surveys at Kalua o Maua, providing baseline data on species abundance and composition at the site.

The community was dominated by *Acanthurus nigrofuscus* (maʻiʻiʻi), with a mean abundance of 5.93/40m². The second most abundant species was *Thalassoma duperrey* (saddle wrasse), at 2.46/40m². Other species contributing to overall abundance included *Plectroglyphidodon imparipennis* (brighteye damselfish) at 1.56/40m²; *Stethojulis balteata* (ʻōmaka) at 1.49/40m²; *Acanthurus triostegus* (manini) at 1.47/40m²; *Acanthurus leucopareius* (maikoiko) at 1.24/40m²; and *Rhinecanthus rectangulus* (reef triggerfish) at 0.53/40m². Additional abundant species were *Kyphosus spp*. (nenue) at 0.50/40m²; *Parupeneus multifasciatus* (manybar goatfish) at 0.42/40m²; and *Thalassoma purpureum* (surge wrasse) at 0.40/40m².

Across all transects at Kalua o Maua, the mean total fish abundance in 2025 was 19.07 individuals per 40m². Establishing this baseline is critical for tracking future ecological changes and evaluating the effectiveness of management actions over time.

D. Schooling Fish Abundance by Year

The abundance of schooling fish has shown a general decrease over the study years, but the data show different patterns within each species.

In both the Tidepools and Cove, *Acanthurus triostegus* (manini) numbers diminished over each year. *Neomyxus leucisus* (‘aua) was seen in far greater quantities in the Cove in 2022, diminished dramatically in 2023, and was not observed in schools larger than five in the Cove in 2024 or 2025.

In previous years in the Tidepools, both schools of *Atherinormous insularum* (‘iao) and *Mugil cephalus* (‘ama‘ama) were observed, but in 2025, they were not seen in groups of larger than five. *Kuhlia sp.* schools in the Tidepools have also been observed to increase in size over time, with a slight decrease in 2025. Overall, schooling species in the Tidepools are more rich and abundant than in the Cove.

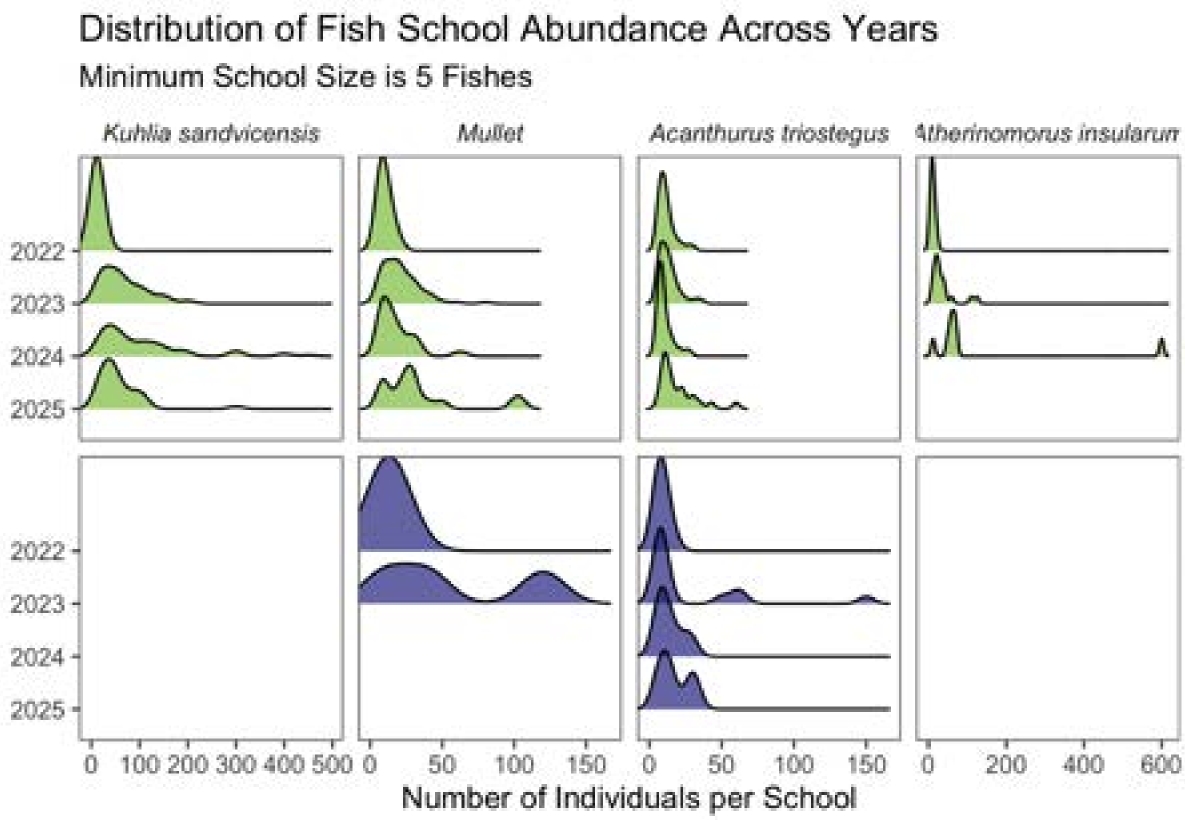


Figure 19. Distribution of schooling species between 2022-2025.

D. Fish Biomass

In Year 3, the methodology was expanded to include recording the total length of fish observed within transect surveys. The following section presents biomass results from transect surveys, focusing on the distribution of biomass across sites and size classes.

When schooling species were removed from the analysis, biomass was highest in the Cove (95% CI: 1049 - 2201). The Cove biomass was 48.5% higher than the biomass of non-schooling fishes in Kalua o Maua (95% CI: 520 - 1180, p = 0.012).

The non-schooling fish biomass in the Tidepools (95% CI: 670 - 1480) was not significantly different from the biomass recorded at either the Cove (p = 0.15) or Kalua o Maua (p = 0.57), despite its mean value being intermediate to the two (Figure 20).

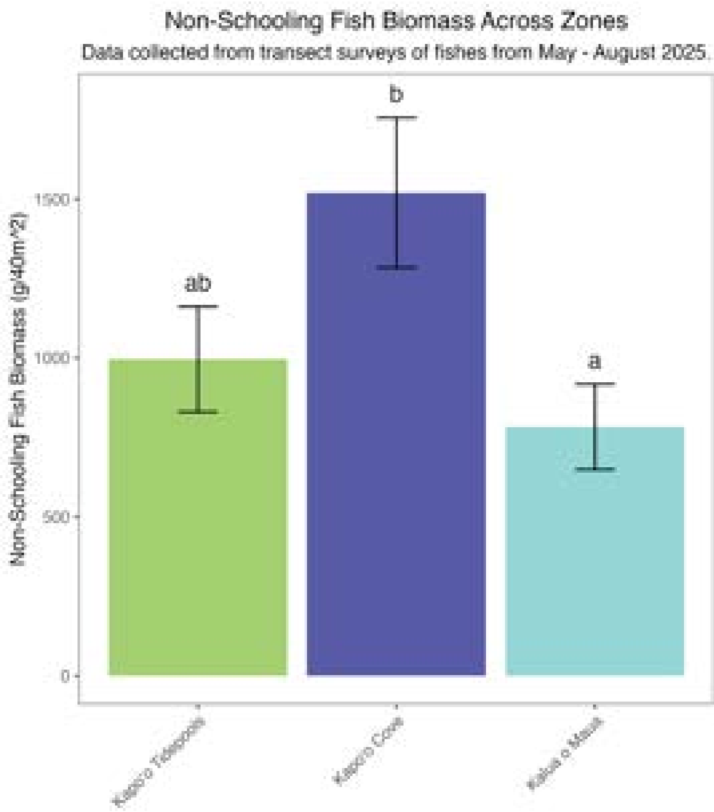


Figure 20. Predicted Biomass per 40m^2 Transect at each zone. Data are shown as model predictions plus and minus the standard error. Letter groupings above the bars denote significant differences between zones.

2. Benthic Composition

Benthic composition was assessed using photo-quadrats across all zones along transects. Percent cover estimates were extracted from these photo-quadrats using CoralNet (UCSD), with measurements based on randomly distributed points.

A. Tidepools

The benthic composition of the Tidepools in 2025 was dominated by unconsolidated sediments and turf algae. Sand comprised 38.73% of the substrate, followed by turf at 33.19%, silt at 13.14%, and bare substrate at 10.91%, which was either uncolonized or had been scraped of its algae (Figure 21). Crustose Coralline Algae (CCA) made up 2.30% of the benthos, with other features at 1.15%, unknown material at 0.73%, mobile invertebrates at 0.28%, *Gracillaria salicornia* at 0.07%, and brown macroalgae at 0.05%.

Coral species recorded include *Montipora capitata* (1.15%), *Pavona varians* (0.30%), and *Porites solida* (0.05%), with recently dead coral at 0.02%.

Compared to previous years, CCA in the Tidepools remains low but showed a slight increase relative to 2024 (0.97%). Overall, the three-year trend continued to show a decline, from 11.1% in 2022 and 2.4% in 2023 to 2.30% CCA in 2025.

In the Tidepools, coral cover remained minimal, with *Montipora capitata*, *Pavona varians*, and *Porites solida* collectively accounting for 1.5% cover, consistent with low coral observations in previous years.

Bare substrate, sand, and silt remained the major components. These patterns are consistent with previous reports indicating that the Tidepools experience limited water movement, which likely restricts calcifier growth compared to areas like the Cove, where higher water motion supports greater CCA cover.

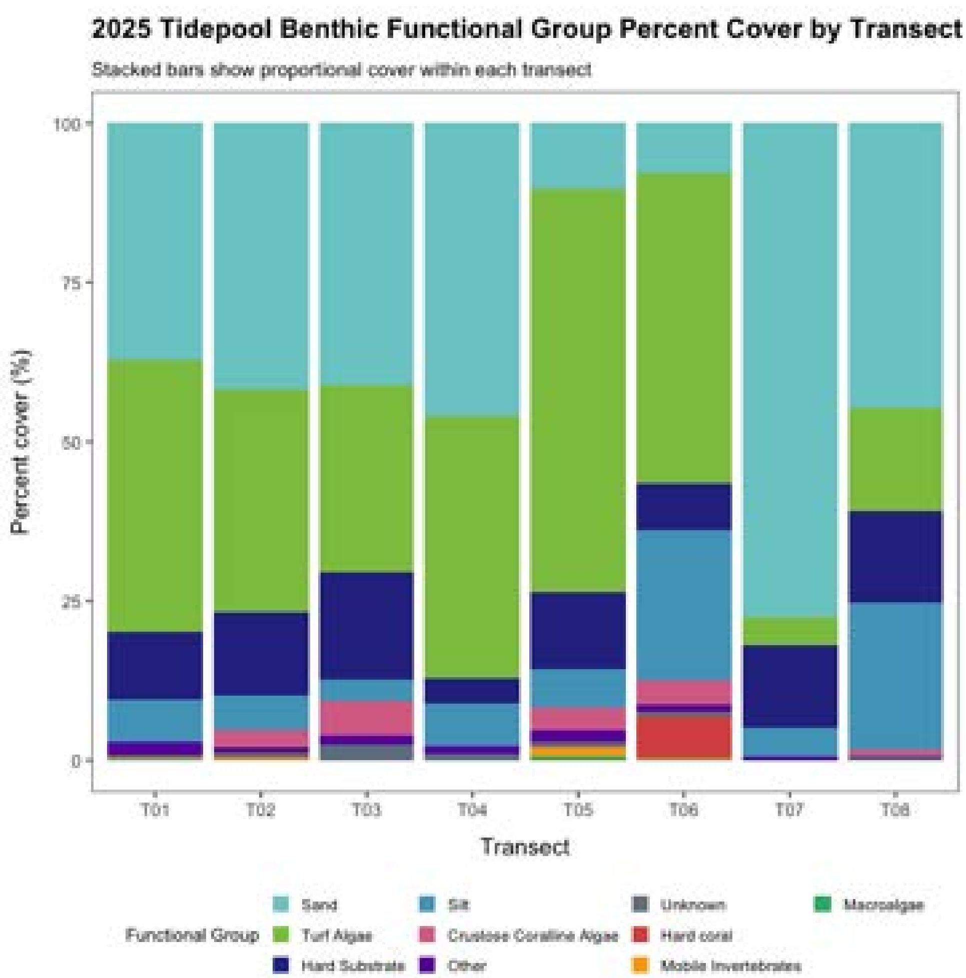


Figure 21. Benthic Composition in the Tidepools in 2025 as assessed by benthic photo-quadrats and analyzed using CoralNet. Sand, turf, and bare substrate dominate the benthos.

Other refers to any human, man-made, or non-benthic objects in the photographs.

Figure 22 shows the percent cover of benthic functional groups by transect and year in the Tidepools, with soft substrate and turf algae consistently dominating across most sites from 2023 to 2025. Soft substrate remains the largest component throughout the three-year period, often making up the majority of benthic cover.

Algae also maintained a strong presence, with increases observed in transects T01, T04, and T05 in 2024 and 2025, indicating a shift toward greater algal dominance in some areas, however there was also a seasonal shift of when photo-quadrats were taken; in 2024, they were done in winter, as opposed to summer in 2025 which may account for some shift in algal cover as more would be expected after winter swells.

At transect T03, a significant change occurs between 2023 and 2024, and again in 2025, with an increase in soft substrate cover and a corresponding decline in hard substrate and turf algae, followed by a second shift again. This shift was likely due to large winter swells, which moved sand and rocks into the transect, burying previously exposed surfaces and altering the benthic composition. Hard coral and other invertebrates remain minor components overall, with only small amounts recorded at T05 in 2024.

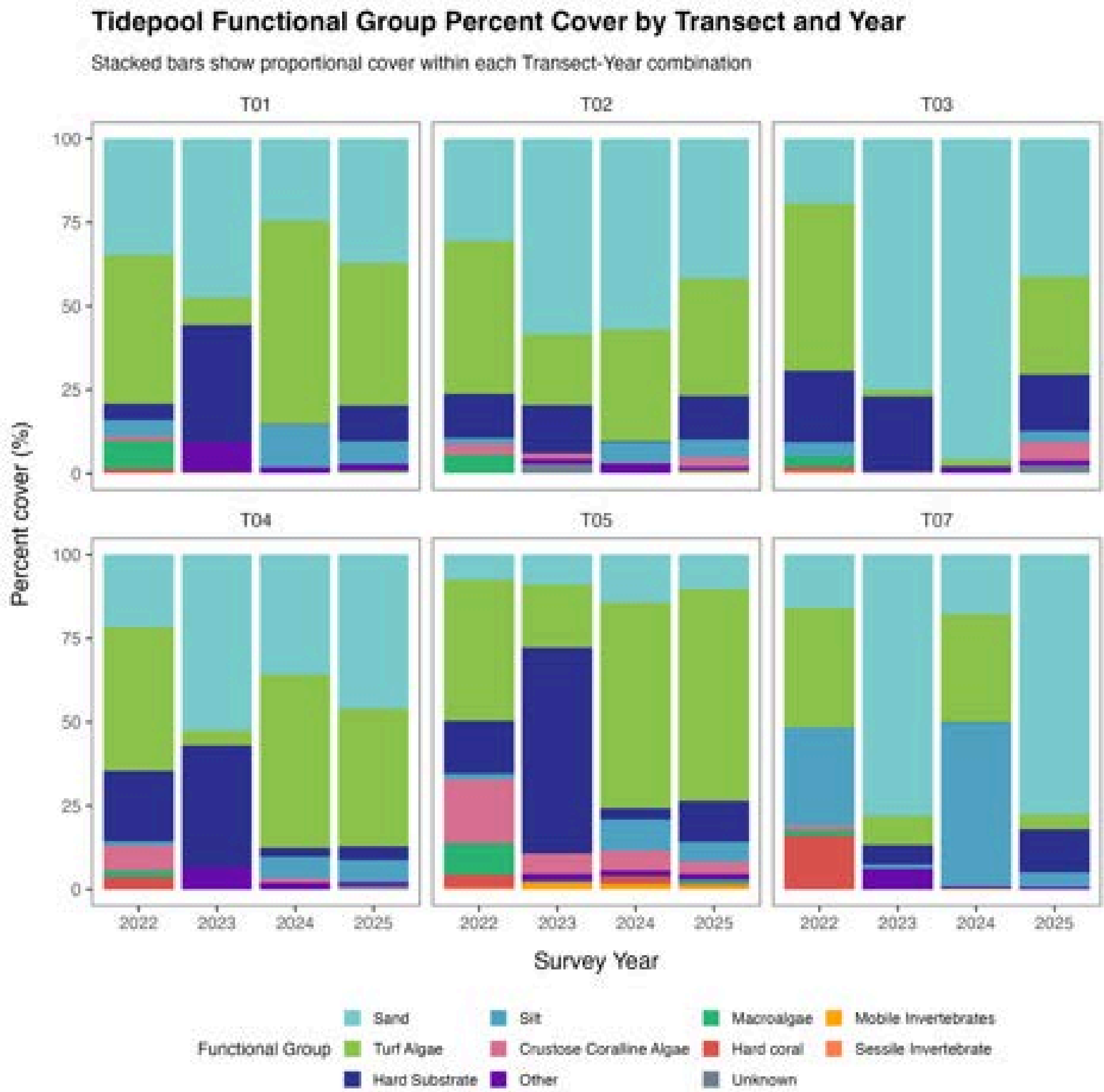


Figure 22. Displays the functional group percent cover of the Tidepools between 2022 and 2025. T08 has been removed because the transect was shifted to T08B, as well as T6 due to the photo-quadrats being taken of the ‘wall’ along the transect at previously unrecorded depths, therefore precluding exact comparisons over time. Other includes “Other” categories (including all human, man-made, and non-benthic objects) as well as “Unknown” (used when an object was indeterminable in the photograph). Data from 2022 are included, although those data were collected with a different, but comparable, methodology.

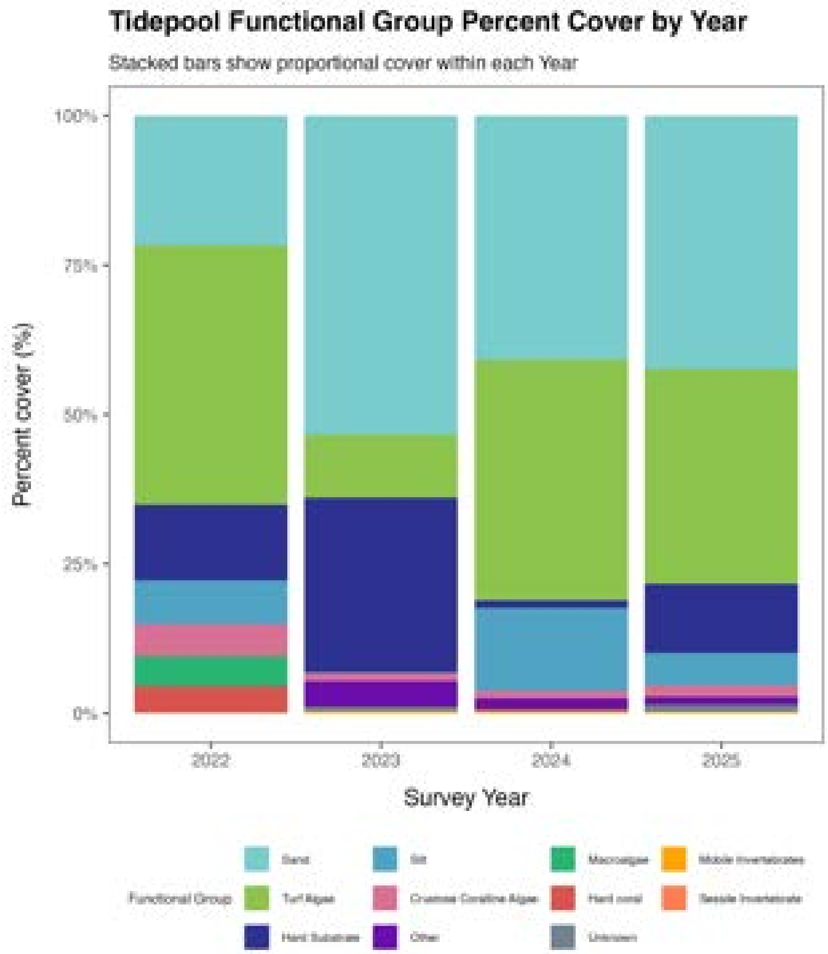


Figure 23. Overall change across all transects in the Kapo‘o Tidepools across years 2022-2025. T8 and T6 have been removed because the transect was shifted to T8B, and T6 due to the photo-quadrats being taken of the ‘wall’ along the transect at previously unrecorded depths, therefore precluding exact comparisons over time. Other includes “Other” categories (including all human, man-made, and non-benthic objects) as well as “Unknown” (used when an object was indeterminable in the photograph). Data from 2022 were included, although those data were collected with a different, but comparable, methodology.

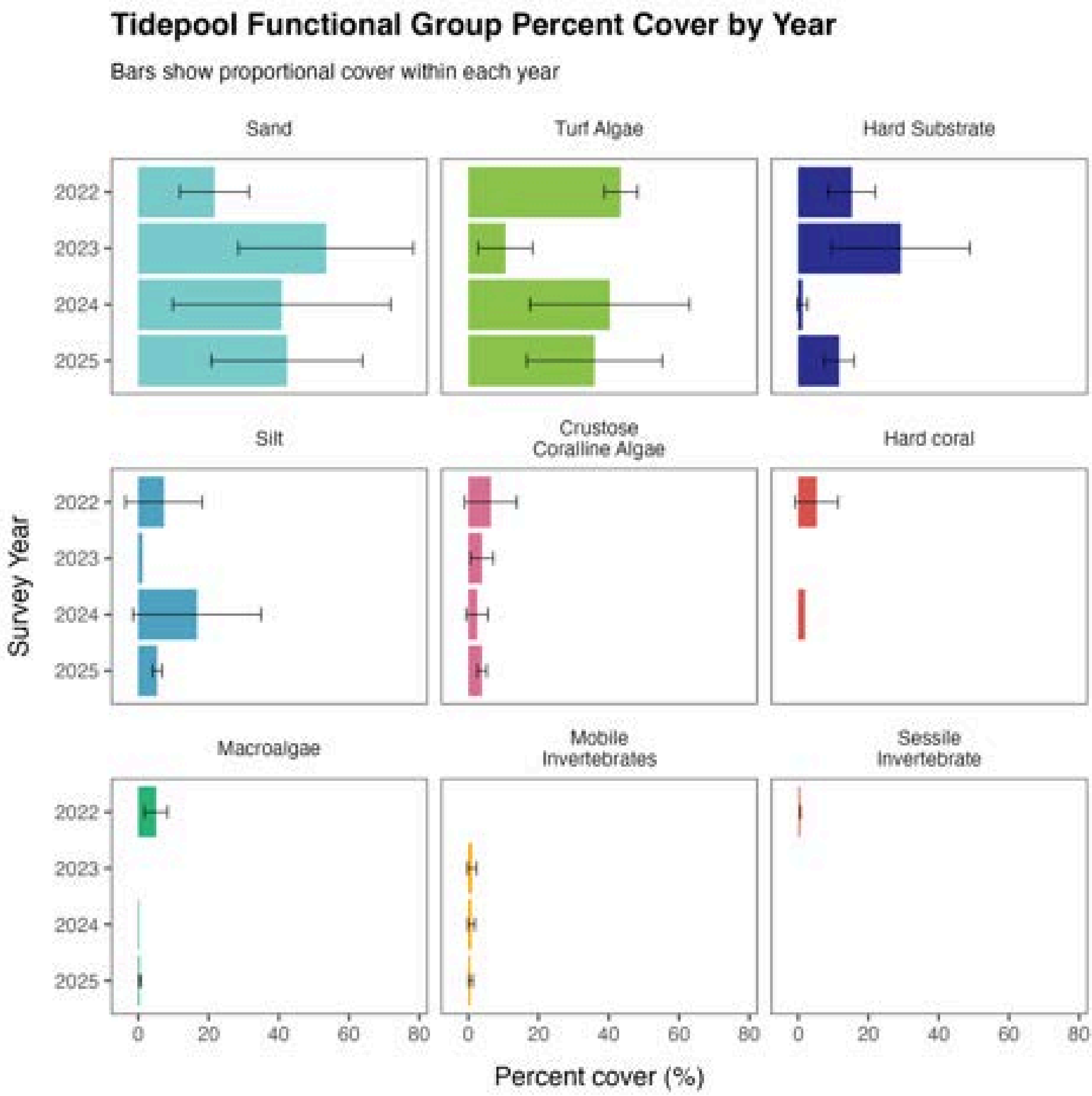


Figure 24**.** Displays the average (colored bar) and standard deviation (black thin bars) of the percent cover of different functional groups across transects in the Tidepools between 2022 and 2025. Other and Unknown categories have been removed.

B. Cove

The benthic composition of the Cove in 2025 was dominated by turf algae and soft sediments.

Turf algae comprised 53.37% of the benthos, followed by silt at 28.18%, crustose coralline algae (CCA) at 16.42%, and sand at 8.98% (Figure 25). Bare, uncolonized substrate accounted for 5.10%. Mobile invertebrates were recorded at 1.81%, and coral cover was relatively low overall, with *Porites lobata* (combined bleached and unbleached) totaling 7.25%, *Pocillopora meandrina* at 4.00%, *Montipora patula* at 0.75%, and octocorals at 1.00%. Additional taxa include *Laurencia* spp. (0.75%) and *Martensia* spp. (0.75%).

Compared to previous years, the Cove continued to show a stable benthic community dominated by turf algae and fine sediment deposition (Figure 26, 27, 28).

In previous years, the percent cover of CCA had decreased from 33.7% in 2022 to 30.7% in 2023, and then sharply to 9.7% in 2024, representing a 30.1% overall decline across three years. In 2025, CCA accounted for 16.42%, suggesting a rebound in calcified cover compared to 2024 levels. This increase may reflect a rebound in conditions that favor calcifier growth in 2025, as this was seen across all transects with the exception of C6, where there was further decline.

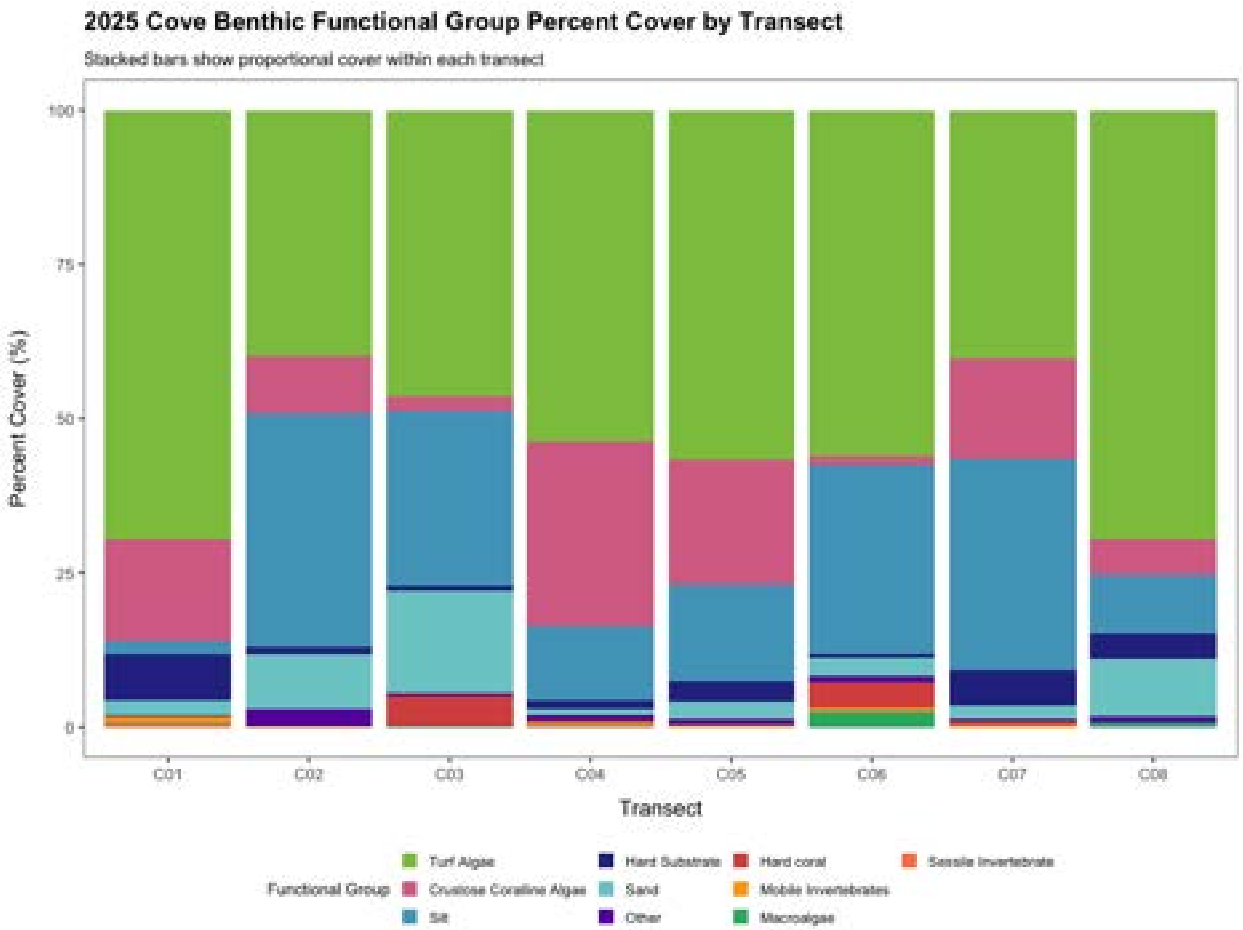


Figure 25. Benthic Composition (% cover) of the Cove by Transect as assessed through benthic photo-quadrats analyzed with CoralNet. “Other” refers to any human, man-made or non-benthic objects.

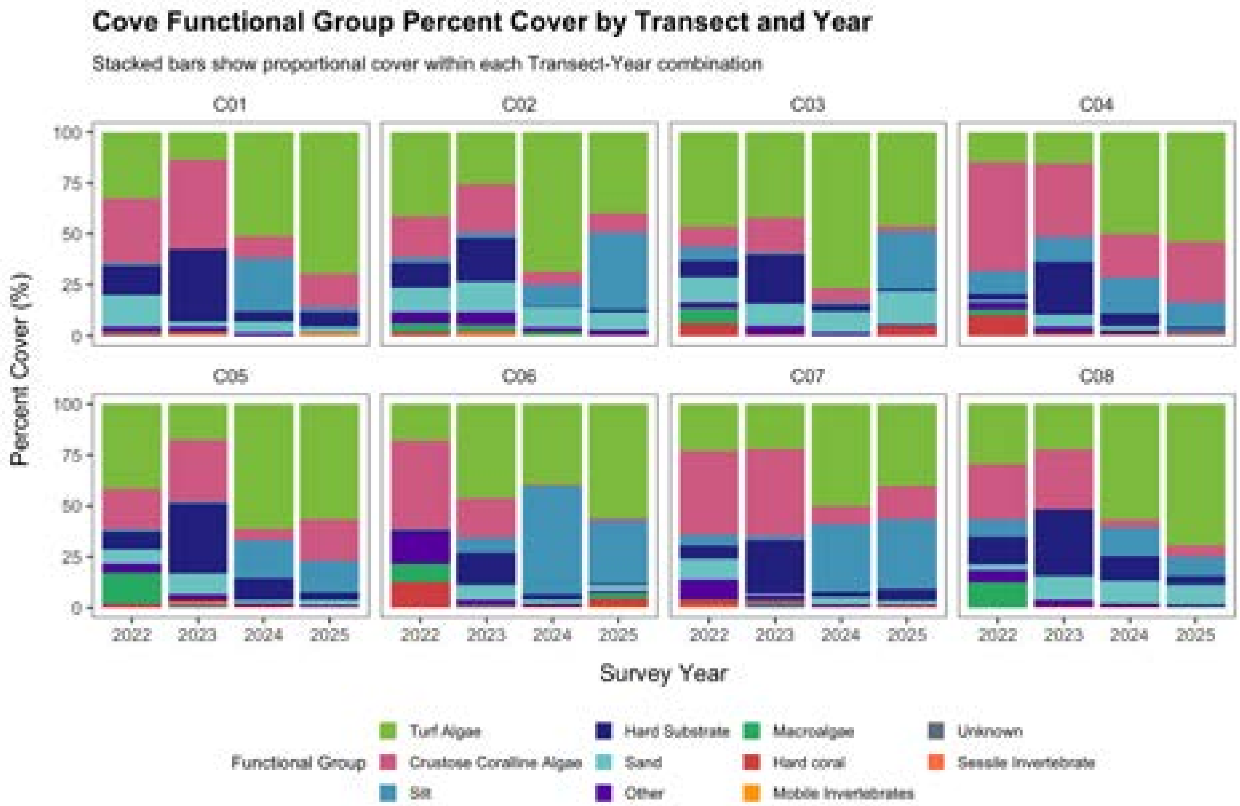


Figure 26. Displays the functional group percent cover of the Cove between 2022 and 2025. Other includes "Other" categories (including all human, man-made, and non-benthic objects) as well as "Unknown" (used when an object was indeterminable in the photograph). Data from 2022 were included, although those data were collected with a different, but comparable, methodology.

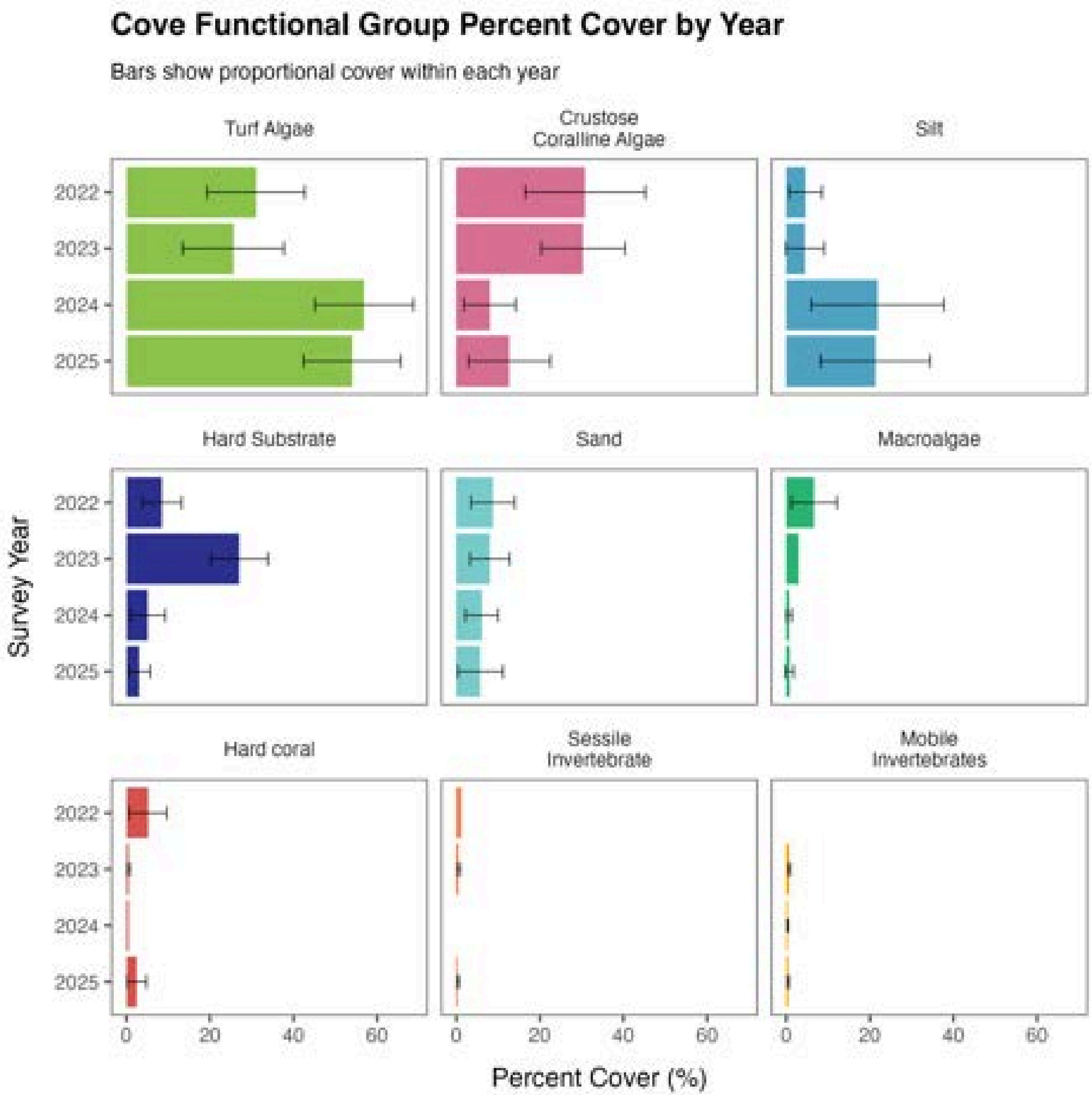


Figure 27. Displays the average (colored bar) and standard deviation (black thin bars) of the percent cover of different functional groups across transects in the Cove between 2022 and 2025. Other and Unknown categories have been removed.

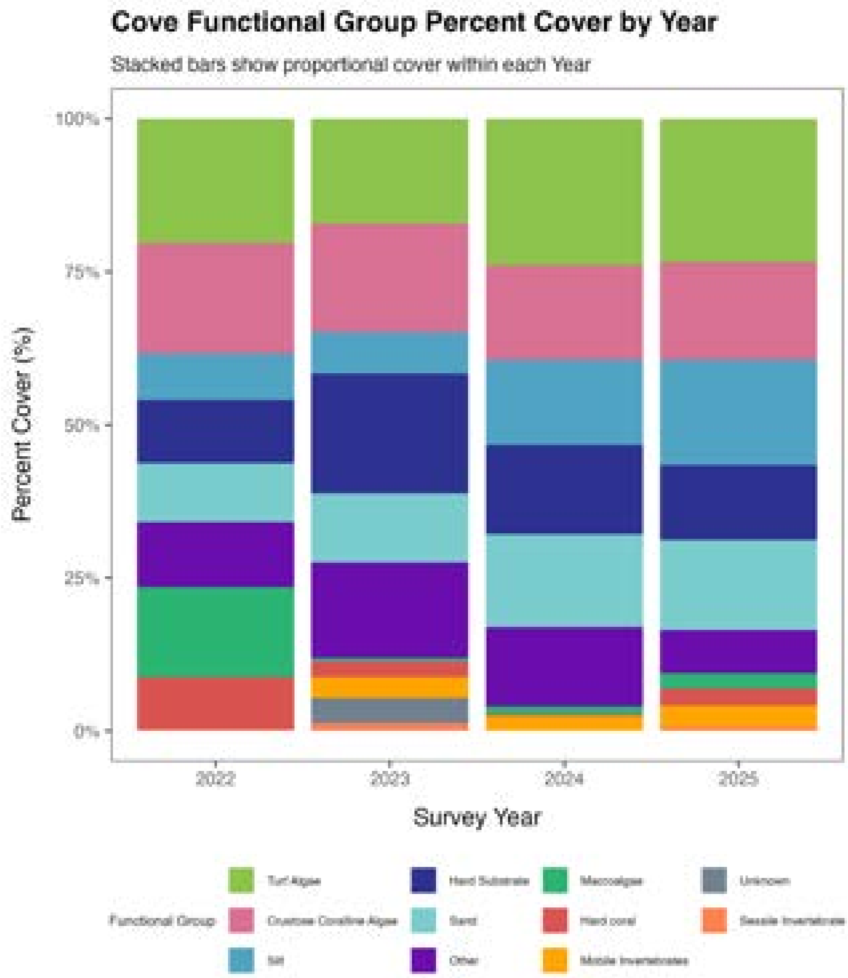


Figure 28. Overall change across all transects in the Kapo‘o Cove across years 2022-2025.Other includes "Other" categories (including all human, man-made, and non-benthic objects) as well as "Unknown" (used when an object was indeterminable in the photograph).
Benthic composition methods changed between 2022 and 2023.

C. Kalua o Maua

The benthic composition of Kalua o Maua was dominated by turf algae, which comprised 47.2% of the benthos overall (Figure 28). Soft substrates also contributed substantially to the benthos, with silt at 7.42% and sand at 9.06%, while bare substrate accounted for 5.90%. Crustose coralline algae was moderately present at 16.1%. Other benthic features included octocorals at 6.23%, *Porites lobata* (combined bleached and unbleached) at 13.1%, *Pocillopora meandrina* (combined bleached and unbleached) at 9.0%, and *Porites evermanni* (combined bleached and unbleached) at 15.6%. Minor contributions (<1%) were recorded from other coral, algal taxa, and mobile invertebrates.

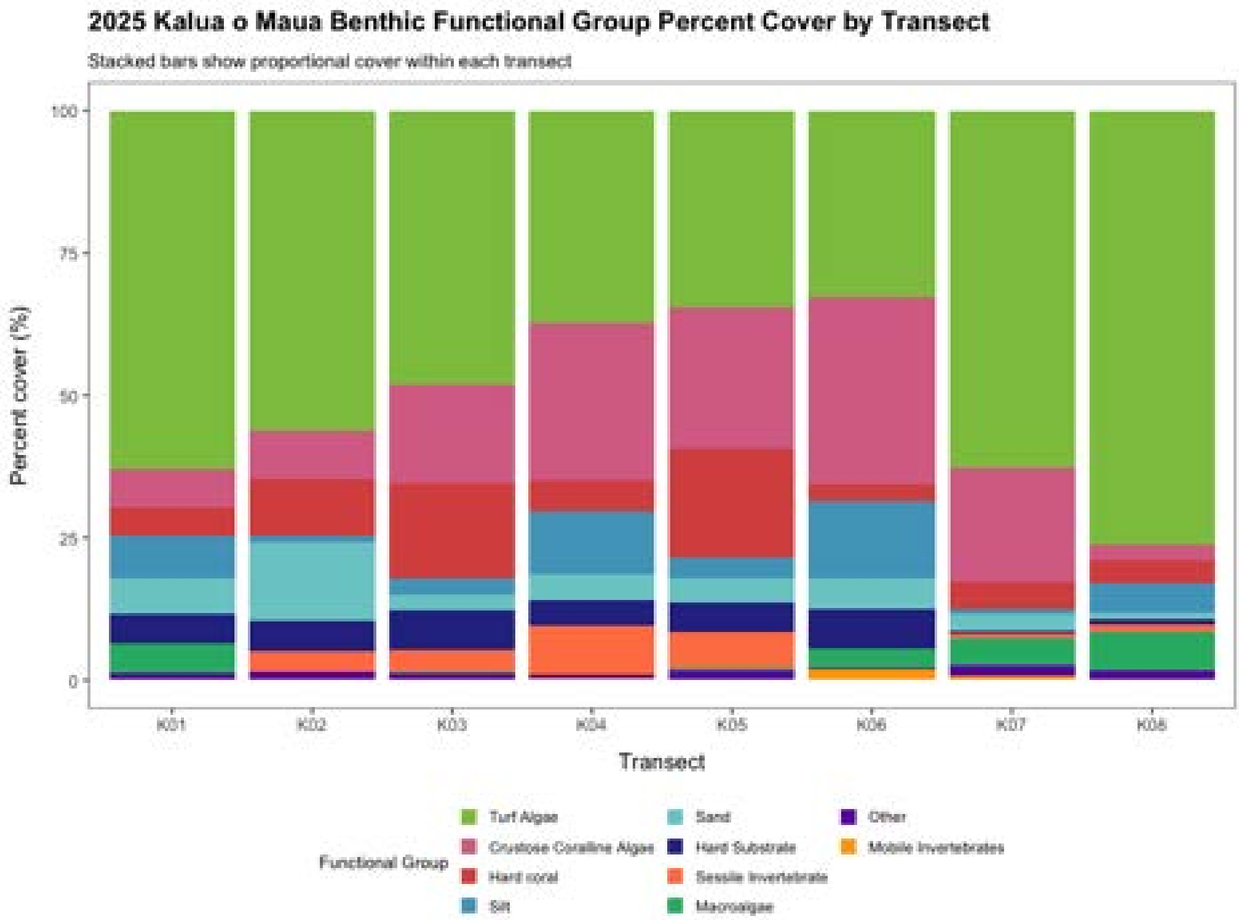


Figure 29. Benthic Composition (% Cover) at Kalua o Maua. These data provide a baseline to gauge future change over time. Kalua o Maua showed higher coral coverage than in the Tidepools and Cove, but was still dominated by turf algae.

3. Coral Diversity and Health

In 2025, a total of 16 species were observed across the Tidepools and Cove (Figure 30). In 2022, 10 species were recorded, increasing to 11 species in 2023, and 13 species in 2024. In total, 19 coral species were observed including the new transects at Kalua o Maua. This indicates an increase of coral species richness over time.

In the Tidepools, the coral community was dominated by *Montipora capitata*, which comprised nearly half of the coral cover. *Porites lobata* was the next most abundant species, followed by *Montipora patula, Pavona varians, and Porites lichen*. Several species occurred only in the Tidepools, including *Leptastrea incustans, Porites brighami, and Porites hawaiiensis.* Octocorals were not recorded. In 2024, *Pavona varians* and *Gardineroseris planulata* were observed in the Tidepools, but not in the Cove.

In the Cove, the coral community was dominated by *Pocillopora meandrina*, which comprised more than half of the coral cover. Other abundant species included *Montipora capitata* and *Montipora patula*, and octocorals were also present. *Porites lobata* and *Montipora flabellata* occurred in smaller proportions, along with *Pocillopora ligulata* and *Gardineroseris planulata*. In 2024, *Montipora flabellata* and *Leptastrea bewickensis* were present in the Cove but not in the Tidepools, and *Gardineroseris planulata* was recorded in both 2022 and 2025 but absent in 2023 and 2024.

At Kalua o Maua, the baseline data established that the coral community was dominated by *Porites lobata* and *Pocillopora meandrina*, followed by octocorals and *Montipora flabellata.* Additional species present included *Montipora capitata, Montipora patula, Pocillopora ligulata, Porites lichen, Pavona varians,* and *Pocillopora damicornis*. Species unique to Kalua o Maua in 2025 included *Leptastrea purpurea, Leptastrea transversa, and Porites evermanni*.

Many of the dominant coral species across all three zones exhibited encrusting, mounding, or low-lying morphologies, particularly *Montipora, Pavona, Porites, and Leptastrea spp.*. These forms are often characteristic of corals adapted to high-energy or high-stress environments, where wave exposure, high irradiance, and frequent human trampling can favor growth forms that minimize breakage risk and reduce shading stress.

Several species were also frequently observed in vertical microhabitats or nestled within crevices, a positioning that may provide additional protection from physical disturbance and thermal stress. Noting these growth forms and microhabitat preferences helps contextualize why certain stress-tolerant taxa dominate the Tidepools and other high-use areas, while more upright or branching species remain uncommon.

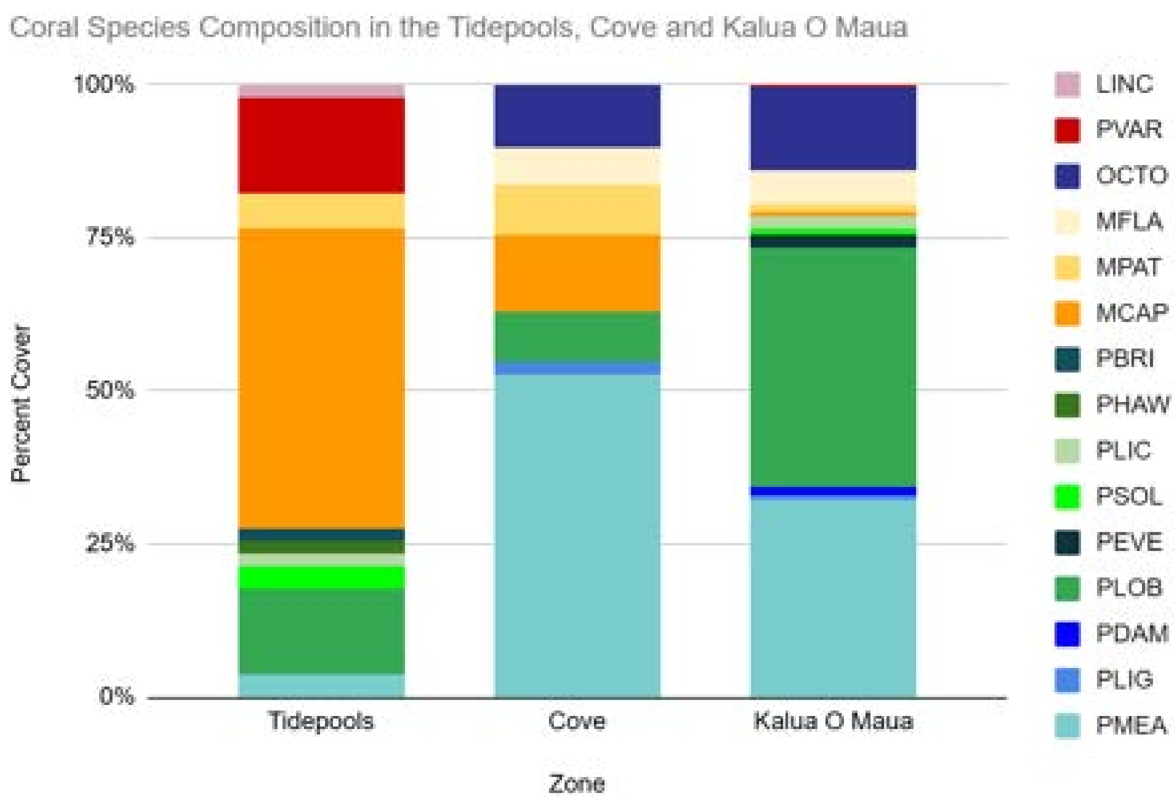


Figure 30. Coral composition of top species by zone in 2025. Species codes from bottom to top: *Pocillopora meandrina, Pocillopora Ligulata, Pocillopora damicornis, Porites lobata, Porites evermanni, Porites solida, Porites lichen, Porites hawaiiensis, Porites brighami, Montipora capitata, Montipora patula, Montipora flabellata,* Octocorals, *Pavona varians, Leptoseris incrustans.*

All coral colonies greater than 10 cm were sampled across all permanent transects at each zone. Across all transects, the study found a relatively high mean percentage of the coral that was living at each zone (≥82%), but also measurable mortality and stress.

As in Years 1 and 2, no coral over 10 cm in diameter was observed in the Tidepools at transect 2, 3, 7 or 8B. In previous years, no coral was recorded in the Cove at transect 8, but Year 3 recorded 2 colonies over 10 cm.

The Tidepools (TP zone; 4 transects with coral present, total n = 51) has the lowest weighted mean % live per coral colony at 82.0%, a relatively high 14.6% pale, ~1.9% bleached, and ~2.9% dead. The Cove (C zone; 8 transects, total n = 49) has a weighted mean % live of 85.3%, with 2.6% pale, 2.0% bleached, and 3.5% dead (Table 1, below). Kalua o Maua (KOM zone; 8 transects, total n = 247) shows the highest weighted mean % live at 87.0%, with weighted means of 5.8% pale, 1.0% bleached, and 7.2% dead.

The corals in the Tidepools stand out for high weighted mean paleness per colony (14.6%) despite having lower dead and bleached percentages. Because these percentages are per-coral-head metrics (not percent cover), the high pale rate in the Tidepools may indicate broad physiological stress across many colonies.

Damage was also observed in the Tidepools to multiple coral heads, including breakage, smothered by debris, and damage from trampling. By contrast, the Cove shows modest mortality (3.5%) but a slightly higher weighted bleaching fraction per colony (2.0%) than Kalua o Maua, which combines the highest coral cover, and associated largest sample size, with the highest observed per colony mortality (weighted dead = 7.2%).

During surveys, damage and disease were also recorded when found. Year 3 researchers received training from Dylan Brown with Ocean Alliance to identify coral disease. At Kalua o Maua, researchers recorded Multifocal White Syndrome, Focal White Syndrome, and *Porites* trematodiasis, with these conditions concentrated on *Porites lobata* hotspots. White syndromes manifest as acute tissue-loss lesions that can advance rapidly and lead to partial or whole-colony mortality, whereas *P. trematodiasis* appears as small, raised pink nodules caused by a trematode infection—visually conspicuous but not always immediately lethal (Aeby et al., 2011).

Also of note was the senescence of *Pocillopora meandrina*, which is a normal part of the demography of the species (Bythell et al., 2018), and is among the most common species at all locations.

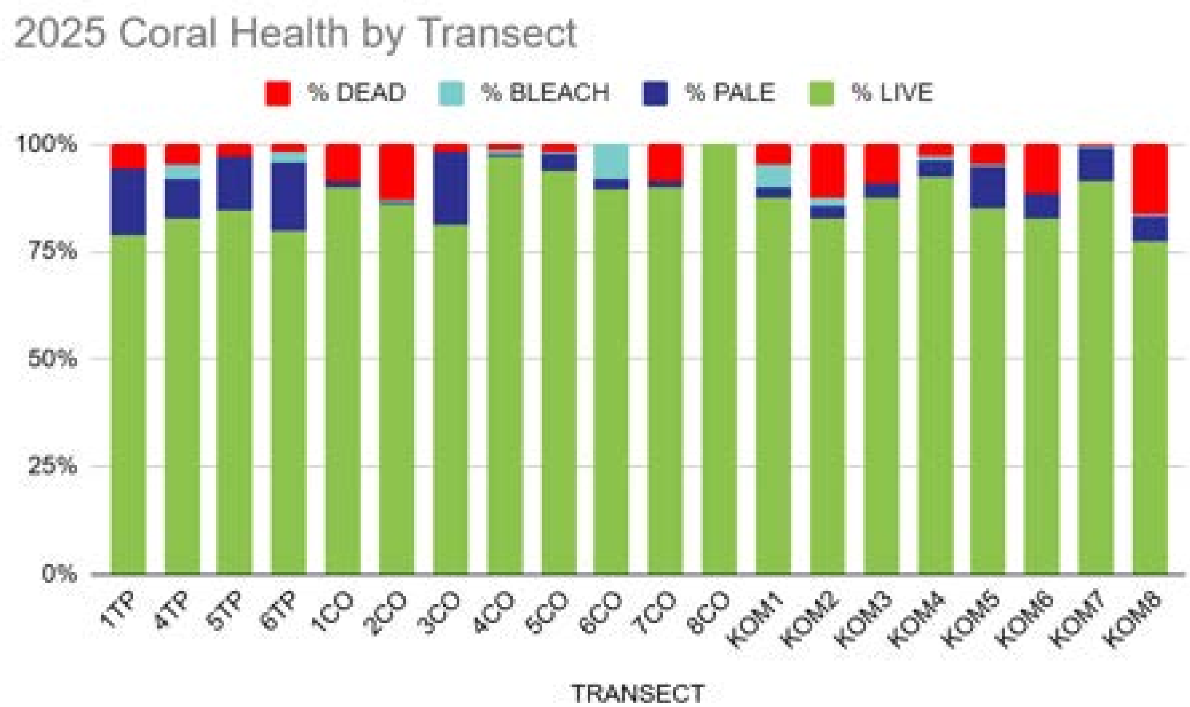


Figure 31. The breakdown of mean per colony percent dead, bleached, pale, and live coral across each transect. For exact data, please see table below.

Table 1. Shows the average percent live, pale, bleached, and dead corals across survey sites in 2025 and the associated sample size and standard error. Percent pale, bleached and dead greater than 10% is bolded.

Tidepool transects 2, 3, 7 and 8B had no corals greater than 10cm.

TRANSECT	SAMPLE SIZE	% LIVE	SE LIVE	% PALE	SE PALE	% BLEACH	SE BLEACH	% DEAD	SE DEAD
1TP	5	87.0	32.5	**17.0**	7.5	0	0	6.0	15.0
4TP	6	84.2	5.5	9.2	4.3	3.3	10	5.0	2.9
5TP	7	88.6	8.8	**12.9**	8.8	0	0	2.9	5.0
6TP	33	79.4	7.2	**15.6**	8.7	2.3	7	2.0	4.3
1CO	7	90	8.5	1.4	5.0	0	0	8.5	11.5
2CO	5	86	18.6	0.6	1.5	0.4	1	**13**	19.2
3CO	3	73.3	9.3	**15**	2.9	0	0	1.7	2.5

4CO	10	88	31.8	0.5	2.5	1	5	1	5.0
5CO	9	93.3	5.1	3.9	3.2	0.5	2.5	1.7	7.5
6CO	11	81.8	17.7	2.3	6.0	7.2	21.8	0	0
7CO	2	90	10.0	1.5	1.5	0	0	8.5	8.5
8CO	2	50	50.0	0	0	0	0	0	0
KOM1	19	87.6	11.6	2.4	6.6	5.3	50.0	4.7	10.9
KOM2	19	84.2	9.2	2.6	6.0	2.1	20.0	**12.6**	10.6
KOM3	34	88.2	10.4	3.1	7.1	0.3	5.0	9.0	9.4
KOM4	30	93.5	7.1	3.6	5.1	1.1	9.5	2.9	9.7
KOM5	61	85.7	9.0	9.6	9.1	0.2	5.0	4.9	8.4
KOM6	28	83.8	11.1	5.5	11.0	0.2	2.5	**11.6**	10.0
KOM7	30	92.7	18.5	7.8	10.5	0.7	10.0	0.3	2.5
KOM8	26	79.0	7.9	5.6	4.3	0.8	5.0	**16.4**	8.7
2TP, 3TP, 7TP, 8TP	No Coral								

4. Mobile Invertebrates

Mobile invertebrates were counted during biweekly surveys at the transect locations. See methods for further details on protocol, and a full invertebrate species list for Year 3 in Appendix B.

A. *Tidepools*

In the Tidepools, the Year 3 study found a total of 22 mobile invertebrate species (Figure 31). This total does not include several species within grouped designations such as brittle stars, Drupe spp., or hermit crabs.

Seven species of urchins were observed, consistent with Years 1 and 2. The most dominant species was *Echinometra mathaei*, with a mean abundance of 35.64 urchins per 20 m^2 transect, representing a total of 95.38% of total observed mobile invertebrates in the Tidepools. The second most abundant species was *Echinometra oblonga,* with a mean abundance of 0.78 urchins per 20 m^2 transect, but representing only 1% of mobile invertebrates recorded in the Tidepools. Other abundance species include *Diadema paucispinum*, *Echinostrephus aciculatus*, and *Holothuridae* (Sea Cucumbers).

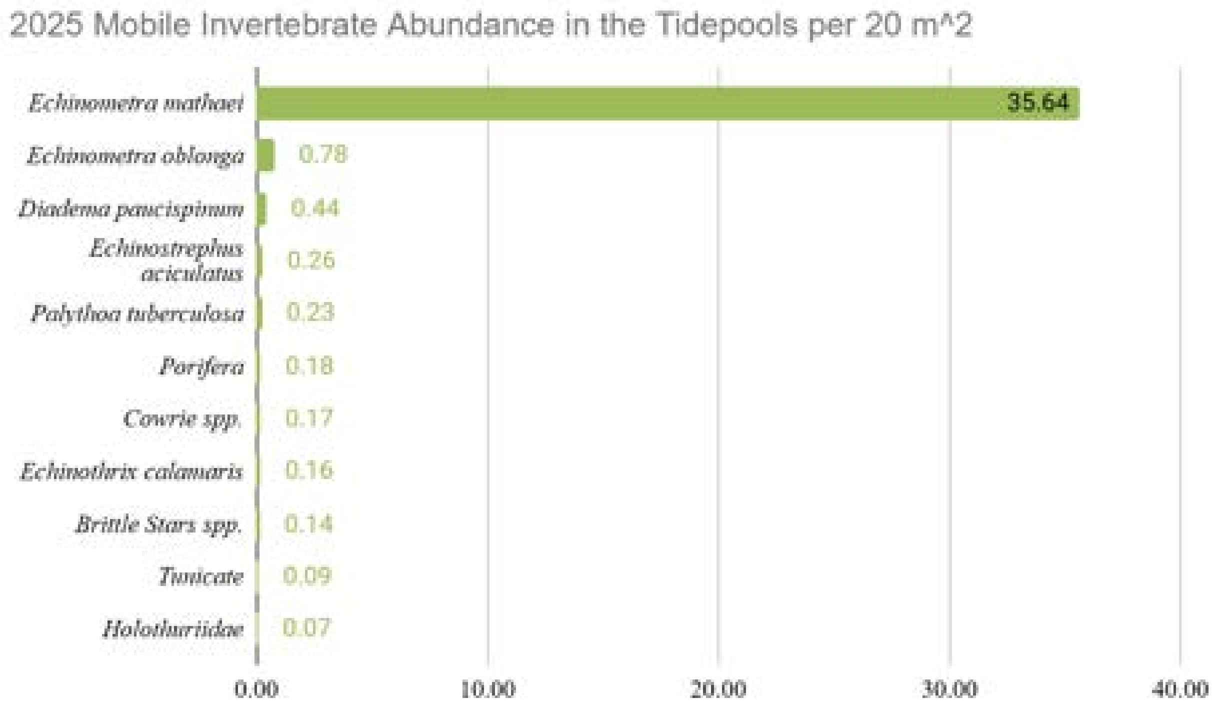


Figure 32. Mean Abundance of Mobile Invertebrates by species per 20m^2 transect

in 2025 in the Tidepools.

B. *Cove*

In the Cove, the study found 15 invertebrate species in Year 3 (Figure 32). This total does not include several species within grouped designations such as brittle star, Drupe spp. or hermit crab.

The mobile invertebrate community was dominated by urchins. *Echinometra mathaei* was the most dominant species in the Cove with a mean of 37.2 individuals per 20 m^2 transect, accounting for 87.24% of individuals observed. *Echinometra oblonga* was the second most abundant species at 0.78 individuals per 20m^2 transect, typically occurring in high surf zones, and representing 11.56% of observed mobile invertebrates in the Cove.

Brittle stars were not previously individually recorded, counted in other years as "other.". In 2025, they were independently counted in their own category and were the fourth most abundant mobile invertebrate in the Cove, when consolidated to one general "Brittle Star" category.

Several invertebrate species recorded in earlier years were not observed during Year 3, including *Opheodesoma spectabilis* (Conspicuous Sea Cucumber), *Dendrodoris carbunculosa* (Carbunculous Nudibranch), and *Pseudoceros paralaticlavus* (Goldrim Flatworm). In contrast, *Carpilius maculatus* (Seven-eleven Crab), *Octopus cyanea* (Day Octopus), *Stenopus hispidus* (Banded Coral Shrimp), and *Loimia medusa* (Spaghetti Worm), which were not observed in Year 2, but were observed in Year 1, were recorded in Year 3.

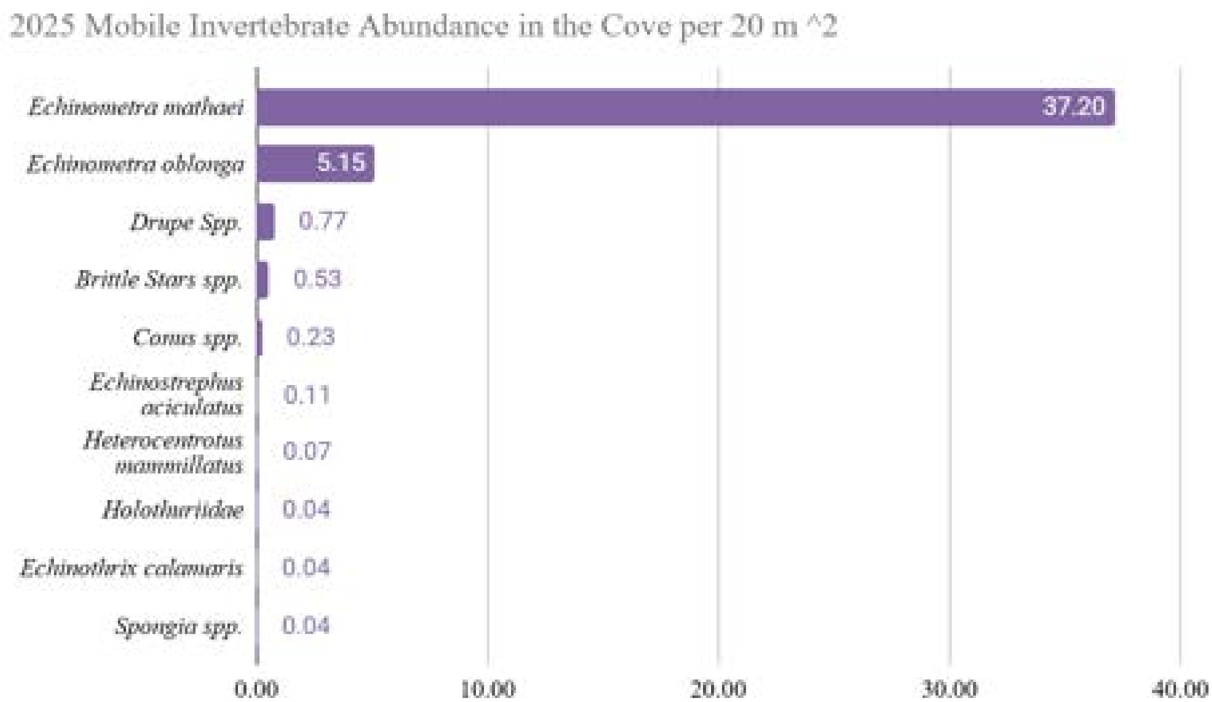


Figure 32. Mean Abundance of Mobile Invertebrates by species per 20m^2 transect

in 2025 in the Cove.

C. *Kalua o Maua*

In Year 3, baseline data were taken for Kalua o Maua's mobile invertebrates that will allow comparison for future years and in the face of change, similarly to the Tidepools and Cove.

Similarly to the Tidepools and Cove, the urchin community was dominant. *Echinometra mathaei* was most abundant, with a mean of 45.85 of individuals per 20m^2 transect, or 76.78% of observed mobile invertebrates (Figure 33).

The second most abundant invertebrate group at Kalua o Maua were brittle stars, with a mean abundance of 9.88 (11.51%) per 20 m^2 transect. This stands apart from the Kapo'o sites, where mean brittle star abundance in the Tidepools was 0.14 per 20m^2 transect, and the 0.53 per 20 m^2 transect in the Cove.

Drupe spp. (Drupella snails) were the third most abundant species when grouped, with 1.44 per 20 m^2 transect on average.

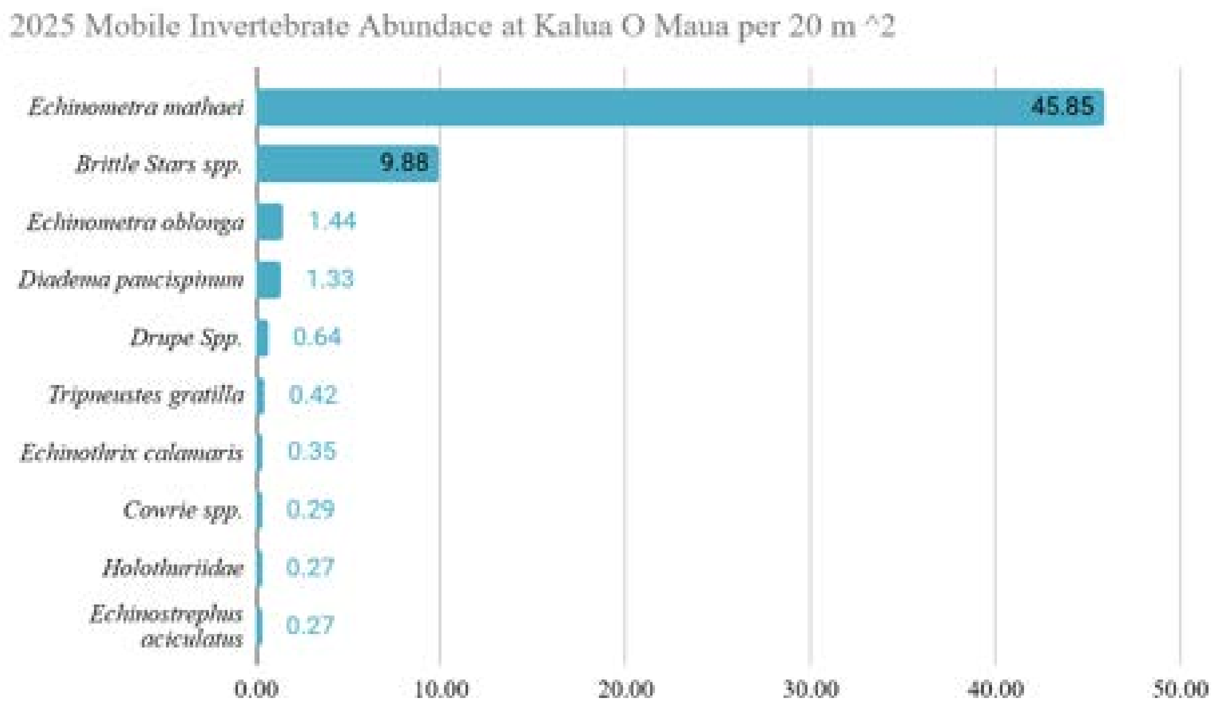


Figure 33. Mean Abundance of Mobile Invertebrates by species per 20m^2 transect in 2025 at Kalua o Maua.

B. Environmental Components

1. Water Clarity

Suspended solids can decrease the amount of light that penetrates to the benthos, which reduces photosynthesis in both corals and algae. Although suspended sediment can be assessed via turbidity, water clarity, or water samples, visual water clarity is an appropriate measurement of the optical effects of suspended solids (Davies-Colley and Smith, 2001), and can be more informative than other turbidity measures to understand the effects of suspended sediment.

Areas with increased sedimentation from runoff experience light reduction, which causes the reef environment to change (Fabricius, 2005). Decreased light availability can reduce the amount of energy available to a coral for metabolic functions, resulting in tissue discoloration and bleaching (Bessell-Browne et al., 2017, Jones et al., 2020).

Deposited sediment results in an allocation of energy by corals to increased mucus production in order to slough off the sediment, a decrease in photosynthesis, and increase in respiration, which can lead to reductions in coral growth (Reigl and Branch, 1995) and fecundity (Jones et al., 2015).

Similar effects from increased suspended sediment have been observed in reef fish. Suspended sediment can reduce gill lamellae length by 20-30% and oxygen consumption by 18-28% in Australian damselfish and anemonefish (Hess et al. 2017). Longer food acquisition times and slower growth rates were observed in damselfish reared in intermediate and high turbidity treatments in addition to a 50% mortality rate of fish in the high sediment treatment (Wenger et al., 2012).

Reduced herbivory on plots with deposited sediment was also observed in herbivorous fish (Bellwood and Fulton, 2008; Tebbett et al., 2018) which has implications for both fish survival rates and overgrowth of corals by turf algae. These types of impacts have resulted in areas with high turbidity experiencing reduced fish biomass in both high and low trophic levels (Brown et al., 2017).

Water clarity can be altered by both anthropogenic and environmental sources. Human recreation within an area can stir up sediment (Neil, 1990) and run-off from land in heavily populated areas can decrease water clarity (Fabricius, 2005). Visual clarity is also dependent on a number of oceanographic factors such as tides and wind (Panseriya et al., 2023).

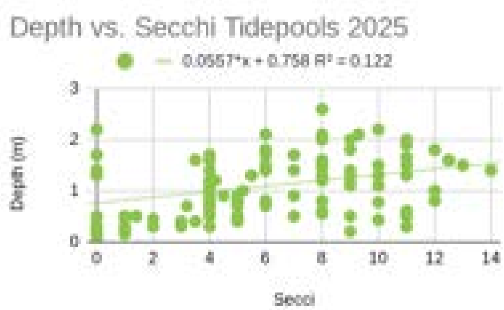
The BCC studies aimed to determine the impacts of suspended sediment on life within the Kapoʻo Tidepools and Cove. In 2025, correlations between water clarity and depth weakened across all previously surveyed sites.

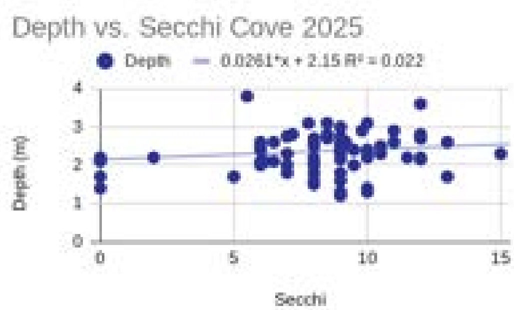
The Tidepools showed a modest positive relationship (correlation coefficient = 0.350), while the Cove exhibited little to no correlation (correlation coefficient = 0.147). At Kalua o Maua, a moderate positive relationship was observed (correlation coefficient = 0.342, $R^2 = 0.117$).

Overall, these findings indicate greater variability and a reduced strength of association between depth and water clarity compared to earlier years.

In both 2023 and 2024, Secchi disk measurements revealed stronger and more consistent positive correlations between water clarity and depth than was found in 2025.

In 2024, this relationship was most pronounced in the Tidepools (correlation coefficient = 0.375, $p < 0.001$) and still evident in the Cove (correlation coefficient = 0.237, $p < 0.001$). In 2023, both zones showed significant positive associations, although the magnitude differed (Tidepools: correlation coefficient = 0.203, $p < 0.001$; Cove: correlation coefficient = 0.509, $p < 0.001$).





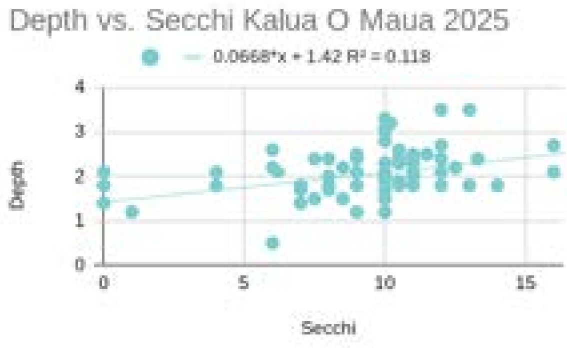


Figure 34. The Depth vs. Water Clarity Relationships shown across each zone in 2025.

2. Temperature

Across the Tidepools' temperature loggers (TP1, TP4, and TP8), temperature conditions in 2025 showed consistent mean values at the start of the monitoring period in June (26.61–26.64°C), but the sensors diverged substantially in their upper temperature ranges as the summer season progressed (Figure 35A).

For this analysis, 29°C was used as the temperature at which thermal stress begins to accumulate and if sustained for long periods may result in coral bleaching for Hawai‘i corals, based on research demonstrating that corals in Hawai‘i begin to exhibit physiological stress and bleaching responses at approximately 29–30°C (Jokiel & Brown 2004).

TP1 remained within a comparatively narrow range (23.1–29.41°C) through mid-summer and did not exceed the threshold until August. In contrast, TP4 and TP8 began exhibiting higher warm-season maxima earlier in the monitoring period, ultimately exceeding the threshold substantially, reaching 35.50°C and 34.52°C, respectively.

Threshold exceedances accumulated at these two transects over the course of the summer and early fall, with TP4 recording 52 readings above 29°C (with 9 continuous events; meaning consecutive hourly exceedance readings) and TP8 recording 119 readings (with 24 continuous events), totaling approximately 52–119 hours above threshold.

By late summer and into September, cumulative thermal exposure across the Tidepools reflected several short-duration heat events. Degree Heating Hours (DHH), calculated as the sum of °C above the 29°C threshold for each hourly reading, ranged from 0.75°C·hr at TP1 to 108.82°C·hr at TP4 and 233.29°C·hr at TP8. These results indicate that TP1 experienced only minimal, short-lived warming above the bleaching threshold, while TP4, and particularly TP8, experienced repeated and longer-lasting spikes in temperature. These values represent short-duration heating events rather than sustained elevation of mean temperatures.

However, under the NOAA Coral Reef Watch Degree Heating Weeks (DHW) calculation, used here only to quantify cumulative heating, all Tidepools sensors registered 0.00 DHW during the monitoring period, as daily mean temperatures did not exceed the accumulation threshold (Liu et al. 2014; Skirving et al. 2019).

The warmest temperatures of the season occurred in late October, when TP4 and TP8 reached their maximum values on October 29: 35.50°C at TP4 and 34.52°C at TP8.

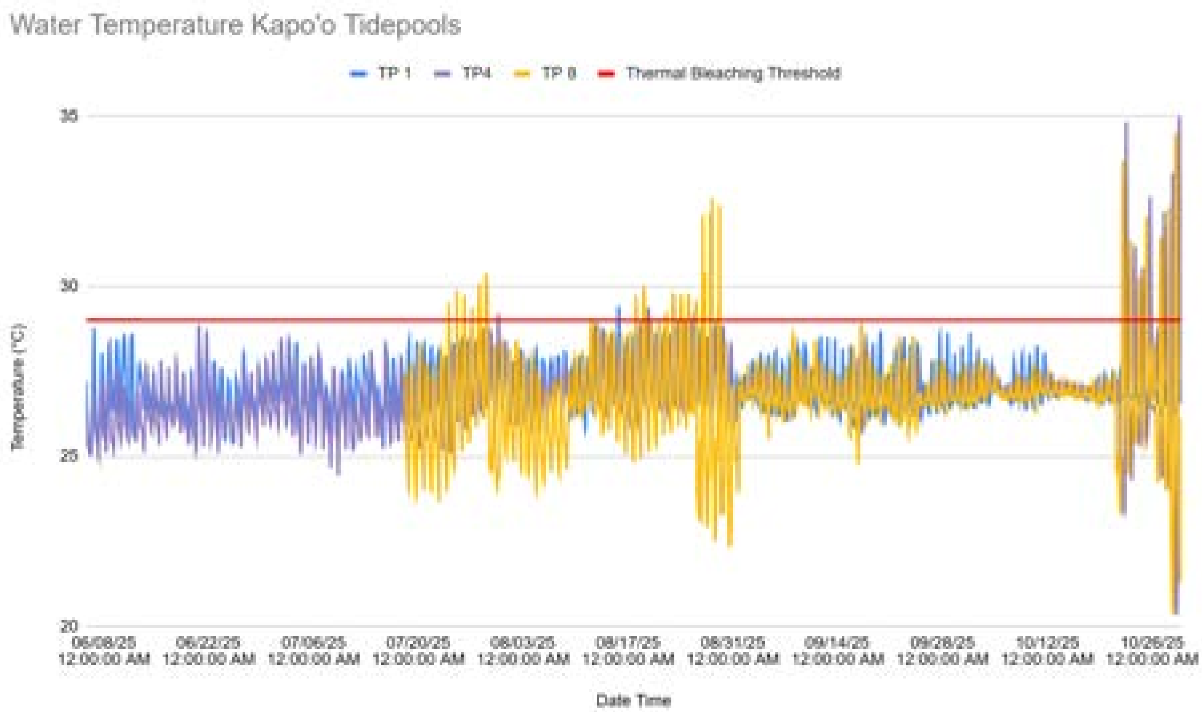


Figure 35A. Temperature of the Tidepools from June-October 2025. The red line at 29°C depicts the temperature at which thermal stress begins to accumulate and if sustained for long periods may result in bleaching for Hawaiian corals.

In the deeper Cove, temperature patterns were more moderate over the same June–September period (Figure 35B). The Cove4 logger recorded temperatures ranging from 25.40°C to a maximum of 28.15°C, with a mean of 26.58°C. No readings exceeded the 29°C bleaching threshold, and no continuous heating events were detected.

As a result, the Cove accumulated 0 total exceedances, 0 hours above threshold, 0°C·hr DHH, and 0.00 DHW. Minor abrupt changes in temperature were present in the record but did not correspond with significant warming events.

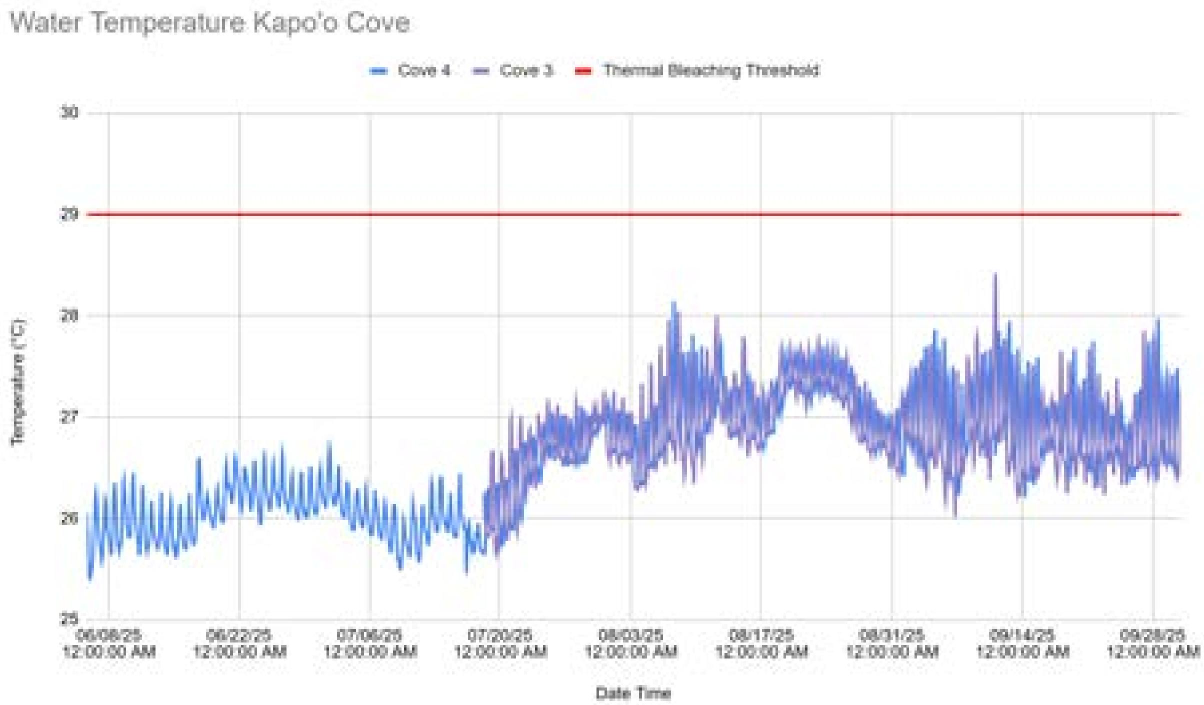


Figure 35B. Temperature of the Cove from June-October 2025. The red line at 29°C depicts the thermal bleaching threshold for Hawaiian corals.

The study did not deploy temperature loggers at Kalua o Maua, which has greater coral cover than the Tidepools and Cove, so adding loggers in that zone is a recommendation for the continued MPW marine science program.

3. Rugosity

Rugosity, a measure of surface complexity, is crucial for understanding how physical environments, particularly marine habitats, change seasonally under the influence of dynamic forces like wave action (Ventura et al.; Baldock et al., 2014).

In Hawaiʻi, the interaction between sand and rocky substrates creates a dynamic environment, heavily influenced by seasonal winter surf. High wave energy events increase sand suspension, leading to sediment redistribution and alterations in substrate structure, which have significant implications for habitat availability for marine organisms (Hanes & Huntley, 1985; Asner et al., 2021).

These seasonal wave patterns play a critical role in resuspending and redistributing sand and sediment across coastal and nearshore environments, driven by variations in wave energy, frequency, and direction throughout the year (Santoso et al., 2021; Harborne et al., 2012).

This study quantified seasonal physical changes in Kapoʻo, and comparative rugosity across zones, by measuring rugosity as an indicator of substrate complexity. Rugosity measurements from 2022 and 2024 were compared to 2025 to evaluate changes in structural characteristics, providing insight into the effects of seasonal wave activity and sediment dynamics on the physical environment.

In 2025, rugosity measurements revealed continued variability across both the Tidepools and the Cove (Table 2). In the Tidepools, changes over the duration of the study period (2023-2025) ranged from a decrease of -1.90 m at TP1 to an increase of +1.55 m at TP3, with TP3 showing a notable recovery in Year 3 after previously losing complexity between Years 1 and 2.

In the Cove, rugosity shifts ranged from -3.10 m at CO7 to +3.30 m at CO8, marking CO8 in the shallow near shore area of the Cove, as the most structurally dynamic site this year. CO7, in the nearshore eastern side of the cove, had shown a substantial increase in earlier years, experienced the sharpest decline in 2025.

On average, the Tidepools exhibited a slight decrease in rugosity of –0.20 m, while the Cove showed an average decrease of –0.30 m during the summer–fall study period. These changes reflect ongoing sediment redistribution likely influenced by seasonal wave energy, storm exposure, and nearshore hydrodynamics. Summer typically brings lower-energy, flat conditions and winter brings higher-energy north swells, and these conditions can influence the direction and magnitude of sand movement.

When compared to previous data from 2022 to 2024, the 2025 results show both continuations and reversals of earlier trends.

During that earlier period, the Tidepools transects showed changes ranging from +2.43 m at TP4 to -1.63 m at TP3, while the Cove transects ranged from -4.37 m at CO6 to +3.43 m at CO7. The 2025 rebound at TP3 and reversal at CO7 highlight the high variability in substrate structure across years, likely linked to shifts caused by swell and sediment load.

Additionally, in 2025, the original Tidepool Transect 8 (TP8) transect had to be relocated to a nearby site (T8B) due to excess sand accumulation that left much of the original area no longer submerged. These patterns underscore the importance of long-term, site-specific monitoring, in addition to year round monitoring as conditions allow, to capture the full extent of variability in physical habitat structure over time.

Rugosity was recorded for the first time in 2025 at Kalua o Maua. Measurements across the eight transects ranged from 10.50 m to 16.30 m, with an average rugosity of 12.45 m. Transect 5 showed the highest structural complexity (16.30 m), while Transects 6 and 7 recorded the lowest values (10.50 m and 10.60 m, respectively). Although no year-to-year comparison is yet possible, this initial dataset offers a reference point for monitoring future changes in substrate complexity and evaluating how physical conditions evolve at this site over time.

Table 2. Rugosity across all transects from 2024 to 2025, from 2022-2025, and the associated change. TP8B was established in 2025 after the original TP8 transect became unusable due to excess sand deposition; no comparative data are available for this site yet. Similarly, Kalua o Maua sites and TP 8B were established in 2025 and do not yet have previous data to compare.

Zone	Transect	2023 Rugosity (m)	2024 Rugosity (m)	2025 Rugosity (m)	Change (2024–2025)	Change (2022-2025)
Tidepool	TP1	13.27	13.70	11.80	-1.90	-1.47
Tidepool	TP2	11.80	11.90	12.00	0.10	0.20
Tidepool	TP3	12.03	10.40	11.95	1.55	-0.08
Tidepool	TP4	11.37	13.80	13.70	-0.10	2.33
Tidepool	TP5	12.97	13.80	13.90	0.10	0.93
Tidepool	TP6	11.40	10.00	10.30	0.30	-1.10
Tidepool	TP7	11.77	11.40	10.90	-0.50	-0.87
Tidepool	TP8B	11.50	—	11.20	—	—-
Cove	CO1		14.20	13.00	-1.2	13.00
Cove	CO2	12.80	13.70	12.10	-1.6	-0.70
Cove	CO3	13.10	13.40	12.20	-1.2	-0.90
Cove	CO4	12.77	13.30	13.60	0.30	0.83
Cove	CO5	14.77	14.80	15.20	0.40	0.43
Cove	CO6	13.07	11.00	11.10	0.10	-1.97
Cove	CO7	15.37	14.90	11.80	-3.10	-3.57
Cove	CO8	11.47	10.00	13.20	3..20	1.73
Kalua o Maua	KOM1	—	—	13.10	—	—
Kalua o Maua	KOM2	—	—	12.60	—	—
Kalua o Maua	KOM3	—	—	12.50	—	—
Kalua o Maua	KOM4	—	—	12.50	—	—
Kalua o Maua	KOM5	—	—	16.30	—	—
Kalua o Maua	KOM6	—	—	10.50	—	—
Kalua o Maua	KOM7	—	—	10.60	—	—
Kalua o Maua	KOM8	—	—	11.50	—	—

C. Human Use

1. Human Counts on Transects

In 2025, during each biweekly transect survey, humans within 10 m of the transect were counted by the in-water researcher or coordinator. The way humans were counted changed between 2023 and 2024 (see Methods, Figure 5). Previously, the researcher counted people located within a circle with a 10 m radius extending from the center of the transect, but this method shifted to counting humans within 10 m of the entire transect length (314.16 m^2).

This change in area was corrected for during analysis, and all values presented here are transformed to be comparable across years. The below analysis uses the transformed data.

In 2025, the transformed human counts along transects ranged from 0 to a peak of 20.16 across zones.

In the Tidepools, human counts averaged 2.92 ± 0.31 SE humans within 10 m of the center of each transect (314.16 m^2), with a maximum of 20.16. The average represents a 37% increase in humans along the transects from 2024 (2.14 ± 0.15 SE per 314.16 m^2) and a 214% increase from the 2022 baseline (0.93 ± 0.14 SE per 314.16 m^2).

In the Cove, human counts averaged 1.64 ± 0.16 SE, with a maximum of 7.94, marking an 89% increase from 2024 (0.87 ± 0.09 SE per 314.16 m^2) but below 2023 levels (2.98 ± 0.29 SE per 314.16 m^2). Compared to 2022 (1.15 ± 0.15 SE per 314.16 m^2), the 2025 average represents a 43% increase in humans along the transects.

Combined across the Tidepools and Cove, the 2025 mean human count was approximately 2.43 people within a 10 m radius of the transect, more than double the 2024 mean, consistent with long-term patterns of increasing human presence at Kapoʻo.

Human use has fluctuated over the four years of monitoring (2022–2025), but overall trends show a sustained rise in visitation compared to the baseline year. In 2022, mean counts across both zones averaged roughly 1.04 humans per transect, ranging from 0–11. Counts increased sharply in 2023 (mean ≈ 3.19, max = 29), then declined in 2024 (mean ≈ 1.50, max = 12.22), before rising again in 2025 to 2.43.

The survey methodology intentionally scheduled observations across the gradient of human presence. Consequently, the resulting dataset exhibits a significant number of surveys with zero human counts near the transects (from early morning observations). Visualizing the shift in the distribution of human counts over time (Figure 36) provides the clearest representation of year-to-year variation in this variable.

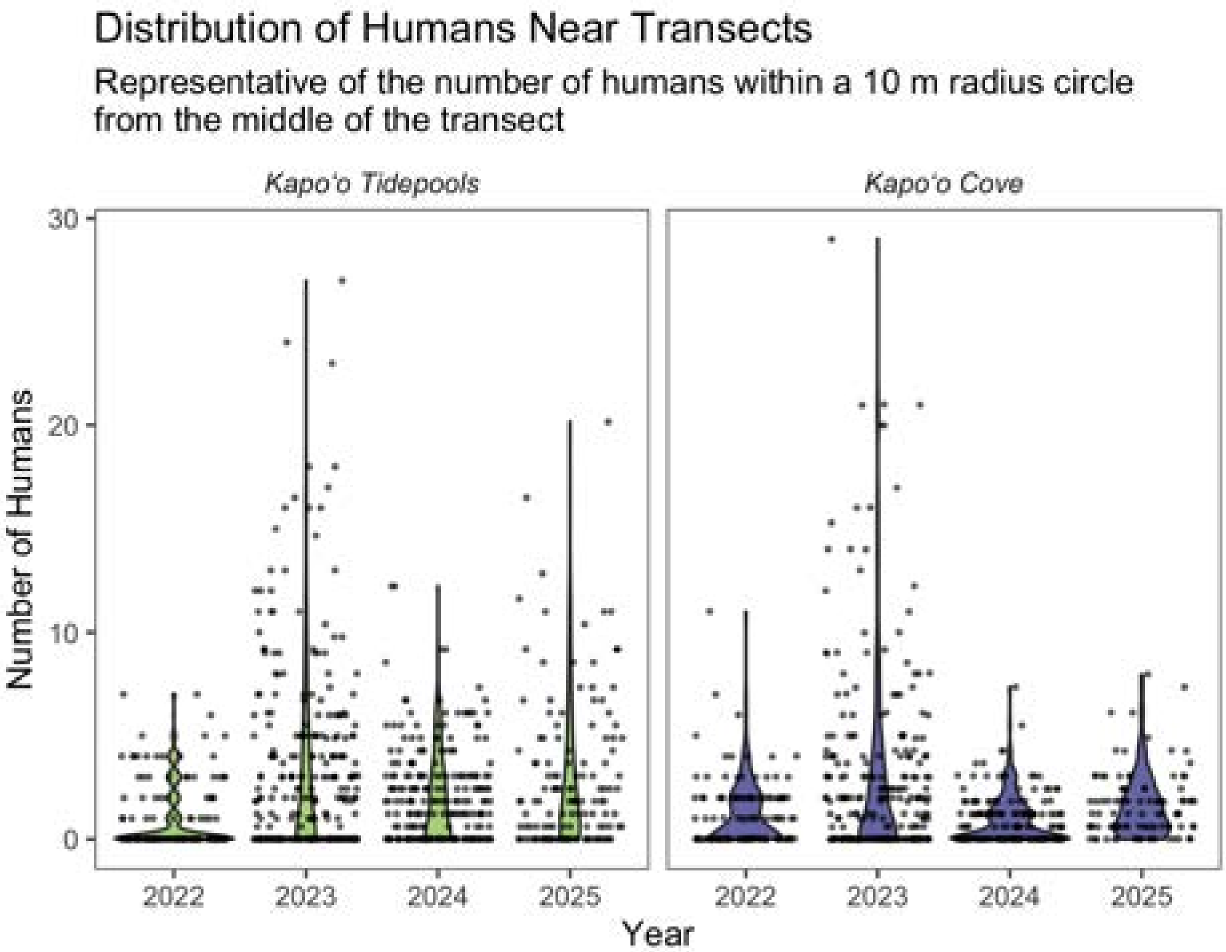


Figure 36. Distribution of the number of humans observed within an area 10 m from the center of the transect observed from on-transect counts. Raw data are plotted as points. Data from 2024 and 2025 have been scaled to represent the same area as counts in 2022 and 2023. Years 2024 and 2025 have been scaled to represent the same area. Data could not be subset to time of day given lack of that data in 2023.

In the Tidepools, human counts have remained consistently higher than at the Cove since 2023. Average counts (± SE) were 0.93 ± 0.14 per 314.16 m^2 in 2022, 3.39 ± 0.28 in 2023, 2.14 ± 0.15 per 314.16 m^2 in 2024, and 2.92 ± 0.31per 314.16 m^2 in 2025. The 2025 maximum of 20.16 people within 10 m of a single transect represents the highest Tidepools value on record (although below the pre-transformation raw maximum of 33).

In the Cove, average counts were 1.15 ± 0.15 in 2022, 2.98 ± 0.29 in 2023, 0.87 ± 0.09 in 2024, and 1.64 ± 0.16 in 2025.

By 2024 and 2025, Tidepools human counts were approximately 1.8–2 times higher than Cove counts, reinforcing a persistent pattern of concentrated human use in the Tidepools.

Marine researchers each year were trained by the researchers from previous years to minimize observer bias, and one researcher (Tiana Tomoda-Bannert) conducted surveys in both 2023 and 2024.

The expanded transects in 2025 at Kalua o Maua showed human counts ranging from 0–8, with an average of 1.42 ± 0.27 SE people per transect. This level of use was substantially lower than at either the Tidepools or Cove, providing a valuable baseline for expanded research and for future management actions that may shift visitor distribution.

Overall, the data indicate rising and spatially concentrated human pressure—particularly within the Tidepools zone—underscoring the need for continued monitoring and potential management strategies to mitigate visitor impacts on this important intertidal habitat of the Pūpūkea MLCD.

2. Point-in-Time Visitor Counts

Using point-in-time human use counts collected by Mālama Pūpūkea-Waimea (MPW)'s Makai Watch staff and volunteers, this study obtained detailed insights into the number and timing of people present within the in-water sections of the Kapoʻo Tidepools, Kapoʻo Cove, and Kalua o Maua during 2025.

These counts represent the number of individuals visible in the water at a single moment and from a single vantage point, offering a consistent metric of real-time site use that complements the transect-based human count data, aerial drone data, and human use Tidepools "people camera" (time-lapse) data.

Data were summarized by hour, day of the week, and month to identify temporal and spatial patterns in visitation.

Point-in-time visitor counts from 2025 show strong consistency across all monitored zones (Figure 37A). In both Kapoʻo Tidepools and Cove, the number of people in the water begins to rise sharply by 8:00 a.m., reaching a peak between 11:00 a.m. and 3:00 p.m., before gradually declining toward sunset. This pattern mirrors observations in previous years (2023–2024).

In 2025, the Tidepools recorded the highest hourly mean, with 115 individuals present on average at peak times (3:00 p.m.).

The Cove followed the same trend but at lower magnitude, peaking at 65 individual visitors around midday and averaging 60-75 people at a point-in-time during other daytime hours.

Weekly patterns in 2025 mirror those observed in 2023 and 2024, showing consistently high visitor numbers throughout the week with little variation (Figure 37B).

At Kalua o Maua in 2025, counts revealed a similar temporal pattern but lower density overall. Hourly means ranged from near-zero use in the early morning (6:00–7:00 a.m.) to an average of 66.9 ± 22.5 SE individuals at 1:00 p.m., representing the daily peak. Use then declined steadily through the afternoon, falling to 46.5 ± 19.5 SE individuals by 5:00 p.m..

Kalua o Maua also saw Saturdays being the busiest day of the week, with the remainder of days also remaining consistently high.

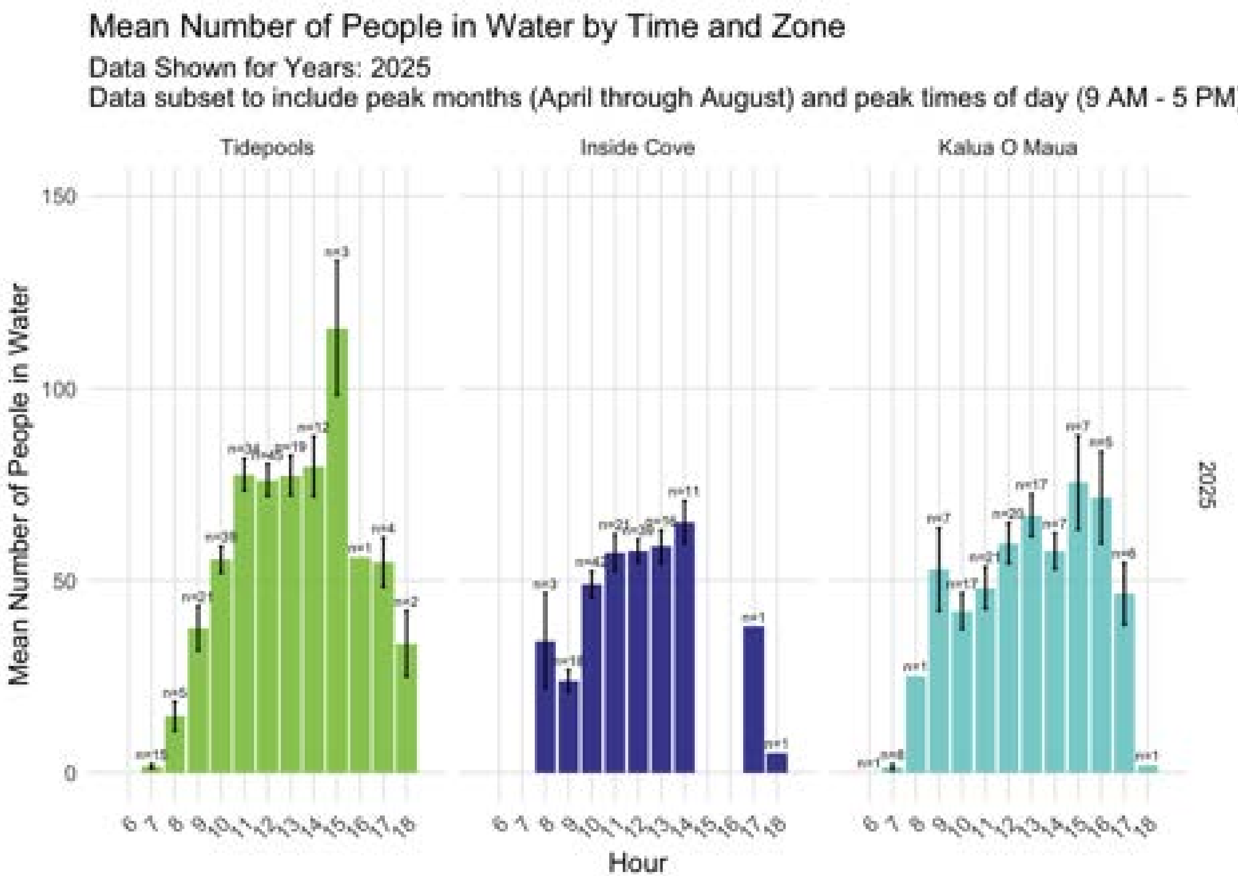


Figure 37A. Average number of visitors (at a single point in time) by hour (in military time) across Kapo'o Tidepools and Cove in 2025. Black bars represent the standard error of observations, and the sample size is printed on top. Areas without sample size is where no observations were recorded. Visitor presence increases throughout the morning, peaks between 11:00 a.m. and 4:00 p.m., and declines into the late afternoon, with the Tidepools consistently showing the greatest use at all hours.

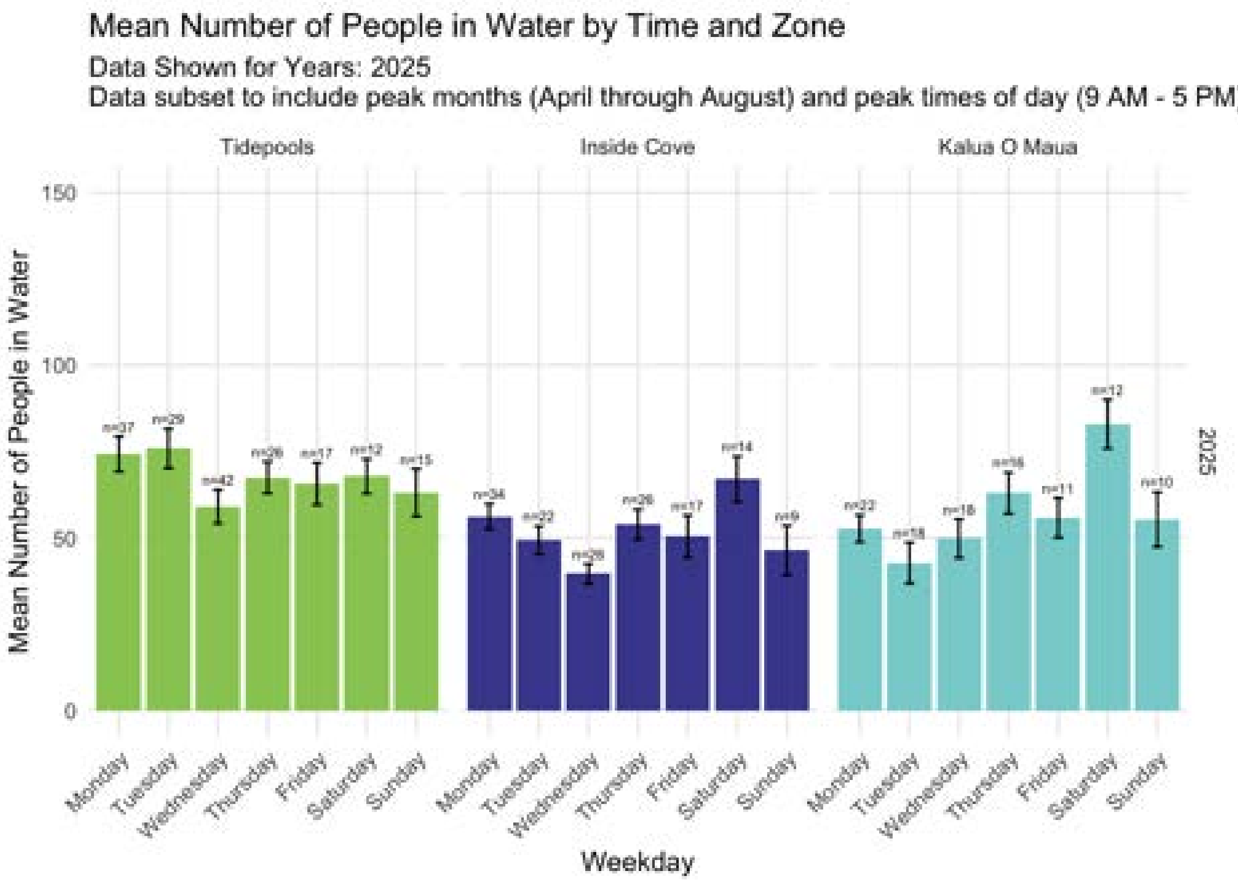


Figure 37B. Average number of visitors (at a single point in time) by day of the week in 2025. Black bars represent the standard error of observations, and the sample size is printed on top. Areas without sample size is where no observations were recorded.
Visitation remains high throughout the week.

Monthly averages of MPW human use counts reveal a seasonal influence of visitation that follows surf conditions but also a notable counterintuitive high level of use of the Tidepools during high surf apparently due to the swells closing out nearby beaches thus concentrating continual visitor use.

The Tidepools' relatively protected geography led to sustained and high levels of use even under hazardous surf conditions, with mean counts of 40–60 individuals still observed during the winter months. This counterintuitive persistence of high use during winter demonstrates that the Tidepools remain a magnet for non-resident visitors seeking calm water when surrounding beaches are closed or unsafe.

Community members have also pointed out that often when the swell is larger, the number of visitors in the Tidepools tends to increase as it is perceived to be more sheltered than surrounding areas. MPW has also observed that residents are more knowledgeable about winter surf hazards and avoid Kapo'o during the winter swells, while non-resident visitors are not aware, do not understand, or always follow the hazard guidance or caution signs or tape by City Ocean Safety.

The visitor use of the Tidepools remains high and relatively consistent year round despite increased wave height and energy in the area making it potentially unsafe.

In the Cove, the MPW human use counts found dramatically fewer people in the winter months during typical winter conditions on the North Shore with higher wave energy (Figure 38). This finding is not surprising given the hazards of high surf in the Cove are more obvious, even to visitors.

Similarly at Kalua o Maua, the human use counts found a steep decline in humans in the water during the winter months, likely due to exposure to swell and more obvious rougher conditions.

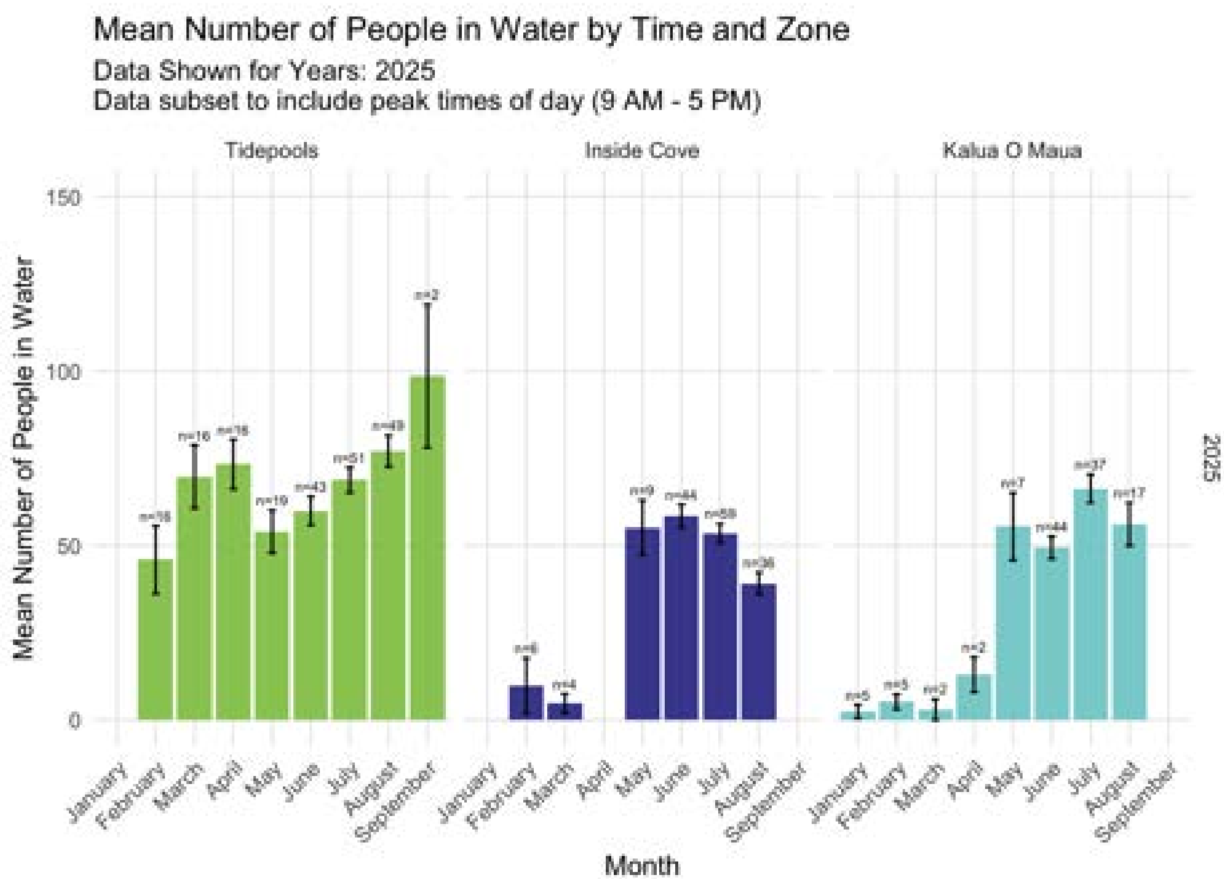


Figure 38. Average number of visitors (at a single point-in-time) by month from January-September 2025. Black bars represent the standard error of observations, and the sample size is printed on top. Areas without sample size is where no observations were recorded. Visitation peaks during summer months, particularly July through September, and declines during winter; however, Tidepools use remains elevated year-round. Data after September were not included due to the report's time constraints.

A. *Human use over the years*

i. Weekday averages and peaks

In 2025, human presence at the Tidepools remained high and consistent throughout the week, with weekday means ranging from 59.0 (± 4.9) on Wednesdays to 75.9 (± 5.7) on Tuesdays. These values are comparable to those recorded in 2024 (67–79 ± 5.0–7.1) and confirm that elevated human use in the Tidepools has persisted since the substantial increase first documented in 2023 (Figure 39).

Across all years, the Tidepools have shown sustained visitor counts well above 2022 levels, when weekday means ranged from 27 (± 5.1) to 102 (± 18.0). Variability, as reflected in the standard error, decreased markedly after 2022, suggesting that visitation patterns have become both more predictable and consistently high. Together, these data indicate that human activity in the Tidepools may have plateaued at elevated levels, with stable weekday use across all four years of monitoring. However, given that no limits or barriers exist currently for the numbers of visitors who access Kapoʻo, the visitor counts could continue to increase even further absent management measures.

In the Cove in 2025, human counts increased notably compared to the previous two years, with weekday averages ranging from 39.6 (± 2.9) on Wednesdays to 67.0 (± 6.6) on Saturdays. This marks a substantial increase from 2024, when weekday means ranged between 29 and 44 (± 3.7–9.4), and from 2023, when counts averaged 23–40 (± 6.3–11.9).

The 2025 data in the Cove also approach or exceed several of the higher counts recorded in 2022 (25–76 ± 9.1–10.0), suggesting a rebound in visitor numbers after the temporary dip observed in 2023–2024. The relatively low SE values in 2025 (± 3.6–7.2) indicate a more consistent pattern of weekday use, with higher and steadier visitation throughout the week. Overall, the “Inside” Cove now shows a steady upward trajectory in human use, although average use remains lower than at the Tidepools likely due to days when swell is higher and the area is less accessible.

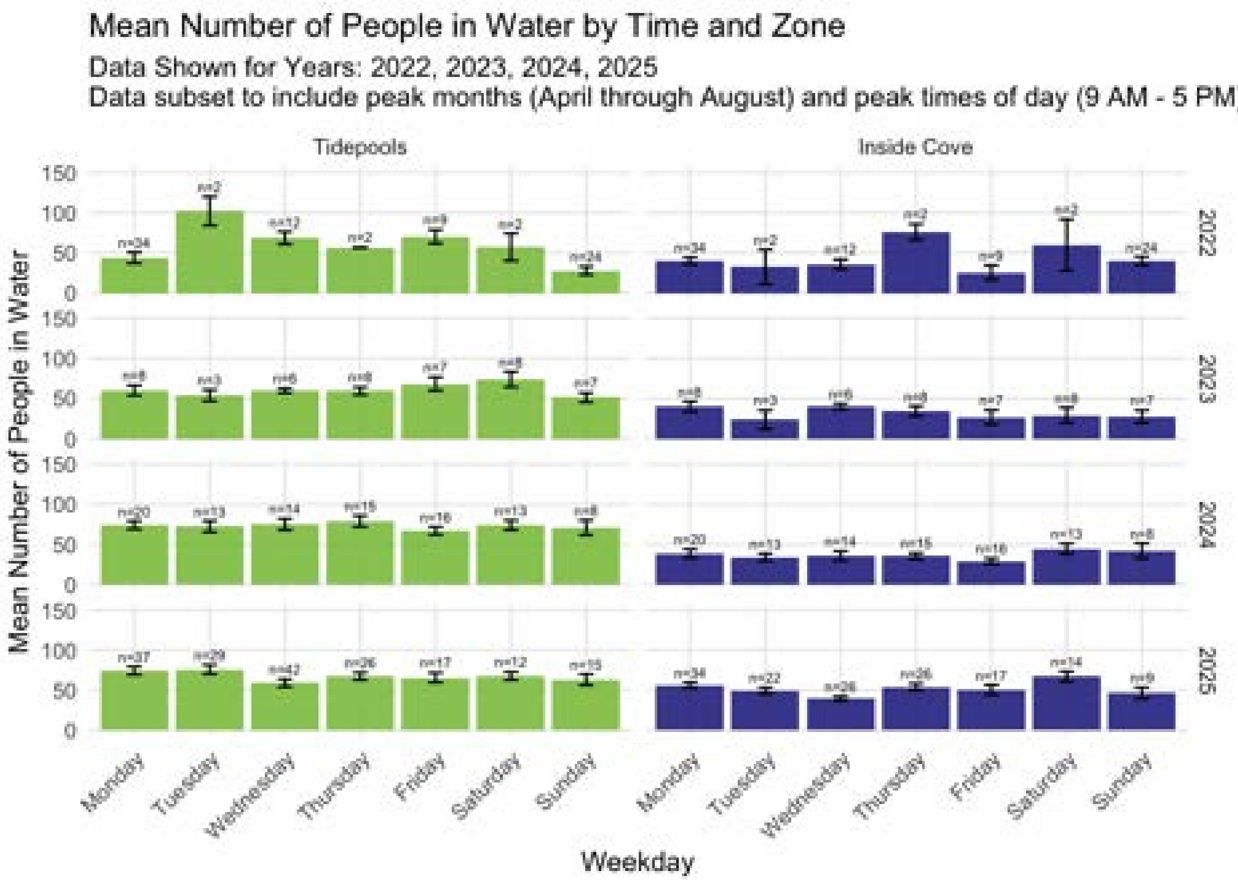


Figure 39. Average number of users in the water recorded through Makai Watch observations at the Tidepools and Cove from 2022 to 2025, summarized by weekday. Bars represent mean counts of people in the water for each day of the week, with error bars showing ± standard error (SE). The data highlight consistently high and stable in-water use at the Tidepools across all years, contrasted with lower but steadily increasing use in the Cove. The 2025 observations indicate the highest total in-water users to date, demonstrating sustained recreational pressure throughout the week in both zones.

ii. Hourly averages and peaks

In 2025, the Tidepools showed sustained high in-water use throughout the mid-day hours, with averages increasing steadily from 9 a.m. (37.5 ± 5.7) to a pronounced peak between 11 a.m. and 2 p.m. (77.5–79.7 ± 4.1–7.8). The highest hourly mean occurred at 3 p.m. (115.7 ± 17.4), indicating extended afternoon activity later than in previous years. This pattern represents a marked shift from 2022, when the primary peak occurred at noon (64.8 ± 6.1) and activity tapered off by 2 p.m. (Figure 40).

In 2023 and 2024, use of the Tidepools intensified and expanded across the late morning and early afternoon (11 a.m.–2 p.m.), stabilizing at mid-day averages of 65–91 ± 6.2–10.3. By 2025, water use remained consistently high across all mid-day hours with slightly narrower standard errors, suggesting that visitor presence in the Tidepools has become both heavier and more evenly distributed through the central part of the day.

In the Cove, total in-water use in 2025 followed a similar diurnal trend but at lower overall levels compared to the Tidepools. Counts rose sharply after 8 a.m. (34.3 ± 12.3) and peaked between 11 a.m. and 2 p.m. (57.2–65.2 ± 2.9–5.4) before gradually declining in the late afternoon. These values represent the highest hourly means observed across the four-year period, exceeding 2024 mid-day averages (40.6–56.5 ± 4.4–7.3) and more than double values from 2022 (25.7–59.7 ± 4.2–10.0).

The 2023 data reflected more moderate use (30–36 ± 5.9–11.0), suggesting a temporary decrease prior to the recent rebound. By 2025, consistent human use across all late-morning to mid-afternoon hours indicates renewed and sustained use at the Cove, although overall numbers remain lower than at the Tidepools.

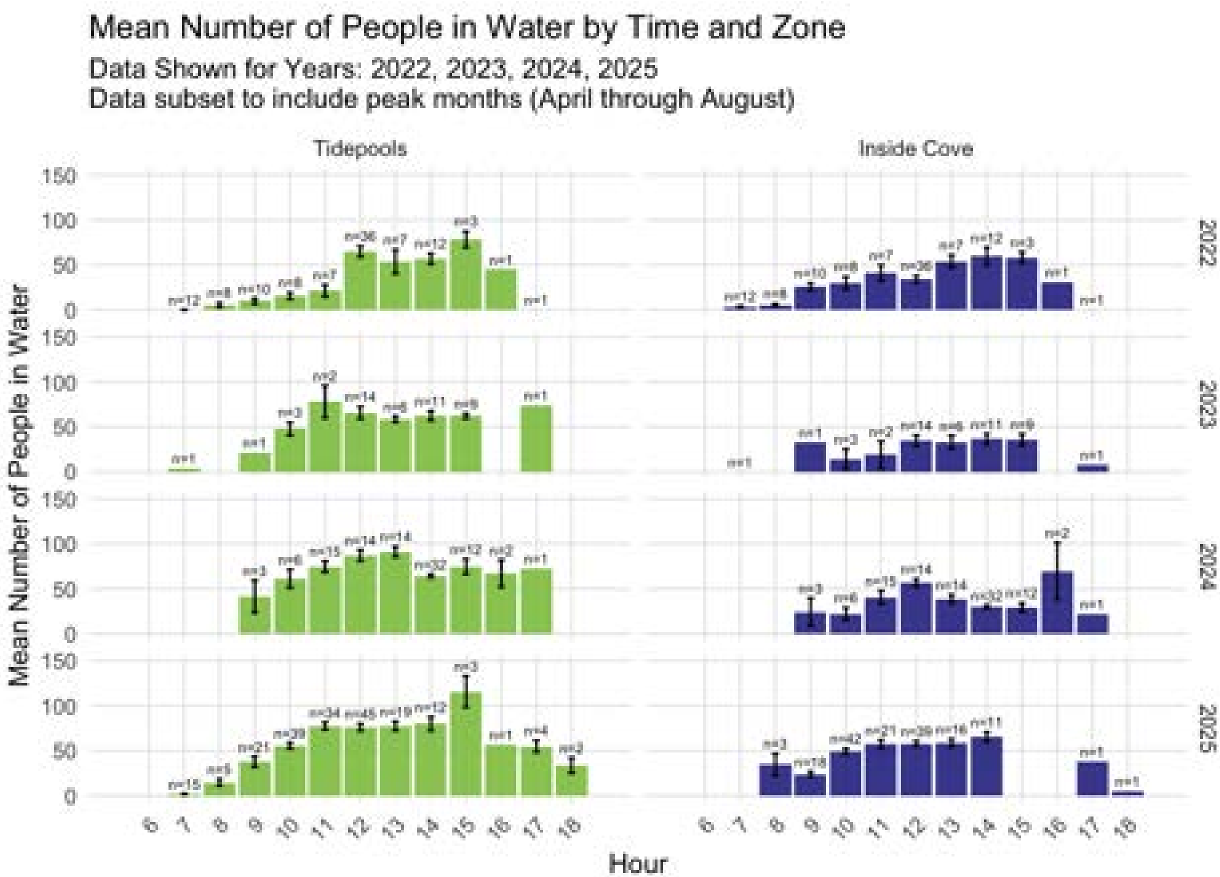


Figure 40. Average number of water users observed through Makai Watch surveys at the Tidepools and Inside Cove from 2022 to 2025, shown by time of day expressed in military time (equivalent to 6 a.m.–6 p.m.). Bars represent mean counts of people in the water during each hourly interval, with error bars showing ± standard error (SE). Peak use at both zones typically occurred between 11 a.m. and 2 p.m., with the Tidepools showing consistently higher user densities than the Cove across all years. The 2025 data show sustained high mid-day use (Tidepools: 77–115 ± 3.4–17.4; Inside Cove: 57–65 ± 2.9–5.4) and

extended afternoon activity compared to earlier years, indicating continued recreational pressure during daylight hours.

iii. Year-round and seasonal use

In 2025, the MPW point-in-time human use counts for the Tidepools remained consistently high throughout the year, with moderate seasonal variation (Figure 41). Monthly averages ranged from 45.9 (± 9.7) in February to 98.5 (± 20.5) in September, and counts rarely fell below an average of 45 users in any month.

The Tidepools continue to attract high year-round use, reflecting both their popularity and their function as a sheltered location during high-surf conditions. Community observations corroborate that the Tidepools often experience increased visitation during periods of large north-shore swell, when the site remains protected and accessible while other nearby areas are unsafe for swimming or snorkeling. This pattern has persisted across all monitoring years, with 2023 and 2024 showing similarly elevated mid-day and mid-year activity (54–91 ± 3.0–8.9) and minimal decline during winter months. Compared to 2022, when usage showed sharper seasonal peaks (33–86 ± 5.7–10.3), the 2025 data reveal a more uniform, sustained pattern of heavy year-round recreational use.

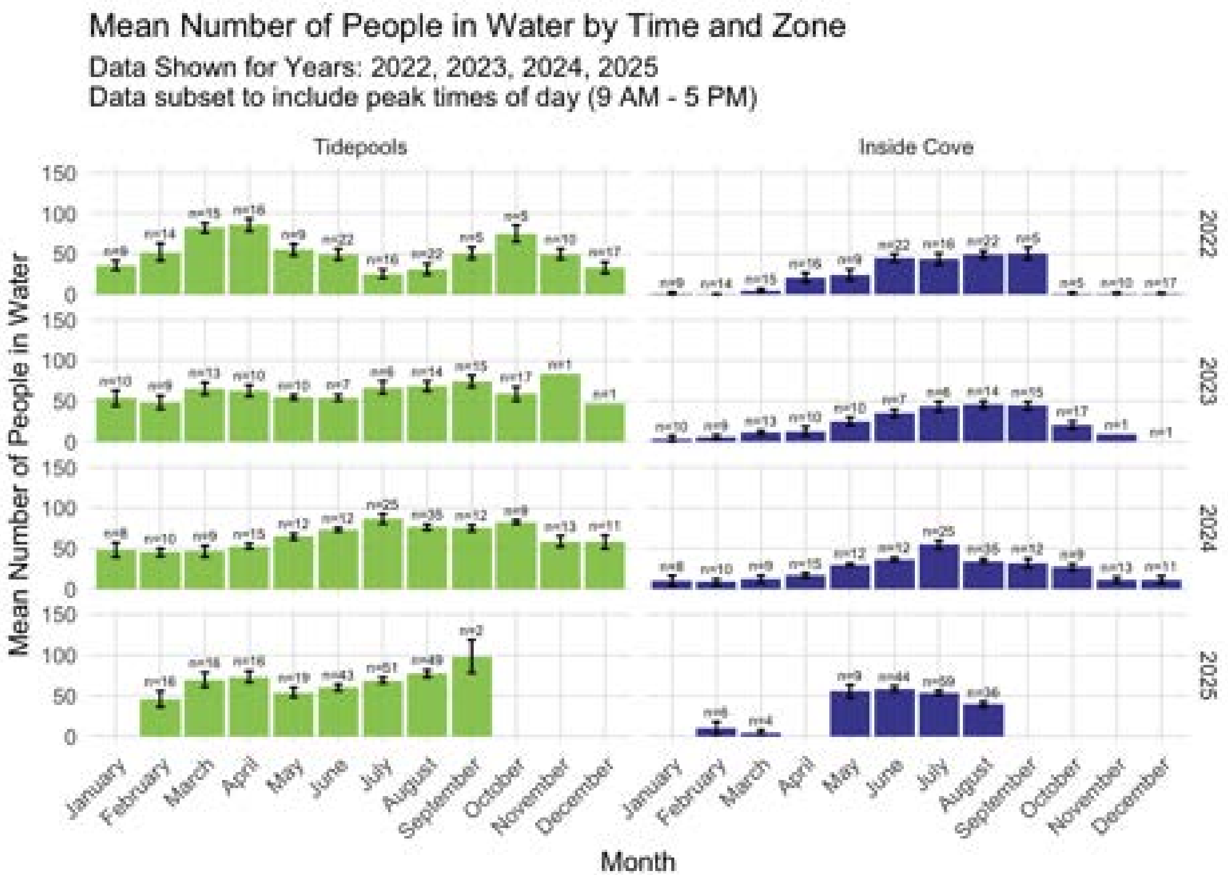


Figure 41**.** The average number of people in the water during peak time of day at the Tidepools and Cove each month between 2022 and 2025.

Overall, the MPW human use data during the Act 31 period displays a continued increase of use of the Kapoʻo Tidepools from 2008 through 2025 (Figure 42).

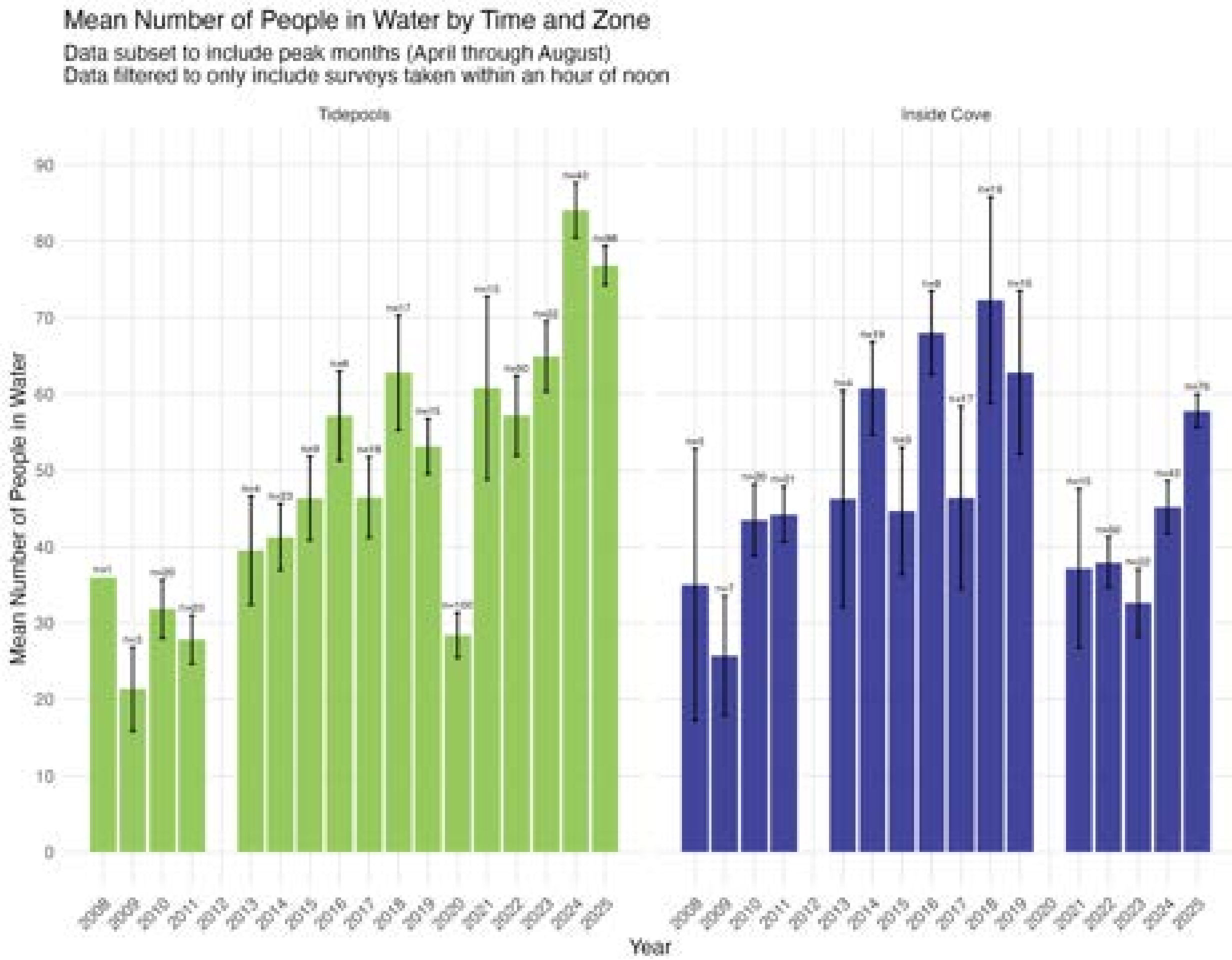


Figure 42. The average number of people in the water during peak time of day and peak months of the year at the Tidepools and Cove between 2008 and 2025.

3. Drone Mapping of Human Use

To further track human use within Kapoʻo, to corroborate the accuracy of MPW human use point-in-time counts, and to identify high-impact areas, four drone flights were conducted each summer in 2022 through 2025. Figure 43 shows the results of the drone mapping of humans (standing and swimming) from all four 2025 UAV surveys.

In 2025, three flights of Kalua o Maua were also included to assess use hot spots and potential detectable impacts. Visitation patterns at Kalua o Maua were highly focused at the southern end of the beach where water access is easier. Beyond this hotspot, human density was quite lower and tended to be swimmers versus waders.

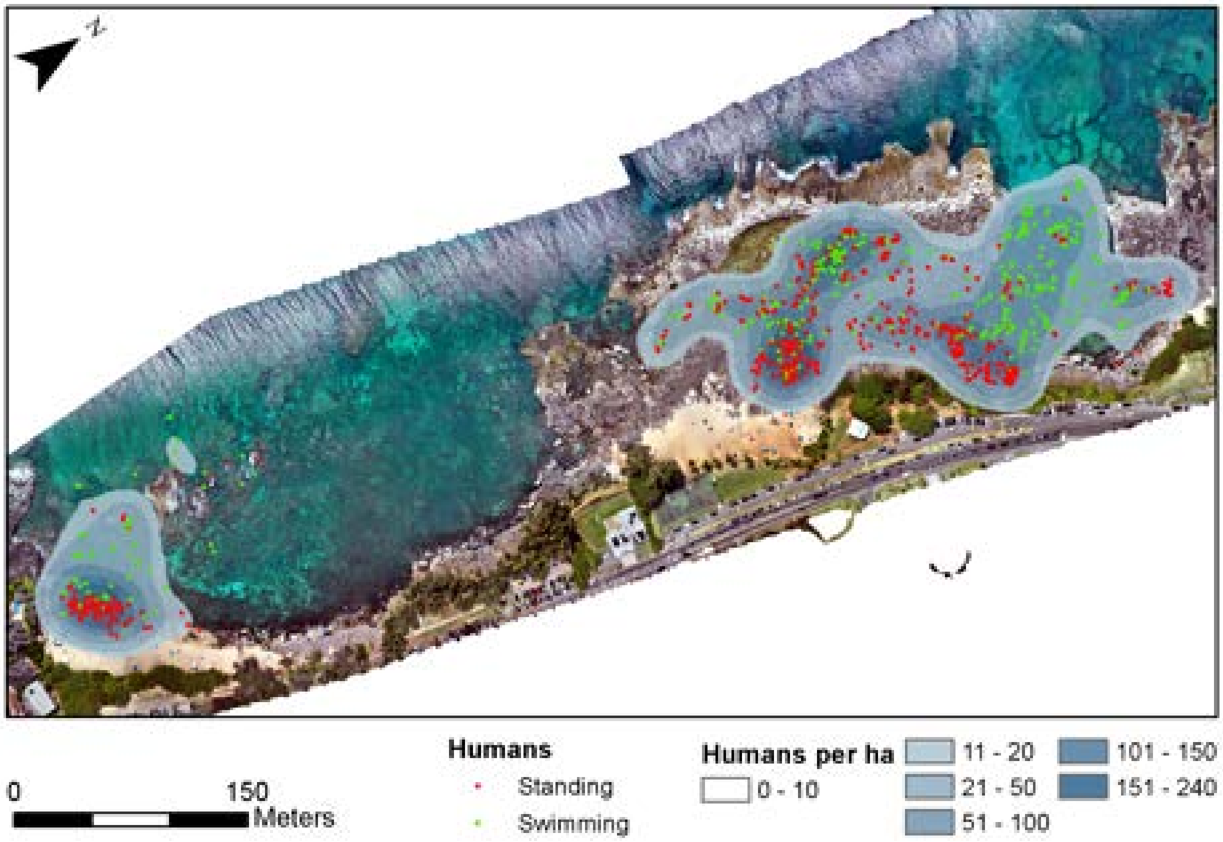


Figure 43**.** Locations of mapped humans (standing and swimming) from all four 2025 UAV surveys combined overlaid on the mean kernel density surface.

Across all years (2022-2025) (Figure 44), the highest levels of activity were centered around the main entrances to both zones, with the Tidepools showing an expanded hotspot in 2023 and 2024 that extended from the entrance toward the seaward "Crack," where deeper water (1–2 m) and ocean inflow attract both visitors and fish. This same corridor, characterized by higher coral abundance on vertical surfaces and frequent schools of āholehole, remained a focal point of human presence through 2025.

In the Cove, the persistent hotspot near the main entrance gradually shifted offshore by 2024, while use at the usually quieter north end (Keiki/Baby Beach) increased, indicating a redistribution of visitors from more evenly spread use in previous years toward these preferred shallow and accessible areas. While spatial patterns of use were similar over the years, density of humans generally increased over time and spread further over time, focused in the areas shown in Figure 44.

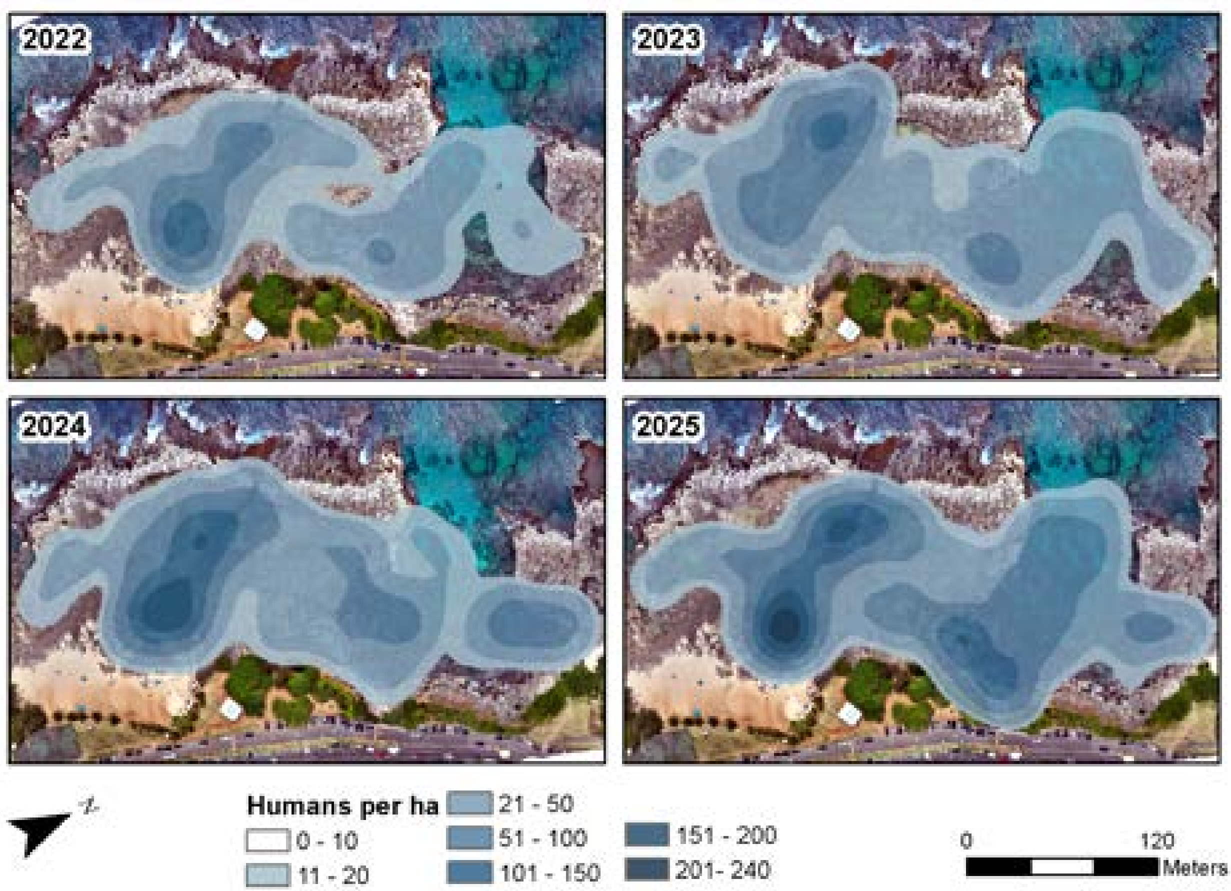


Figure 44. Average human density at Kapoʻo Tidepools and Cove across years based on annual UAV surveys.

D. Human Impacts on Biodiversity

The following section assesses the ecological consequences of sustained high human use, focusing on effects to fish richness and abundance, benthic composition, coral health and damage, and visitor impacts as measured through substrate contacts.

1. Fish

A. 2025 Patterns

i. Human impacts on fish abundance

In 2025, non-schooling fish abundance varied modestly with human presence when averaged across zones. However, while overall relationships were weak, the Tidepools, where visitor numbers were highest, exhibited a clear negative association between human activity and fish abundance, suggesting that sustained high use may depress local non-schooling fish populations (Figure 45).

Non-schooling fish abundance showed differing relationships with human presence across zones, and other than the Tidepools impact, most effects were modest within the observed range of visitor numbers (Figure 45).

Water clarity was positively associated with fish abundance ($\beta = 0.18 \pm 0.04$ SE, $p < 0.001$), while depth had no significant effect ($\beta = –0.08 \pm 0.06$ SE, $p = 0.19$). The analysis did not detect an overall relationship between human presence and fish abundance across zones ($\beta = –0.12 \pm 0.09$ SE, $p = 0.19$), but significant zone-specific trends emerged.

In the Tidepools, where in-water human counts in the vicinity of transects (10m radius from transect center) were highest (mean = 2.9, max = 20), non-schooling fish abundance declined significantly with increasing human presence (trend = $–0.12 \pm 0.04$ SE, $p = 0.005$). This suggests that at higher visitation levels typical of the Tidepools, human use may be impacting marine life by reducing local fish abundance.

In contrast, the Cove had relatively low human use counts in the vicinity of transects (mean = 1.6, max = 8) and the data showed no significant trend related to fish abundance and human use ($\beta = –0.12 \pm 0.09$ SE, $p = 0.37$). Likewise, Kalua o Maua experienced even lower visitor use, measured by in-water transect counts (mean = 0.9, max = 5), and no trend with fish abundance ($\beta = 0.21 \pm 0.18$ SE, $p = 0.37$).

Overall, the statistical model that included zone, depth, water clarity, and human presence as well as variation associated with the repeated measures of the transects, explained roughly half of the total variance in abundance (conditional $R^2 = 0.50$; marginal $R^2 = 0.16$), with most variability arising from differences among transects. These 2025 results indicate that sustained or high-intensity use observed in the Tidepools may negatively affect local abundance and that in other areas non-schooling fish are generally stable across typical visitor levels.

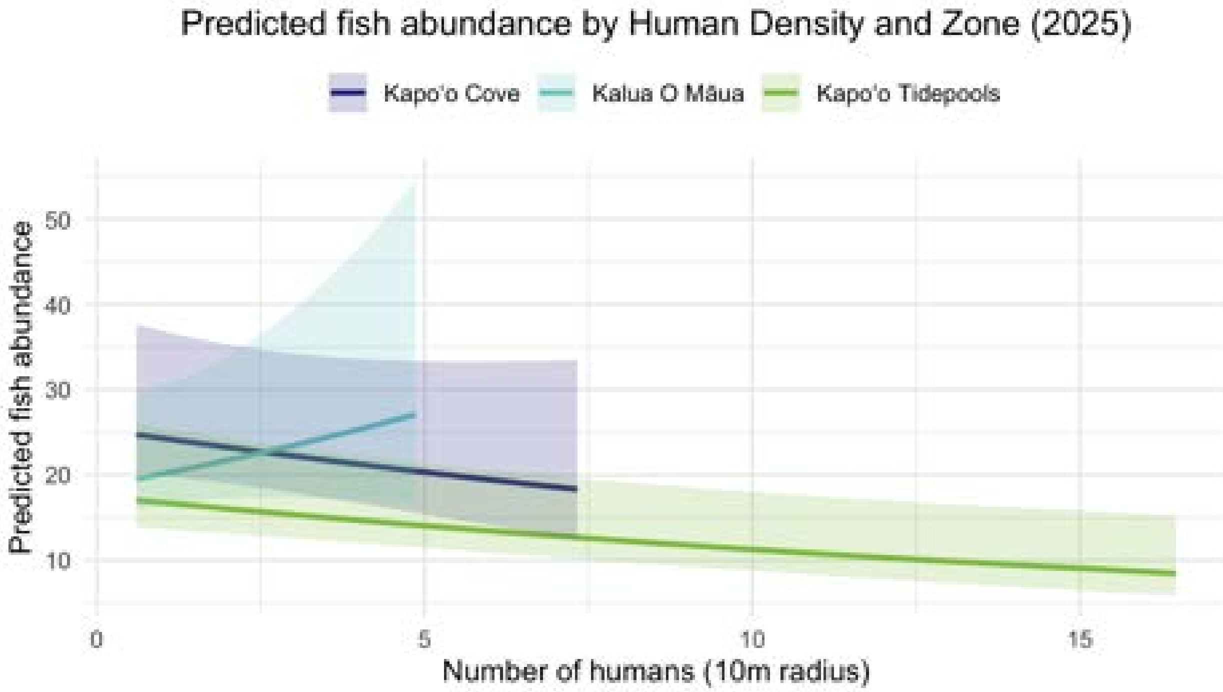


Figure 45. Non-schooling fish abundance by number of humans and reef zone in 2025.
Dark lines are predicted patterns of fish abundance after accounting for depth and water clarity, and shaded areas are 95% confidence intervals. Predictions were limited to the observed range of humans in each zone.

ii. Human impacts on fish richness

In 2025, there was minimal evidence of consistent response in non-schooling fish species richness to human presence among zones. Richness remained largely stable across observed visitor levels, with only slight variation between areas, lower at the Tidepools and Kalua o Maua relative to the Cove, suggesting that moderate human activity had limited measurable influence on local species diversity. In 2025, species richness was positively associated with water clarity ($\beta = 0.10 \pm 0.03$ SE, $p < 0.001$), while depth had no significant effect ($\beta = 0.00 \pm 0.05$ SE, $p = 0.93$).

Overall, richness did not vary significantly with human counts ($\beta = -0.05 \pm 0.07$ SE, $p = 0.43$). Mean richness was lower at the Tidepools compared to the Cove ($\beta = -0.43 \pm 0.16$ SE, $p = 0.008$), and slightly lower at Kalua o Maua ($\beta = -0.23 \pm 0.16$ SE, $p = 0.14$). Although the Tidepools exhibited a weak negative trend (trend = -0.07 ± 0.03 SE, $p = 0.17$), interaction terms showed no significant differences in the relationship between richness and human presence among areas.

iii. Human impacts on fish biomass

The non-schooling fish biomass data followed a similar pattern. Biomass increased significantly with water clarity ($\beta = 0.20 \pm 0.06$ SE, $p < 0.001$) and was lower at Kalua o Maua relative to the Cove ($\beta = -0.62 \pm 0.30$ SE, $p = 0.04$). The Tidepools showed no significant difference in non-schooling fish biomass compared to the Cove ($\beta = -0.40 \pm 0.30$ SE, $p = 0.19$). Depth and human presence were not significant predictors of biomass. Likewise, there were no clear biomass trends with increasing human activity (Tidepools: $\beta = 0.09 \pm 0.06$ SE, $p = 0.33$; Cove: $\beta = -0.15 \pm 0.16$ SE, $p = 0.41$; Kalua o Maua: $\beta = 0.38 \pm 0.30$ SE, $p = 0.41$).

B. Annual patterns of human impacts on fish abundance and richness

i. Fish abundance

Patterns of human impacts on non-schooling fish abundance and species richness varied among years from 2022 to 2025, with the strength and direction of their relationships to human presence shifting over time. Due to the survey methods change in 2023, the data from that year were not included in the multi-year analysis of the relationship between fish metrics and human presence.

Non-schooling fish abundance across 2022, 2024, and 2025 for the Tidepools and Cove showed a significant overall negative effect of human presence ($\beta = -0.26 \pm 0.05$ SE, $p < 0.001$), together with positive effects of water clarity ($\beta = 0.12 \pm 0.02$ SE, $p < 0.001$) and a modest negative effect of depth ($\beta = -0.12 \pm 0.04$ SE, $p = 0.002$) (Figure 46). Fish abundance differed among years and was lower in both 2024 and 2025 relative to 2022 ($\beta = -0.57 \pm 0.05$ SE and $\beta = -0.57 \pm 0.06$ SE, both $p < 0.001$). The interaction between human counts and year remained significant, indicating that the strength of the human–fish relationship changed through time.

In 2022, fish abundance across both zones declined sharply with increasing human presence (slope = -0.30 ± 0.04 SE, $p < 0.001$), whereas in 2024 and 2025 the Tidepools and Cove showed different patterns. In the Tidepools, abundance declined significantly with increasing human numbers in both 2024 (slope = -0.09 ± 0.03 SE, $p = 0.011$) and 2025 (slope = -0.12 ± 0.03 SE, $p < 0.001$), while fish abundance in the Cove showed no relationship with human presence in 2024 or 2025.

The overall model explained a high proportion of variance (conditional $R^2 = 0.74$; marginal $R^2 = 0.46$), with transect-level variability accounting for a large amount of the residual variation.

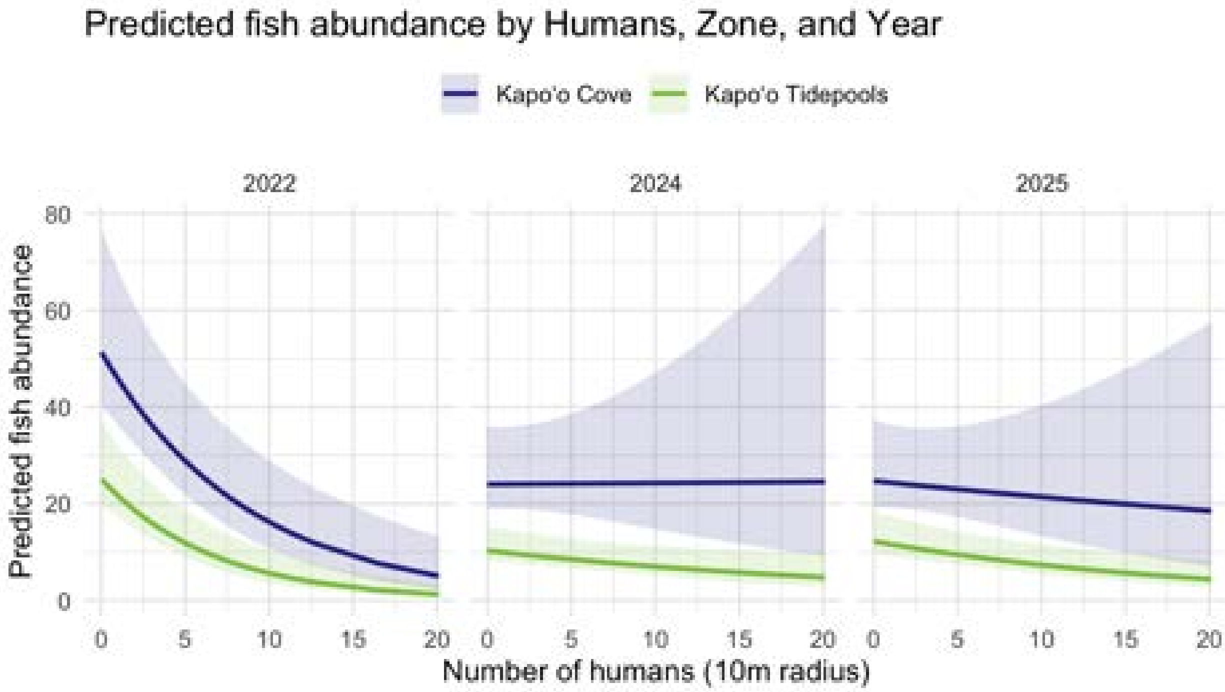


Figure 46. Predicted fish abundance (excluding schooling species) in relation to the number of humans observed across survey sites. Predictions are shown for two zones: Kapo‘o Cove (blue) and the Kapo‘o Tidepool**s** (green). Lines represent the estimated relationship between scaled human counts and non-schooling fish abundance, while shaded ribbons show 95% confidence intervals. Each panel corresponds to a different survey year (2022, 2024, 2025). The model included transect as a random effect and accounted for depth and water clarity measured by secchi disc.

ii. Species richness

For species richness, patterns were broadly similar to abundance (Figure 47). Richness was negatively related to human presence ($\beta = -0.12 \pm 0.04$ SE, $p = 0.001$), positively associated with water clarity ($\beta = 0.07 \pm 0.02$ SE, $p < 0.001$), and lower at the Tidepools compared to the Cove ($\beta = -0.55 \pm 0.16$ SE, $p < 0.001$). Annual effects indicated significant declines in richness after 2022 ($\beta = -0.37 \pm 0.04$ SE in 2024; $\beta = -0.41 \pm 0.05$ SE in 2025; both $p < 0.001$).

The interaction between human presence and year again showed that relationships changed through time and differed between zones. Richness over both Tidepools and Cove declined with increasing human numbers in 2022 (slope = -0.12 ± 0.04 SE, $p = 0.0036$) and a significant negative trend persisted at the Tidepools, where richness declined with increasing human numbers in both 2024 (slope = -0.07 ± 0.03 SE, $p = 0.021$) and 2025 (slope = -0.08 ± 0.03 SE, $p = 0.015$). The data did not show a significant effect of human presence on fish richness at theCove in 2024 or 2025.

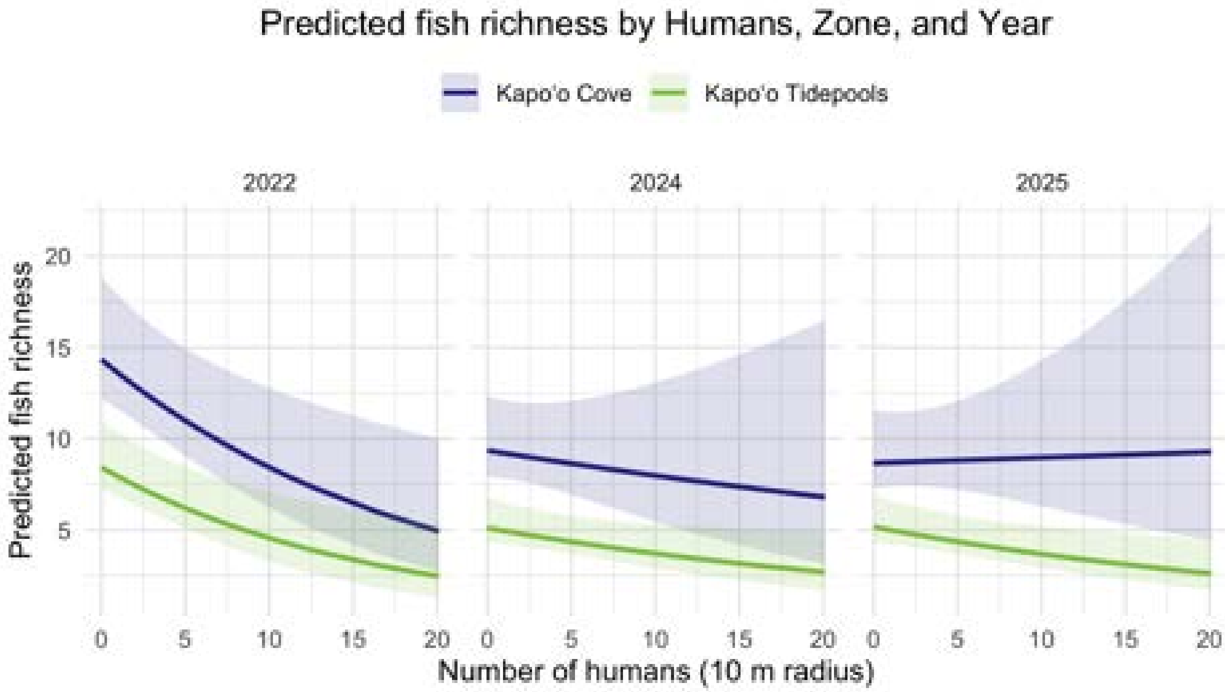


Figure 47. Predicted fish richness (excluding schooling species) in relation to the number of humans observed across survey sites. Predictions are shown for two zones: Kapo‘o Cove (blue) and the Kapo‘o Tidepools (green). Lines represent the estimated relationship between scaled human counts and non-schooling fish richness, while shaded ribbons show 95% confidence intervals. Each panel corresponds to a different survey year (2022–2025). The model included transect as a random effect and accounted for depth and water clarity measured by secchi disc.

These findings indicate that both non-schooling fish abundance and species richness were negatively related to human presence at both the Kapo‘o Tidepools and Cove in 2022, and showed weaker but still significant declines with higher visitor numbers at the Tidepools in 2024 and 2025. This pattern suggests that localized human disturbance continues to influence non-schooling fish communities in high-use areas despite some interannual variability in sampling conditions.

C. Human Impacts on Fish Community Composition

To further explore the analysis of human impacts on fish, inon-metric multidimensional scaling (NMDS) was performed on the bray-curtis dissimilarity matrix of fish abundance in 2025 of each zone individually, due to the highly variable communities and differences in number of humans on each zone observed. To balance the importance of rarer and schooling species, each species presence in a sample was scaled to its maximum abundance across the dataset. Each zone was tested with all species included (the unfiltered species set) and on a subset of species that were found in at least 5% of all samples in that zone (the filtered species set).

For the Tidepools, the two-dimensional solution of all fishes converged with a stress value of 0.25, meaning these communities are highly multivariate and difficult to describe in 2-dimensional space.

Increasing numbers of humans within 10 m of the transects was correlated with a change in fish community ($p = 0.023$), although this result explained little of the overall variation ($R^2 = 0.06$). Water quality ($p = 0.016$), depth ($p < 0.01$), and transect ID ($p < 0.01$) were also found to be significantly correlated with changes in the observed fish community (Figure 48). In filtered samples, the study included 22 out of 86 total species, although with little overall improvement to the stress value (stress = 0.24). Findings were consistent across filtered and unfiltered species sets.

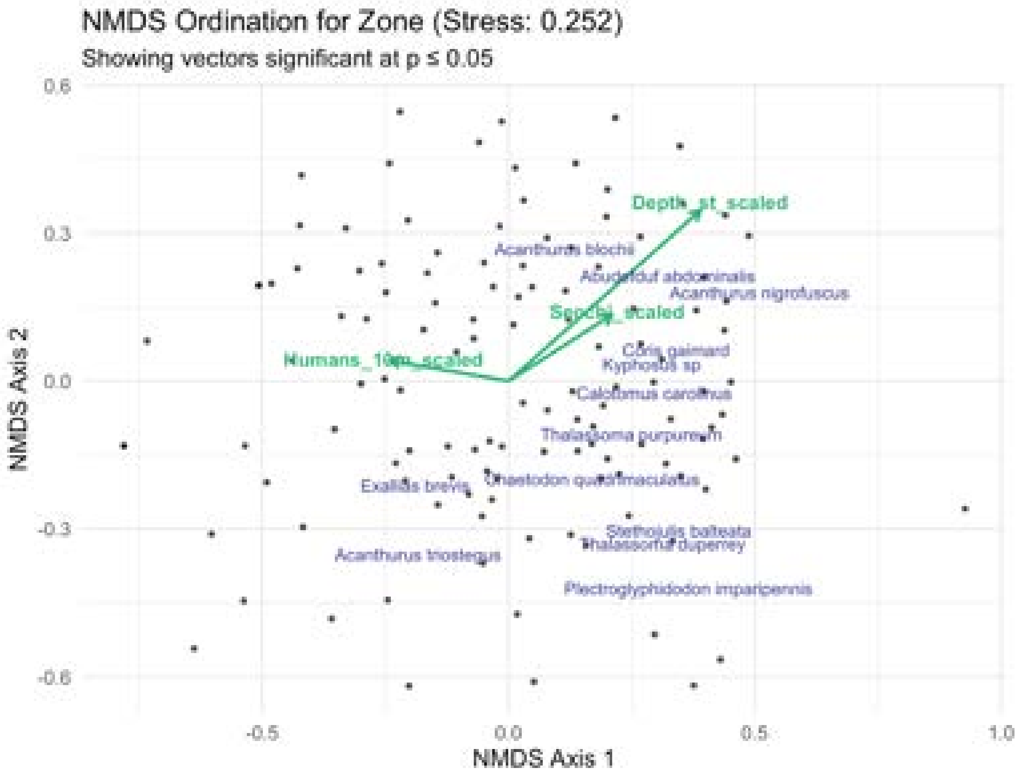


Figure 48. Non-metric multidimensional scaling plot showing ordination of all community samples within the Tidepools. Each point represents one sample of a fish community along a transect. Species names in blue are more common within nearby sample points. Vectors of significant environmental parameters are overlain in green showing the direction of correlated change in the observed fish community.

In the Cove, the two-dimensional solution of all fishes converged with a stress value of 0.30. No correlations were found between the ordination of fishes in the Cove and number of nearby humans, depth, or water quality. Transect ID was found to be a factor shaping these communities ($p < 0.01$). In filtered samples, the study included 28 out of 86 total species, with no improvement to the stress value (stress = 0.30). Findings were consistent across filtered and unfiltered species sets.

The results from Kalua o Maua areas were similar to the Cove. The NMDS converged with the stress value of 0.29, and none of the environmental variables produced changes in these communities.

For all of the sample sets, the study found high stress values, i.e. between .25 (Tidepools) and .30 (Cove), in the NMDS. A stress value in this range (typically > 0.2) suggests that the configuration is a poor representation of the full rank order of dissimilarities among samples, meaning the distances in the ordination plot may not reliably reflect true ecological distances between samples. As such, caution is warranted when interpreting the spatial arrangement of the samples in the NMDS plot. Further analyses of these samples using additional methods may be able to add confidence to these findings.

2. Benthic

A. Human Impacts on Coral

The 2025 roving coral survey revealed a range of damage, coral disease, and algae overgrowth for corals in each study zone. To look at the potential influence of human visitor density on coral damage, the study considered occurrence of "recent" damage, which includes breaks, scrapes, partial mortality, paleness, and bleaching and excluded coral disease, natural predation, and dead coral overgrown by algae.

Figure 49 shows the proportion of recently damaged coral colonies surveyed at each location, overlaid on a map of human density derived from the drone surveys. Locations with the highest occurrence of coral damage (in red and orange) were found near the Crack in the Tidepools, near the ocean access points at the Cove and Kalua o Maua. Each of these areas also corresponded to high visitor densities (Figure 49).

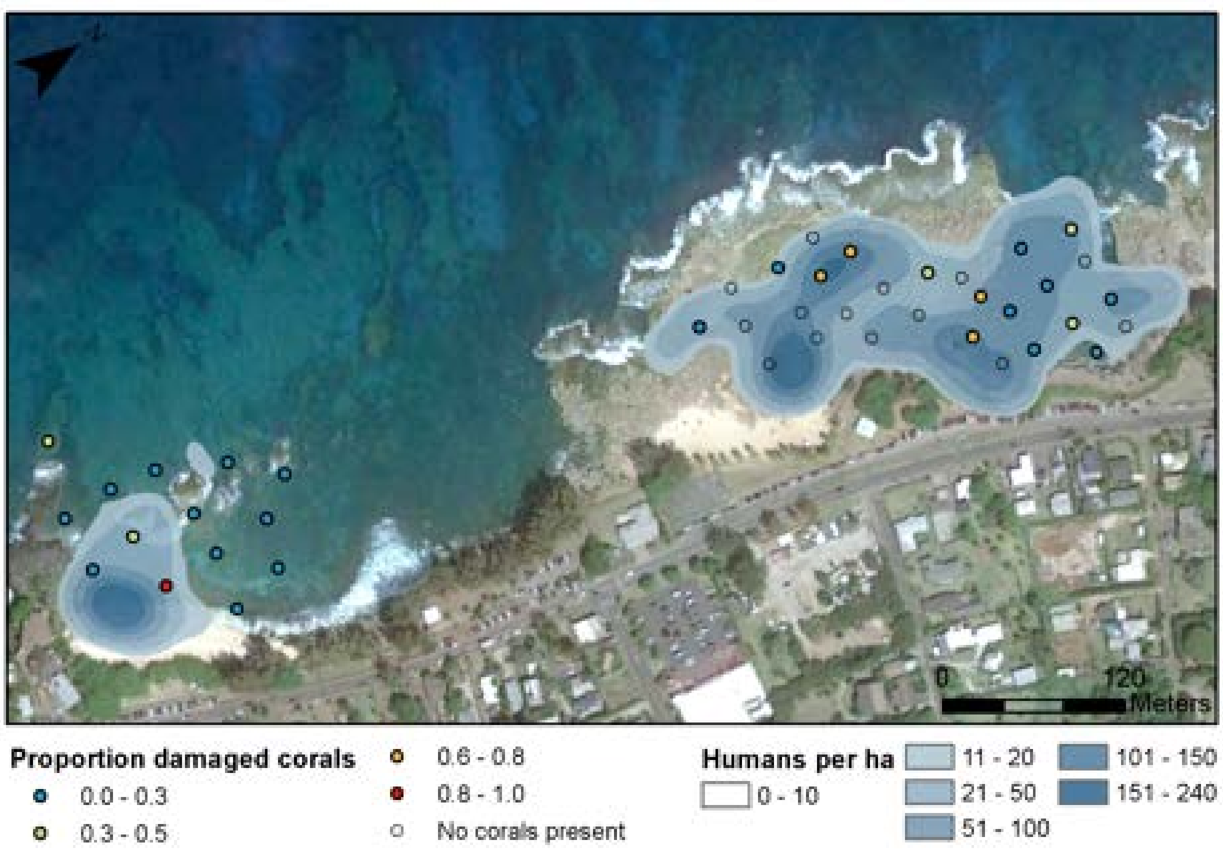


Figure 49. Proportion of damaged corals from the roving coral survey overlaid on human density from the UAV surveys at Kalua o Maua (to the left) and Kapo'o Tidepools and Cove (to the right).

The relationship between visitor density and coral damage in 2025 was tested statistically with a logistic mixed-effects model, which showed that coral damage increased significantly with human density across the survey areas ($\beta = 0.34 \pm 0.16$ SE, $p = 0.035$) (Figure 50). Human densities derived from drone surveys ranged widely, from 0–1 persons per hectare in the least-visited locations to over 150 persons per hectare in the most heavily used portions of the zones.

Model predictions indicated that corals in low-use areas (0–1 persons ha^{-1}) had an estimated damage probability of roughly 15–20%, whereas at the highest observed densities (>100 persons ha^{-1}), predicted damage probabilities exceed 40%, even after controlling for colony depth and size. Neither depth ($p = 0.32$) nor colony diameter ($p = 0.84$) were significant predictors, highlighting that spatial variation in human use, not intrinsic coral traits, is the strongest correlate of recent physical and stress-related coral damage across the study area.

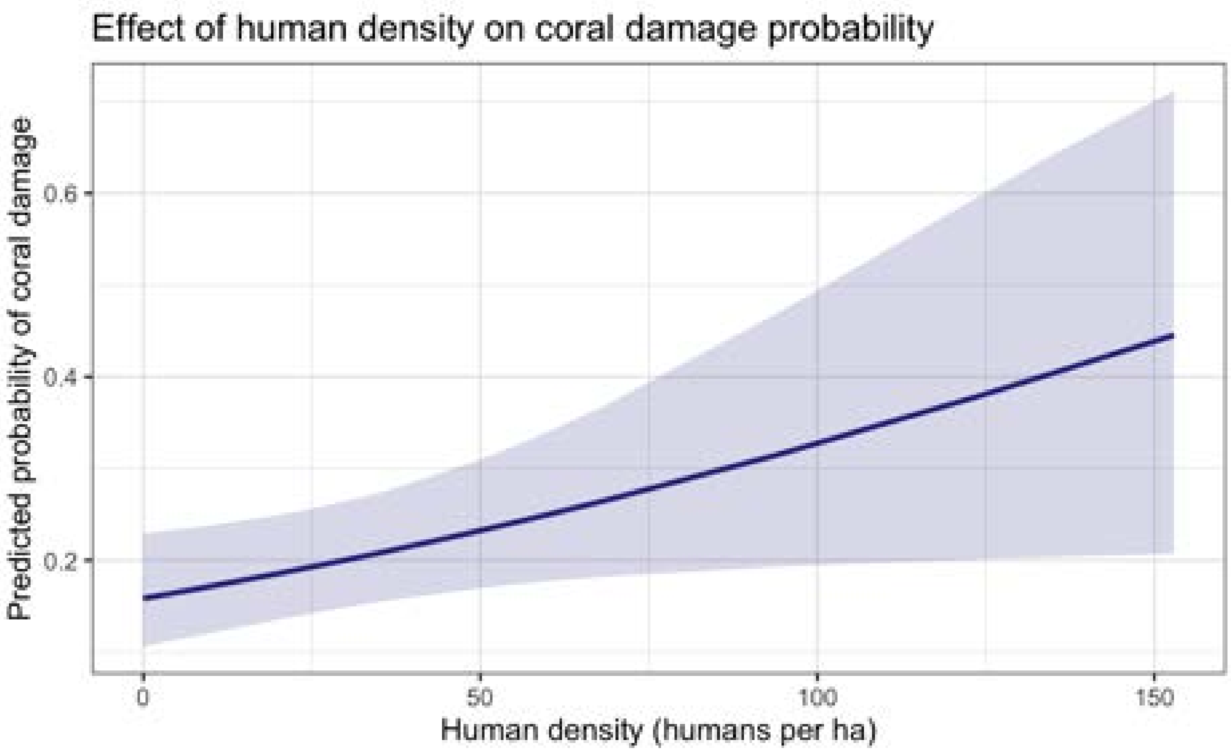


Figure 50. Predicted probability of recent coral damage as a function of human density across all zones - Kapo‘o Tidepools, Cove, and Kalua o Maua. Predictions are derived from a logistic mixed-effects model including human density, depth, and colony diameter as fixed effects, with survey location as a random intercept. Human density values are back-transformed to represent the original density of people estimated from drone surveys. The solid line shows the model-predicted probability of coral damage, and the shaded band represents the 95% confidence interval. The positive slope indicates that corals located in areas with higher chronic human use have a higher probability of displaying recent physical or stress-related damage.

In this analysis, the study focused specifically on recent coral damage, defined as breaks, scrapes, partial tissue loss, paleness, and bleaching because these conditions develop over short time scales and are therefore the most likely to reflect acute or near-term interactions with human activity in the survey area. The drone-based human-density layer represents persistent patterns of visitor use during the tourist season, and recent physical or stress-related damage provided a biologically appropriate response variable that can be reasonably linked to chronic localized exposure.

Longer-term indicators such as algal overgrowth, disease, and old mortality were excluded because they arise from broader ecological processes (e.g., nutrient loading, thermal stress, water quality, historical disturbance) that are not directly attributable to immediate human presence and may accumulate over months to years. By isolating recent injury and short-term stress responses, the study reduced confounding from these wider environmental drivers and provided a more direct assessment of how spatial variation in human use intensity influences coral condition across the study area.

Although these results demonstrate a clear spatial correlation between recent coral damage and high human densities, other environmental factors, such as wave exposure, water quality, past thermal stress, and natural ecological dynamics, also contribute to the condition of corals in this system. Thus, the study analysis does not attribute all observed damage solely to human presence.

Nevertheless, the consistent increase in damage probability in heavily visited areas indicates that human use is an important and manageable source of stress on these already vulnerable corals. Reducing visitor numbers, limiting access during peak periods, or redistributing use away from sensitive microhabitats would meaningfully lessen direct physical impacts and improve the resilience of the coral community.

B. Human Impacts Detected by Visitor Impact Surveys

Following the methodology of Meyer & Holland (2008), and modifying methods used in the earlier years of the study period, the 2025 study used a student team of in-water snorkelers - Visitor Impact Surveyors (VIS) - from SEA Institute, Woods Hole, Massachusetts on a two-day site visit to track the route and substrate impact of 52 visitors during the first 10 minutes of entering the water at both the Kapo’o Tidepools and Kalua o Maua.

Unlike previous years, Year 3 surveys did not incorporate GPS tracking of visitor movements, placing greater emphasis instead on the frequency, type, and potential ecological consequences of substrate contact. This year’s inclusion of footwear (fins, booties/reef shoes, or none) also aimed to expand the understanding of different types of visitor impacts.

Across all observed categories of footwear, the number of substrate contacts varied notably (Figure 51). Individuals wearing shoes made the highest average number of contacts with the substrate (6.50), followed by those wearing fins (4.85). Participants who were barefoot made the fewest substrate contacts, averaging only 2.86. Overall, these results suggest that footwear type influences the frequency of contact with the substrate, with enclosed shoes associated with the greatest amount of contact and bare feet the least.

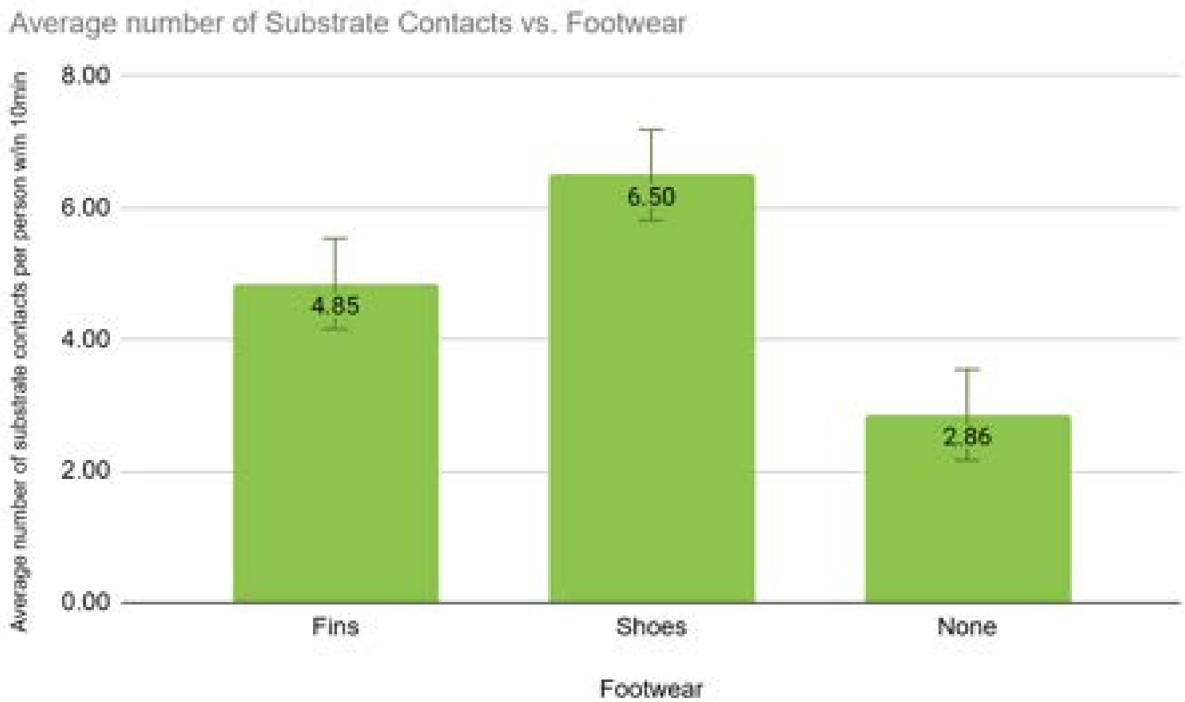


Figure 51. 2025 VIS surveyors followed visitors for their first 10 minutes in the water and noted their footwear and how often they came into contact with various forms of substrate. Users wearing shoes (including reef walkers, tabis, and all street shoes) had much higher incidences of substrate contact compared to users in fins or who were barefoot (none).

When looking more closely at the types of substrate contacted, distinct patterns emerged. Participants wearing fins made the most contact with coral (average = 6) and had frequent contact with turf or colonized rock (4.38), but made no contact with limu. Those barefoot had minimal coral contact (1), moderate contact with limu (1.2), and fewer contacts with turf/colonized rock (2.12) compared to other groups. In contrast, individuals wearing shoes had relatively high contact with turf/colonized rock (5.38), while contacting coral and limu less frequently (2 and 1, respectively).

Overall, these findings suggest that footwear type influences not only the total frequency of substrate contact but also which substrates are most affected. Footwear with hard soles or fins tends to increase contact with coral and rocky surfaces, whereas being barefoot results in fewer total contacts and less potential disturbance to the substrate.

Users unaccustomed to wearing fins may not realize when the longer blade is coming into contact with corals that tend to be shallower than the surrounding benthos. Individuals wearing shoes will also be more likely to be walking or standing instead of swimming, increasing the likelihood of stirring up sediment and coming into contact with the benthos.

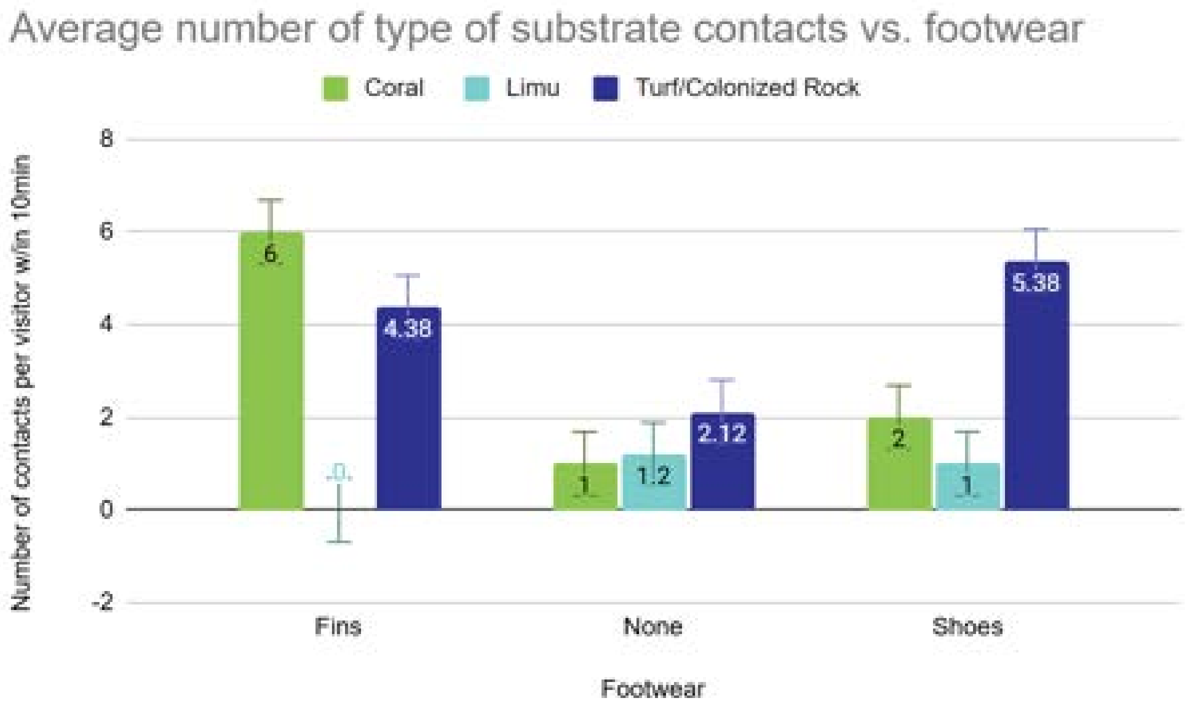


Figure 52. VIS survey data broken down into incidence of substrate contact during the first 10 minutes of entering the water by Coral, Limu, and Turf/Colonized Rock. CCA contact is not included as it was not observed during this survey. None refers to barefoot users, and “shoes” is inclusive of reef shoes, booties/tabis, and all street shoes.

E. Biological Carrying Capacity - Fish Abundance Threshold

Biological carrying capacity (BCC) is defined within the Act 31 framework as the threshold level of human use beyond which measurable, unacceptable ecological impacts occur to the fishes, corals, benthic communities, and associated habitats of Kapoʻo. This study applied that definition by integrating multiple indicators—fish and benthic responses, coral damage patterns, human-use intensity, substrate-contact frequencies, and environmental conditions—to identify where biological communities begin to shift under increasing visitor pressure.

Based on analysis of the relationships between human visitation and multiple biological indicators, the most dynamic (across the range of human density) and persistent effect (across study years) was on non-schooling fish abundance in the Kapo’o Tidepools. For this reason, the marine team focused on this relationship to identify a specific threshold of human use to apply for management. Furthermore, as shown previously, overall fish abundance declined after 2022 which contributed to the weakening of the modeled negative relationship. This led the marine team to focus on 2022 data to quantify the human threshold for management, the biological carrying capacity based on fish abundance.

The study estimated multiple metrics for interpreting thresholds of human presence on fish abundance. With non-schooling fish species abundance as a response variable, a Generalized Additive Mixed Model (GAMM) was used and fit with the *mgcv* package in R. Models followed a similar structure to those in previous sections, with human presence, depth, and water clarity has fixed predictors and transect as a random effect. The GAMM allows for estimating nonlinear relationships, and following methods described in Hennessey et al. (2025), thresholds can be estimated when nonlinearities are found.

Specifically, a nonlinearity was identified only if the model estimated degrees of freedom for the focal variable (human presence) was > 2 and the p value ≤ 0.05 for the null hypothesis that the spline(s) are equal to zero, and the model deviance explained ≥ 0.20. In the presence of a nonlinearity, thresholds were estimated using the first and second derivatives of the spline (i.e., the nonlinear curve). To account for uncertainty in the nonlinear relationship between human presence and non-schooling fish abundance, the first and second derivatives were each simulated 1000 times using the variance in the estimated model with the *gratia* package in R.

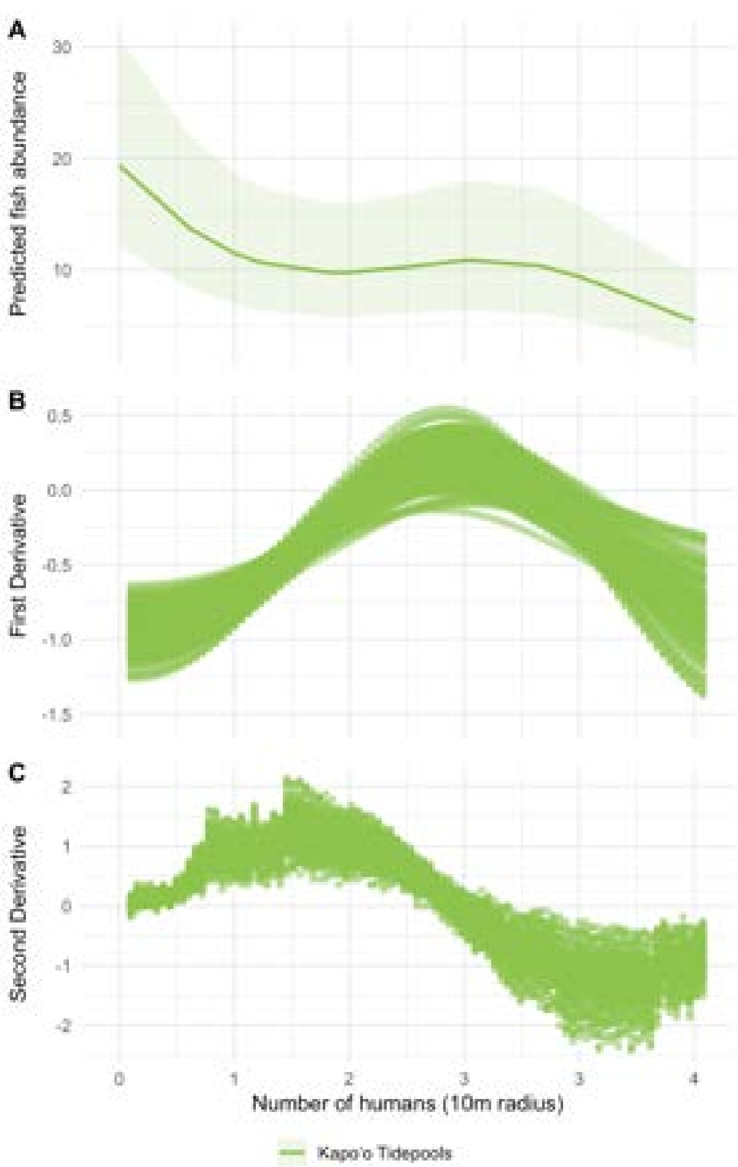


Figure 53. Predicted nonlinear relationship and estimated thresholds between non-schooling fish abundance and number of humans on a transect (10 m radius) for the Tidepools in 2022 from a Generalized Additive Mixed Model. (A) The thick line is the estimated relationship and the shaded area is a 95% confidence interval. (B-C) Each point is an estimated first (A) or second (C) derivative at continuous values of the human presence based on 1000 simulations of the model, with the first 100 simulations plotted.

The analysis found a significant nonlinear relationship between non-schooling fish abundance and human presence in the Cove and Tidepools in 2022 (edf = 2.901, $p < 0.01$; Figure 53A), and all other terms in the model were also significant except for depth. Focusing on patterns in 2022 in the Tidepools, fish abundance dropped steeply at very low values of human presence, with the steepest part of the curve equal to where the first derivative is minimized at 0 (Figure 53B). At around half of the abundance at zero human presence, the curve flattened where the second derivative is maximed at 1.21-1.36 humans per 10 m radius (Figure 53C).

Given that fish abundance is maximized when human presence was at zero and reaches a local minima at a little over 1 human per 10m radius, a proposed threshold of 1 human per 10m radius provides a conservative estimate for a biological carrying capacity for Kapoʻo Tidepools.

Human counts in the transect vicinity (10m radius from center) and associated analyses do not include the researcher conducting each transect survey. While surveyors followed minimally invasive protocols to limit their effects, their presence was still part of the monitoring process and potentially exerted some level of influence on fish abundance. However, this observer effect could not be quantified using the methods employed and therefore could not be isolated from the measured data. As such, the study based the threshold estimate on the data as collected. Even so, the pronounced decline observed between the addition of one and two humans highlights that the resulting threshold should be interpreted as conservative.

1. Area-Based Visitor Limits

The results of this study clearly show the effects of human presence on fish abundance and species richness, as well as coral health. The threshold of human density upon which management actions could be based were identified for fish abundance, the indicator most sensitive to human presence.
This was 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 = 2.5 acres). This human density threshold was applied to two area calculations of the Tidepools (performed in ArcMap 10.8.2) to derive a range of biological carrying capacity values for each study zone (Figure 54).

The first calculation represents the water area of the Tidepools as delineated at 1:200 scale using drone imagery captured at (0.5 m) low tide and is equal to 0.98 ha (2.4 acres). The second calculation represents the area where 90% of humans were found based on the human density surface derived from the 2025 drone surveys, as a subset of the area at low tide described above, and is equal to 0.85 ha (2.1 acres) (Figure 53). By multiplying these area values by the threshold identified above, it yields a carrying capacity range of 27 - 31 humans in the Tidepools at any given time.

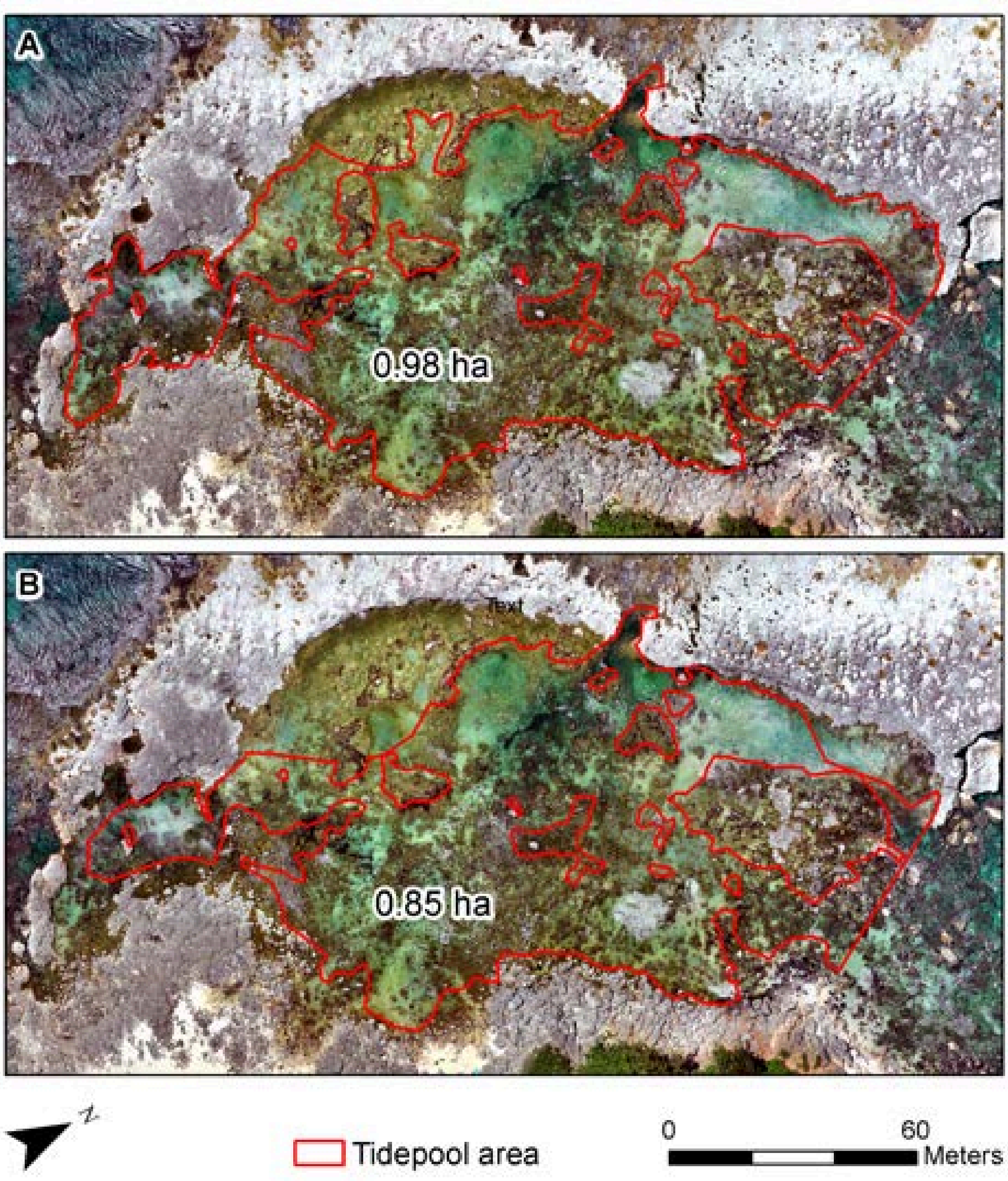


Figure 54. Area calculations for the Kapo‘o Tidepools. A) Low tide area and B) area where 90% of mapped humans were found. Low tide estimate excludes areas exposed at low tide. The area where 90% of humans were found is based on 2025 drone surveys of visitor distributions.

V. Conclusions

The 2025 Act 31 Year 3 Biological Carrying Capacity (BCC) assessment demonstrates that while the Pūpūkea Marine Life Conservation District (MLCD) continues to sustain substantial biological diversity, the system remains under significant pressure from sustained and concentrated human use.

As explained in the key findings and recommendations laid out in the Executive Summary, this study underscores that unmanaged or sustained in-water human activity continues to drive localized ecological degradation, particularly in the Kapoʻo Tidepools. The evidence supports implementation of pilot closures, visitor capacity limits, and enforcement of no-contact zones to mitigate impacts and promote resilience. Adaptive management modeled after successful precedents such as Hanauma Bay, adapted to the unique conditions at the Pūpūkea MLCD, would align with the statutory objectives of Act 31 and the long-term Pūpūkea MLCD Management Plan.

The Year 3 results provide a robust, multi-year in-depth study demonstrating that reduction in visitor pressure correlates with measurable ecological improvement and that continued monitoring and management action are essential to safeguard this high-value marine ecosystem.

VI. Next Steps and Recommendations

The following next steps and recommendations from the Act 31 marine team are grounded in the findings of the 2023–2025 Biological Monitoring and Carrying Capacity Assessments for the Pūpūkea Marine Life Conservation District (MLCD), many years of prior scientific studies by numerous researchers, and decades of human use counts by MPW.

These recommendations focus on the science-based management actions necessary to address the documented ecological degradation associated with excessive and prolonged human use at Kapoʻo (Sharks Cove) Tidepools and Cove, and should also be considered for Kalua o Maua over time based on additional monitoring.

Taken together, these measures represent an initial phase of adaptive management to be evaluated and refined through continued monitoring and stakeholder collaboration. In the view of the marine team, the scientific foundation provided by the Act 31 program strongly supports the following recommendations for DLNR action during 2026–2027 and beyond.

A. Recommendations to DLNR

1. Establish a Visitor Access and Fee System for Kapoʻo Tidepools and Kalua o Maua

Recommendation: Establish a structured Visitor Access and Fee Program (VAFP) for Kapoʻo Tidepools and Kalua o Maua to manage visitor capacity limits and generate sustainable funding for site management, ecological monitoring, restoration, and visitor safety. The access system should include online reservations, capacity limits (see 4 below), and daily enforcement at access points. Fees should apply to all non-resident visitors, not to Hawaiʻi residents. Closure or rest days, like at Hanauma Bay, should be at least two days a week, with an additional day designated for residents only (e.g., Sundays). Rest days not only protect marine life but allow marine research and park maintenance to occur, and reduce wear and tear on public infrastructure.

Rationale: Visitor access and fee programs are well-established management tools used globally to mitigate tourism impacts, fund conservation, and regulate access at sensitive marine ecosystems. Hanauma Bay Nature Preserve, a City Beach Park adjacent to and surrounding the State-designated Hanauma Bay MLCD, provides a successful local precedent: following implementation of an entrance fee and reservation system for non-resident visitors, the site experienced reduced daily visitation, improved water quality, and measurable biological recovery. Similar fee models at high-use reef systems in Thailand, Palau, the Seychelles, and Ningaloo Marine Park demonstrate that regulated access combined with conservation financing increases compliance, reduces trampling and anchor damage, and supports monitoring and enforcement capacity.

Given the biological sensitivity of Kapoʻo and Kalua o Maua—and the demonstrated link between human density and declines in fish abundance, species richness, and coral health—and based on community consultation and adaptive management approaches, the VAFP program offers an equitable mechanism for reducing overcrowding while funding essential management interventions, and protects resident access to and enjoyment of the area.

Supporting Evidence: Act 31 monitoring shows strong evidence of declining ecosystem conditions associated with high visitor use. Non-schooling fish abundance declined by more than 50% across the study period at heavily visited sites, species richness decreased significantly, and coral damage was positively associated with human density. At peak periods, Kapoʻo Tidepools supported visitation exceeding 100+ individuals in water simultaneously, creating sustained ecological pressure that exceeds documented recovery thresholds in comparable systems.

Hanauma Bay provides a relevant management precedent: implementation of a visitor access system , a parking and entry fee (currently $25 for non-residents and $0 for residents), mandatory education program, reservation system to even out crowds throughout the day with limited open hours for non-residents, and daily caps (currently capped at 1400 visitors daily) (see below) resulted in increases in coral cover, improved water clarity, and 40–70% increases in key fish groups (Madin et al. 2024; Graham 2024). Globally, user-fee systems—such as the Palau Green Fee, Bonaire Marine Park Tag, and Phi Phi Islands Marine Visitor Fee—successfully fund reef monitoring, restoration, safety personnel, and waste infrastructure. These examples demonstrate that well-designed access management and fee systems reduce uncontrolled visitation while improving funding reliability for conservation actions.

A comparable program at Kapoʻo and Kalua o Maua would address chronic underfunding of enforcement and site maintenance while simultaneously reducing daily visitation to ecologically sustainable levels. Revenue could support lifeguard or safety officers, sustained marine science and enhanced data collection, education and outreach, erosion-control infrastructure, and community stewardship programs like MPW's effective Ocean Education Ambassador (OEA) program.

2. Establish a Permanent, Integrated, and Community-Based Marine Science, Monitoring, and Data Program for the Pūpūkea MLCD

Recommendation: Use visitor fees (see above), Ocean Stewardship User Fee funds, or other sources to establish a permanent, integrated, community-based marine science, monitoring, and data program for the Pūpūkea MLCD. The program should include biological monitoring of the entire MLCD, nearby "spillover" and control areas, and partnerships for additional research.

The monitoring program should integrate all available biological, physical, and human-use data across all zones using standardized methods and annual public reporting. Implementation should occur in collaboration with MPW, building on Act 31 research methods, and include expanded studies on carrying capacity, socio-ecological dynamics, and adaptive management. The program should maintain at least twice-monthly fish and mobile invertebrate surveys expanded to include all zones within the MLCD (adjusted for swell during winter months), annual benthic photo-quadrats, human use and visitor impact surveys, and annual broad-scale coral impact surveys.

The marine science program should facilitate partnerships to pursue focused applied-research initiatives in collaboration with MPW, DLNR, and academic partners to inform science-based management. All current methods should continue and additional areas of research should include:

- *Wastewater source and impact assessment*, including a dye study to trace and quantify wastewater flow from the septic systems of the comfort stations; and dye or other methods to trace flow and impacts of showers, water fountains, parking lot run-off, storm drain run-off, and surrounding infrastructure into nearshore waters of the MLCD.
- *Population-genetic and spawning studies* of Āholehole and ʻAmaʻama to evaluate connectivity, spillover, and local spawning timing. Reports from Moʻomomi (Molokaʻi) indicate winter spawning peaks, while other parts of Oʻahu exhibit year-round activity with greater frequency in winter. Determining the spawning seasonality at Pūpūkea could inform the design and timing of seasonal closures. Monitoring limu and herbivore seasonal relationships would also be useful.
- *Carrying-capacity assessments* for additional MLCD zones beyond Kapoʻo, including building on the baseline study of Kalua o Maua and extending surveys to Waimea Bay, to identify sustainable visitor thresholds and detect and manage user translocation.
- *Collaborative research partnerships* to expand socio-ecological and ecosystem connectivity studies that directly inform adaptive management.

Rationale: A permanent, integrated (meaning with shared information and collaboration among MPW, DLNR, and NOAA) marine monitoring program is essential to maintain the scientific foundation for adaptive management, policy evaluation, and long-term reef resilience of the Pūpūkea MLCD. The Act 31 program demonstrated both the feasibility and value of consistent, community-based data collection. A sustained program will preserve methodological integrity, prevent data loss during funding gaps, and ensure that local knowledge continues to inform DLNR decision-making. Integrating ecological metrics (fish, coral, and benthos) with visitor-use data (counts, drone imagery, and VIS surveys) provides a comprehensive understanding of the coupled human–natural system, enabling early detection of degradation, evaluation of management outcomes, and data-driven policy adjustments.

Continued monitoring across all zones will be essential to detect human translocation effects, evaluate management effectiveness, and track overall reef recovery. A permanent community-based program, led collaboratively by MPW, DLNR-DAR, and partners, will preserve methodological continuity, expand monitoring throughout the MLCD, and produce annual *Pūpūkea MLCD Monitoring Reports* summarizing ecosystem condition and visitor-use trends to guide future adaptive management. Annual public reporting will strengthen transparency, coordination, and accountability under the Ocean Stewardship User Fee program.

These additional scientific studies will address key knowledge gaps identified through Act 31 monitoring. Understanding water quality, population connectivity, recruitment dynamics, and spatial variation in human-use impacts will strengthen the scientific basis for future rulemaking and community co-management. Expanding research across zones ensures that adaptive management measures remain data-driven, equitable, and responsive to the evolving ecological conditions of the Pūpūkea MLCD.

Supporting Evidence: The Act 31 program provided an extensive biological dataset for the sensitive, most visitor-impacted areas of the MLCD, including a total of 108 survey days, 920 hours in the water, and 1,617 transect and radial surveys. These data established multi-year baselines for fish abundance, richness, biomass, benthic cover, coral health, and water quality. Integration of human-use counts, drone mapping, and Visitor Impact Surveys revealed strong correlations between visitor density and ecological condition.

New baseline values from Kalua o Maua also now serve as a critical control for evaluating ecological change and assessing whether visitor pressure shifts over time.

3. Enact Seasonal Closures of Kapoʻo Tidepools and Cove during Winter Months

Recommendation: Commence an annual closure of the Kapoʻo Tidepools and Cove for five months (November – March).

Rationale: Provide a seasonal rest period for marine life to recover from chronic disturbance and reduce shoreline degradation during high-surf months when public-safety risk is elevated.

Supporting Evidence: Act 31 Year 3 data showed a 53% cumulative decline in non-schooling fish abundance (2022–2024), a 42% decline in species richness, and minimal calcifier recovery (CCA = 2.30%). Peak human densities averaged 115 ± 17.4 individuals in-water at 3 p.m., indicating sustained biological stress.

Additionally, kilo from community members during the Covid-19 anthropause (Rutz et al., 2020) suggested that a rest period from humans dramatically increased limu and juvenile fish production (Yagodich, Personal Communications). Similar findings were reported at Hanuama Bay (Madin et al., 2025; Graham 2024).

4. Set Visitor Caps for Kapoʻo Tidepools

Recommendation: Implement quantitative, science-based “visitor” (non-Hawai‘i resident) caps or number thresholds derived from Act 31 data using an hourly reservation system and daily limits.

Rationale: Unregulated visitation has resulted in sustained biological stress and measurable ecological degradation across Kapo‘o. Continuous daily use, often exceeding 100 individuals simultaneously in the water in a single zone, has reduced fish abundance and richness, diminished calcifier cover, and altered coral and benthic structure. Setting an explicit visitor hourly or point-in-time and daily cap for the Tidepools will allow the reef to recover from chronic disturbance, provide real-time evaluation of carrying-capacity limits, and restore equitable resident access that has been displaced by over-tourism. Such measures mirror the proven success of time-based access management used at Hanauma Bay, where controlled visitation significantly improved coral and fish recovery.

Supporting Evidence: Act 31 Year 3 monitoring demonstrated a significant negative correlation between human presence and non-schooling fish abundance (trend = –0.12 ± 0.04 SE, $p = 0.005$). Mean weekday in-water counts ranged from 59 to 76 individuals, which are well above ecological tolerance thresholds identified through generalized linear mixed-model analyses.

This study identified a threshold of **1 human within a 10 m radius circle** expanding from the center of a transect. This threshold is equivalent to 31.8 humans per hectare. This value was then multiplied by measures of the Tidepools area in hectares to calculate carrying capacity limits (Stamoulis 2023).

1. The area at low tide was 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.
2. The area with the majority (90%) of humans based on the human density surface derived from the 2025 drone surveys, as a subset of the area at low tide described above.

This analysis yielded a carrying capacity range of 27 - 31 humans in the Tidepools at any given time. Selecting from within this range, **the study recommends implementing a limit of 30 visitors in the Tidepools at any given time**. Since the data from the 2023 visitor impact survey (see Coberly et al., 2024 for methods) displayed an average use of 49 minutes in the Tidepools across 77 follows (and 43 minutes overall across 151 follows, with similar findings in 2023), **the marine science team also recommends 30 people as a number to be used for reservations per hour**. These limits could be implemented through an online reservation system (similar to the system used for Hanauma Bay).

A daily cap on visitors, similar to management of Hanauma Bay, can be determined by scaling the hourly recommendation by the trend in hourly use (Figure 41) and the hour with the maximum mean number of visitors can be determined. Setting the usage during this peak hour equal to a factor of 1, the relative usage factor for every other hour compared to this peak hour (e.g., if a non-peak hour has half the visitors, its factor is 0.5) can be determined. Summing all these hourly factors yields Z, which represents the total proportional units or reservations per day. This scaling factor (Z) can then be multiplied by the recommended hourly use (X) to generate (A) total permits per day.

5. Initiate Rulemaking To Implement Long-Term Management Measures

Recommendation: Use results from pilot closures to commence formal rulemaking to authorize and implement the management measures outlined above within the Pūpūkea MLCD.

Rationale: Establish a legal framework that allows DLNR, the City, MPW, and partners, to implement data-driven adjustments in response to quantified ecological thresholds and human-use impacts.

Supporting Evidence: Three years of Act 31 studies documented > 40 % declines in fish richness, rugosity reductions of 0.2 – 0.3 m, and fluctuating CCA cover (9.7 – 16.4 %), among other effects, under sustained high human use in the Tidepools. Permanent regulatory changes will be necessary to protect the marine life of the sensitive areas of the MLCD.

6. Establish a Permanent Community-Based Ocean Education Ambassador Program

Recommendation: The human use counts taken by MPW over the years through the Makai Watch partnership with DLNR and its Ocean Education Ambassadors (OEA) program provide an essential data set that supports and integrates with the marine transect and ecological conditions data and analysis. The OEA program also provides critical direct educational and management capacity to protect marine life on a daily basis. Establishing a permanent OEA program for the Pūpūkea MLCD in collaboration with MPW that can cover the existing study zones as well as expand to Waimea Bay in the future is an important next step to complement the science-based management recommendations stated above. At Hanauma Bay, Sea Grant currently provides the educational and outreach staff, along with City management staff, to operate the park and support infrastructure, using the fees from the reservation system for non-residents. On-the-beach staffing is essential to the success of access management for a marine life protection district.

Rationale: The effectiveness of future management measures at the Pūpūkea MLCD depend not only on a continued excellent marine science program but also on consistent and robust human use counts.

Supporting Evidence: The MPW OEA Report for 2025 (provided as an Appendix to the Act 31 Final Report) provides data that show the effectiveness of the currently small program – part-time contractors, and volunteers conduct 3- to 4-hour field shifts five days a week at the Kapoʻo Tidepools and Cove, and at Kalua o Maua, within the Pūpūkea MLCD and Pūpūkea Beach Park.

OEA Metric	**2025**
People Educated	4,002
Educational Interventions	1,289
Pounds of Trash Removed	2,343
Hours Contributed (Makai Watch/OEA)	815

B. Recommendations to the City

The marine team supports the MPW Final Report recommendations to the City regarding new management measures at Pūpūkea Beach Park. Please refer to that report for details.

C. Recommendations to the State Legislature

The marine team supports the MPW Final Report recommendations to the State Legislature regarding statutory changes that will further the protection of all MLCDs statewide. Please refer to that report for details.

* * *

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Appendices

A. Fish Species List

Scientific Name	‘Ōlelo Hawai‘i Name	Common Name
Abudefduf abdominalis	mamo	Hawaiian Sergeant
Abudefduf sordidus	kūpīpī	Blackspot Sergeant
Acanthurus achilles	pāku‘iku‘i	Achilles Tang

Acanthurus blochii	pualu	Ringtail Surgeonfish
Acanthurus dussumieri	palani	Whitespine Surgeonfish
Acanthurus guttatus	'api	Whitespotted Surgeonfish
Acanthurus leucopareius	maikoiko	Whitebar Surgeonfish
Acanthurus nigrofuscus	ma‘i‘i‘i	Lavender/Brown Tang
Acanthurus olivaceus	na‘ena‘e	Olive Tang/ Orangeband Surgeonfish
Acanthurus triostegus	manini	Convict Tang
Anampses cuvier	‘opule	Pearl Wrasse
Atherinomorus insularum	‘iao	Hawaiian Silverside
Aulostomus chinensis	nunu	Trumpetfish
Bothus pantherinus	pāki‘i	Flounder
Calotomus carolinus	pōnuhunuhu/pahanui	Stareye Parrotfish
Cantherhines dumerilii	'ō'ili	Barred Filefish
Canthigaster amboinensis	n/a	Ambon Puffer
Canthigaster jactator	n/a	Whitespotted Toby
Caranx melampygus	‘omilu	Blue Trevally
Centropyge potteri	n/a	Potter‘s Angelfish
Cephalopholis argus	roi	Peacock Grouper
Chaetodon auriga	kīkākapu	Threadfin Butterflyfish
Chaetodon fremblii	kīkākapu	Bluestripe Butterflyfish
Chaetodon lunula	kīkākapu	Raccoon Butterflyfish
Chaetodon miliaris	kīkākapu	Milletseed Butterflyfish
Chaetodon ornatissimus	kīkākapu	Ornate Butterflyfish
Chaetodon quadrimaculatus	kīkākapu	Fourspot Butterflyfish
Chaetodon unimaculatus	kīkākapu	Onespot Butterflyfish
Chlorurus perspicillatus	uhu 'ahu'ula (F), uhu uliuli (M)	Spectacled Parrotfish

Chromis ovalis	n/a	Oval Chromis
Chromis vanderbilti	n/a	Blackfin Chromis
Cirrhitus pinnulatus	po‘o pa‘a	Stocky Hawkfish
Coris flavovittata	hīnālea	Yellowstripe Coris
Coris gaimard	hīnālea	Yellowtail Wrasse
Coris venusta	hīnālea	Elegant Coris
Ctenochaetus strigosus	kole	Goldring Surgeonfish
Diodon hystrix	kōkala	Spotted Porcupinefish
Dascyllus albisella	'ālo'ilo'i	Hawaiian Domino Damsel or Humbug
Echidna nebulosa	puhi	Snowflake Moray Eel
Fistularia commersonii	nunu peke	Smooth Cornetfish
Forcipiger flavissimus	lauwiliwili nukunuku 'oi'oi	Forcepsfish
Gomphosus varius	hīnālea ‘akilolo	Bird Wrasse
Gymnomuraena zebra	puhi	Zebra Moray Eel
Gymnothorax flavimarginatus	puhi paka	Yellowmargined Moray Eel
Gymnothorax meleagris	puhi 'ōni'o	Whitemouth Moray Eel
Halichoeres ornatissimus	hīnālea	Ornamented Wrasse
Kuhlia sandvicensis/xenura	āholehole	Hawaiian Flagtail
Kyphosus sp	nenue	Chubs
Labroides phthirophagus	n/a	Hawaiian Cleaner Wrasse
Lutjanus fulvus	to‘au	Blacktail Snapper
Macropharyngodon geoffroy	n/a	Shortnose Wrasse
Mugil cephalus	‘ama‘ama	Striped Mullet
Mulloidichthys flavolineatus	weke‘a	Yellowline Goatfish
Mulloidichthys vanicolensis	weke 'ula	Yellowfin Goatfish
Naso lituratus	umaumalei	Orangespine Unicornfish

Naso unicornis	kala	Bluespine Unicornfish
Neomyxus leuciscus	uouoa	Sharpnose Mullet
Ostracion meleagris	moa	Whitespotted Boxfish
Paracirrhites arcatus	piliko'a	Arceye Hawkfish
Parupeneus cyclostomus	moano kea	Gold Saddle Goatfish
Parupeneus multifasciatus	moano	Manybar Goatfish
Parupeneus porphyreus	moano	White Saddle Goatfish
Plectroglyphidodon imparipennis	n/a	Brighteye Damselfish
Plectroglyphidodon johnstonianus/marginatus	n/a	Hawaiian Gregory
Rhinecanthus rectangulus	humuhumunukunukuapuaʻa	Reef Triggerfish
Scarus dubius	lauia	Regal Parrotfish
Scarus psittacus	uhu	Palenose Parrotfish
Scarus rubroviolaceus	uhu pālukaluka (F), uhu 'ele'ele (M)	Redlip Parrotfish
Scomberoides lysan	lai	Leatherskin or Spotted Queenfish
Stethojulis balteata	hīnālea	Belted Wrasse
Sufflamen bursa	humuhumu lei	Boomerang Triggerfish
Thalassoma duperrey	hīnālea lauwili	Saddle Wrasse
Thalassoma purpureum	hou	Surge Wrasse
Thalassoma trilobatum	ʻawela	Christmas Wrasse
Zanclus cornutus	kihikihi	Moorish Idol

B.

Invertebrate Species List

Scientific Name	ʻŌlelo Hawaiʻi Name	Common Name
Actinopyga obesa		Plump Sea Cucumber
Actinopyga varians		White-Spotted Sea Cucumber

Carpilius maculatus	‘alakuma	7-11 or Blood-Spotted Crab
Chelidonura hirundinina?		Blue Swallowtail Slug
Cypraea (Mauritia) maculifera maculifera		Hawaiian Reticulated Cowrie
Dendrodoris carbunculosa?		Carbunculous Nudibranch
Diadema paucispinum	Wana	Long-Spined Urchin
Echinometra mathaei	‘Ina	Pale Rock-Boring Urchin
Echinometra oblonga		Black Rock-Boring Urchin
Echinostrephus aciculatus		Needle-Spined Urchin
Echinothrix calamaris	Wana	Banded Urchin
Heterocentrotus mammillatus	hā‘uke‘uke ‘ula‘ula	Slate Pencil Urchin
Holothuria atra	loli okuh kuhi	Black Sea Cucumber
Holothuria hilla		Light-Spotted Sea Cucumber
Holothuria impatiens		Impatient Sea Cucumber
Hypselodoris imperialis		Imperial Nudibranch
Isognomon californicum		Black Purse Shell
Loimia medusa	kauna‘oa	Spaghetti Worm
morolet or dwarf or golden yellow		Small cone snails
Octopus cyanea	He‘e Mauli	Day Octopus
Ophiocoma erinaceus		Spiny Brittle Star
Palythoa tuberculosa		Rubbery or Pillow Zoanthid
Panulirus marginatus	‘Ula	Hawaiian Spiny Lobster
Percnon planissimum		Flat Rock Crab
Pseudoceros paralaticlavus		Goldrim Flatworm
Stenopus hispidus		Banded Coral Shrimp
Tripneustes gratilla	Hawae	Collector Urchin

C. Detailed Procedures

Monitoring surveys were conducted all three study years and for one year prior within the Kapo‘o Tidepools and adjacent Cove within the Pūpūkea Marine Life Conservation District. Survey areas are outlined in the map below in black and survey locations are noted in red (Figure 1). There are eight transects in each survey zone, for a total of sixteen fixed (by GPS and benthic features, without pins) transects (GPS locations noted in Table 1).

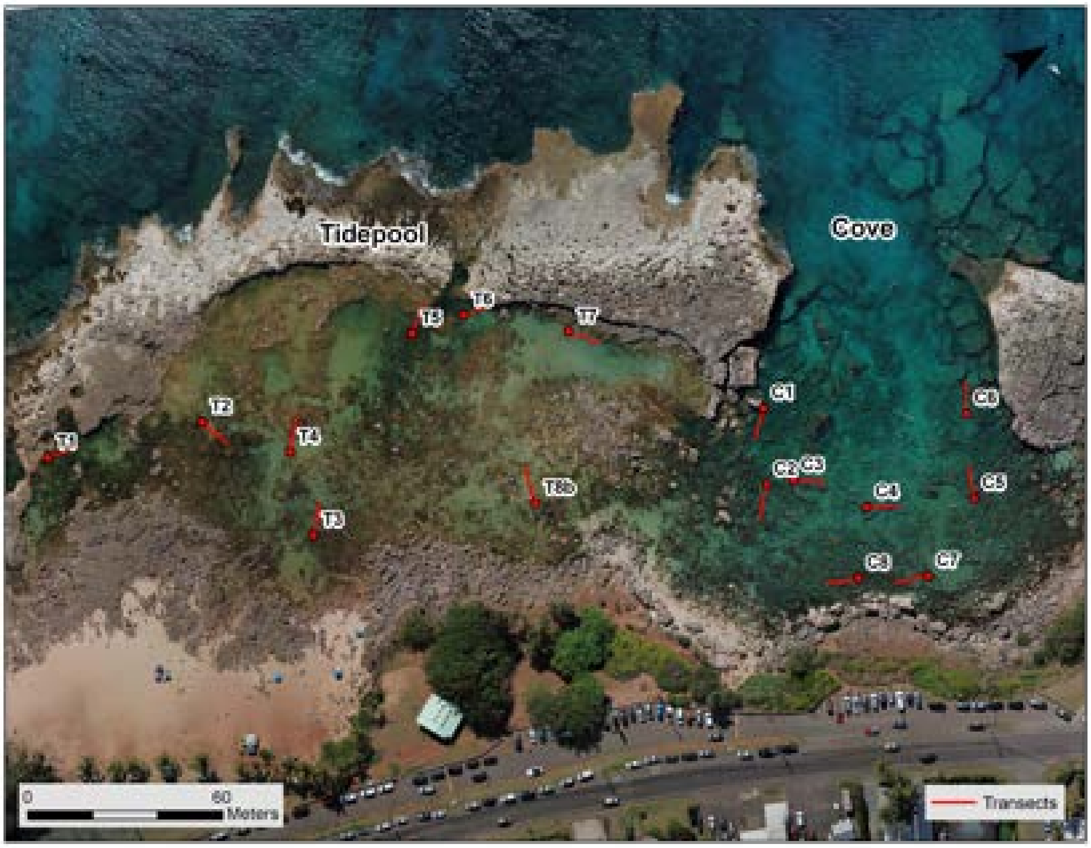

Figure 1. Map of survey areas and transect locations within the Kapo‘o Tidepools and Cove.

Figure 2. Map of survey areas and transect locations at Kalua o Maua.

Table 1. GPS coordinates of each of the 16 permanent transect start points.

Zone	Transect	Latitude Start	Longitude Start
Tidepools	1	21.64943429	-158.06362491
Tidepools	2	21.64986642	-158.06347301
Tidepools	3	21.65006085	-158.06316371
Tidepools	4	21.65021455	-158.06328029
Tidepools	5	21.65045318	-158.06339326
Tidepools	6	21.65062202	-158.06340236
Tidepools	7	21.65078729	-158.06322004
Tidepools	8	21.65056657	-158.06271094

Tidepools	8B	21.650538	-158.062779
Cove	1	21.65125969	-158.06269865
Cove	2	21.65115010	-158.06253465
Cove	3	21.65116865	-158.06243944
Cove	4	21.65125853	-158.06232455
Cove	5	21.65154771	-158.06232440
Cove	6	21.65144799	-158.06220102
Cove	7	21.65129213	-158.06211577
Cove	8	21.65122320	-158.06219282
Kalua o Maua	1	21.645929	-158.064175
Kalua o Maua	2	21.646249	-158.063874
Kalua o Maua	3	21.646473	-158.063969
Kalua o Maua	4	21.646776	-158.064134
Kalua o Maua	5	21.646367	-158.064177
Kalua o Maua	6	21.646379	-158.064674
Kalua o Maua	7	21.645837	-158.064656
Kalua o Maua	8	21.645967	-158.065282

1. Fish and Mobile Invertebrate Transects with Human Use Counts

Fish and mobile invertebrate richness and abundance, human density, and water clarity were quantified through biweekly visual transects for the duration of the study period. Year 3 expanded to include recording the total length of fish within transect surveys, which was used along with established length–weight relationships to calculate biomass.

Sixteen transects which were established by the 2022 Marine Science Coordinator Ellie Jones in consultation with MPW were repeated within the study area: eight in the Tidepools and eight in the Cove. Transect location criteria included a ten-meter by four-meter area with greater than 50% hard bottom habitat in generally heavily-visited portions of the surveyed area. In Year 3, Transect 8 in the Tidepools was shifted to nearby "T8B," due to changing benthic composition and an inundation of sand and boulders that left a portion of the original transect out of the water (Figure 2). Additionally in Year 3, a new set of eight transects was also established in the Kalua o Mauaaua study area by Emily Summers, Kosta Stamoulis and Callie Stephenson, following the same criteria for establishment as the Kapoʻo transects (Figure 2). For further reference, please see photographs of each Transect Location.

The marine research team counted, sized and identified fish within two meters of the permanent ten-meter transect line, and mobile invertebrates within one-meter to either side of the transect (Figure 3). Water clarity was then measured with a 2.5 inch diameter secchi disk at each transect (Figure 4), which provides a measurement of visual distance underwater and is used as a proxy for water clarity.

Fish Surveys

1. Navigate to the beginning of the transect, taking care to avoid any transect areas.
2. Record the time, and document the number of people within 10m of the transect.
3. Tie off transect end on uncolonized substrate.
4. Swim slowly along the transect, rolling the line out as you go, and record fish abundance within 2m on either side of the transect line. Record instantaneously in “snapshots” in segments along the transect.
5. Record the estimated total length of each fish in cm.
6. Identify to the species level.
    a. Photograph any species not identifiable in the field to identify later.
7. At 10m, stop the survey and secure the transect line ensuring the line is taut.

Invert Surveys

1. Upon completion of the fish surveys and securing the transect line, begin the mobile invertebrate survey by swimming back along the transect line.
2. Record any *mobile* invertebrates within 1m on either side of the transect. Record the abundance of all species observed.

Water clarity

1. After the mobile invertebrate surveys measure the water clarity using a secchi disk.
2. One observer holds the secchi disk and the end of the transect line, the other surveyor rolls out the transect until they can no longer discern the pattern on the disk. Record this distance.
3. Swim away for a few more meters. Turn around and begin rolling up the transect until the pattern is discernible again. Record this distance.
4. When inputting the data take the average of these two measurements.
5. Remove the transect line from the substrate and measure depth.
6. Repeat fish surveys, mobile invertebrate surveys, and water clarity measurements for all 8 transects in one area, take a break for water and a snack, then continue for all 8 transects in the following area.

Uploading Data Using Access

1. At the bottom of the data entry page, select the “go to last record” then “add new record” button.
2. Fill out metadata
    a. Location (Tidepool or Cove)
    b. Date

   c. Transect (benthic was previously used for benthic quadrats before transitioning to photo-quadrats)
   d. Observer
   e. Depth
   f. Water clarity
   g. Number of people (use the "within 10m" field)
3. Fill out fish data using the species list
   a. If a species has been observed that is not within the species list, notify Kosta because additional information will be required to include the species within the analysis)
   b. For biomass, just use the "min length" field
4. Fill out mobile invertebrate data using the "benthic" tab next to the "fish" tab
   a. The invertebrate species list is in a different format from the fish acronyms (first letter of genus, first three letters of species name)
5. Make sure to save the database when entry is completed.

2. Benthic Cover

Benthic cover is obtained using a series of photo-quadrats taken along each of the permanent transects in the Tidepools and Cove and analyzed using CoralNet (UCSD) to obtain an analysis of benthic community composition.

Photo-quadrats:

1. Reel out transect
2. Beginning at the 0m mark, place the photo-quadrat with the lower left corner on the mark on the left side of the transect.
3. Take a photo of the quadrat so that the entire 0.5m x 0.5m quadrat is visible.
4. Repeat 10 times

Image Analysis using CoralNet

Source Creation

1. Sign in to access your sources. If this is the first time your account has a source, there will be no active sources. A source is a set of images you have grouped together, usually as a part of a project.
2. Under the "Your Sources" label, there will be a table that shows your personal sources. Under that table should be an option to "+ Create a new Source," select this.
3. Follow the prompts to fill out the information for your new source.
   a. Metadata is optional but it can be helpful, fill out as desired.
   b. Under "Data Annotation" you can select how much of the photo will be visible, in 2023-5 the study used the parameters:
      Left Boundary X: 0% Right Boundary X: 100%
      Top Boundary Y: 0% Bottom Boundary Y: 100%

   c. Under "Point Generation Method," select "Simple Random" -> 50 annotation points
   d. Use the default Feature extractor (EfficientNet). This is the AI tool.
   e. Set the coordinates of the source: Latitude: 21.65125 Longitude: 158.0629

Uploading a Labelset

CoralNet will not allow you to mark a point without an existing label in your dataset.

1. Download the Labelset from the MPW drive. It will be in a .csv format.
2. Select the "Labelset" tab.
3. Select "Import a labelset from a CSV file."
4. If any additional labels are desired, select from "Choose labels for your labelset."

Uploading Images

1. Select the "Upload Images" tab.
2. Select the "Upload Images" option.
3. Upload the images from your desktop.
    a. Sometimes CoralNet will glitch, or become slow. If this happens, upload fewer photos in a single upload.
    b. Name the images in an easily identifiable way before uploading (i.e. for Cove Transect 1, Quadrat 1: CO1 Q1)
4. To find your uploaded images, select the "Images" tab.

Annotating Images

1. Select an image.
2. Select the "Annotation Tool."
3. Select the first point from the sidebar to edit (the point on the photo will change color)
4. Determine what the point is on (coral, rock, CCA, algae, etc.) and select the appropriate label. There are tools to zoom in and out on the side, or click the image to zoom in.
5. Continue for all points on the photo.
6. Once finished, select "save."

Exporting Data

1. On the "Browse Images" tab, scroll down to the bottom. There will be an "Image Actions" box.
2. Select the "Export Image Covers" option and how many images' data to export to retrieve the percent cover information.
3. Export as either a .csv or excel file.

3. Coral Health Surveys

Bleaching surveys are conducted once each month. These allow the study to observe changes in coral health and physical damage caused by humans.

1. Complete fish and mobile invertebrate surveys, and water clarity measurement for the transect. Once completed and the transect is secured, begin from the start of the transect.
2. Record the corals over 10cm in diameter within one-meter on either side of the transect. Record species, diameter, % live, pale, bleached, and dead coral tissue, the corresponding Koʻa card (Bahr et al. 2020) color, damage, and any fish bites observed for the length of the transect.
3. Repeat for all 16 transects.

4. Broad Scale Coral Impact Survey (previously Roving Coral Survey)

In Year 3 the annual broad scale coral impact survey (previously the roving coral survey) methods were updated to more effectively assess coral community structure and health across all sites. Rather than using GPS tracking along a lawnmower pattern, points within a grid were selected to be surveyed across the entirety of each survey zone. These points were uploaded to a GPS and navigated to, and then each coral above 10 cm was surveyed within a 2 m radius. The species, longest diameter, depth, any damage, and Ko'a card number were all recorded, and a photograph was taken and attached to each entry. This approach allowed for consistent long-term monitoring of coral size, species composition, and visible damage.

Protocol

1. Upload Points to GPS – Upload the GPS points for each survey area into a GPS unit at the start of the study and revisit these points in subsequent years.
2. Navigate to each point.
3. Lay Transects – At each point, roll each of two transects rolled to 4 m perpendicular to one another at the center points to visualize a circle with a 2 m radius.
4. Survey Corals – Within your circle, survey every coral colony greater than 10 cm.
    a. Identify it to the lowest possible taxonomic level
    b. measure its longest diameter
    c. Measure depth at highest point
    d. Record any damage, disease, predation, bleaching, etc.
    e. Record Ko'a card number
    f. Take a photograph and note the image number for each.

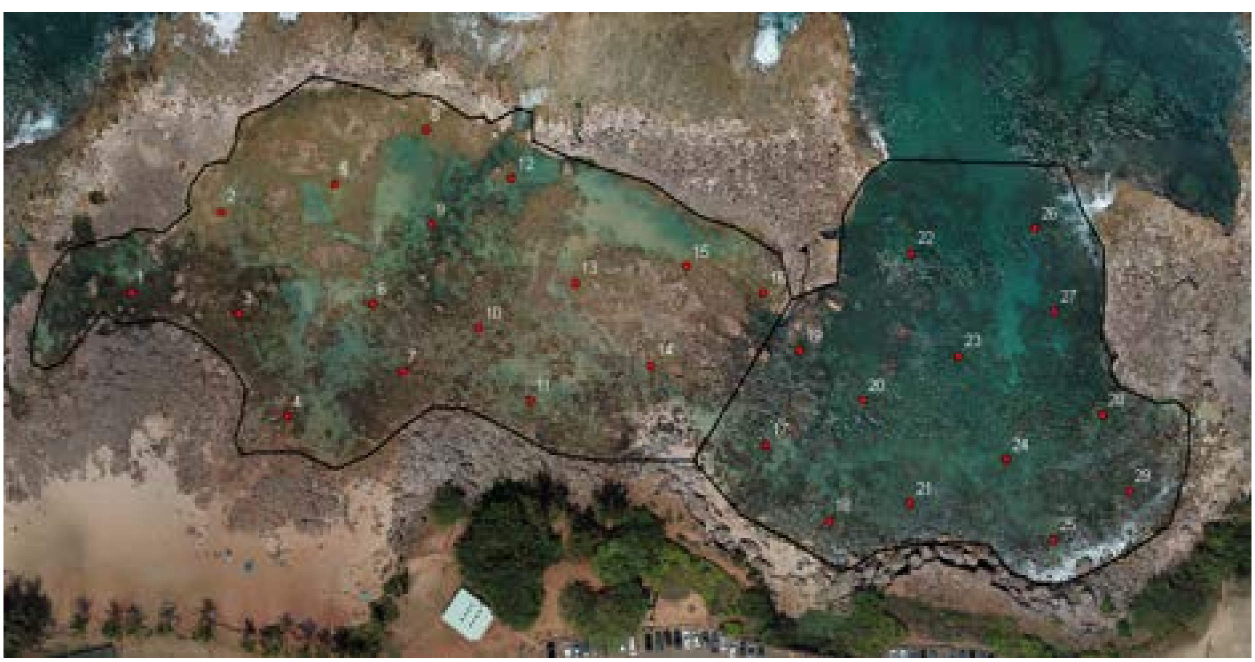

Figure 3. Broad Scale Coral Impact Survey points in the Tidepools and Cove.

Table 2. GPS Coordinates of Broad Scale Coral Impact Survey Points.

Point	**Latitude**	**Longitude**
T1	-158.06351	21.64956
T2	-158.0636	21.64985
T3	-158.06335	21.64979
T4	-158.06306	21.64978
T5	-158.06354	21.65015
T6	-158.06322	21.65011
T7	-158.06303	21.6501
T8	-158.06357	21.65042
T9	-158.06334	21.65033
T10	-158.06305	21.65033
T11	-158.06283	21.65037
T12	-158.06336	21.65056
T13	-158.06305	21.6506
T14	-158.06278	21.65068
T15	-158.06297	21.65087
T16	-158.06282	21.65102
C17	-158.06247	21.65087
C18	-158.06222	21.65093
C19	-158.06265	21.65105
C20	-158.06247	21.65114
C21	-158.06218	21.65113
C22	-158.06276	21.65141
C23	-158.06247	21.65141
C24	-158.06218	21.65141
C25	-158.06194	21.65143
C26	-158.06268	21.65172
C27	-158.06246	21.65168
C28	-158.06217	21.65168

C29	-158.06197	21.65166
KOM1	-158.0648	21.64579
KOM2	-158.06443	21.64575
KOM3	-158.06527	21.64597
KOM4	-158.06479	21.64611
KOM5	-158.06446	21.64606
KOM6	-158.06408	21.64606
KOM7	-158.06473	21.6464
KOM8	-158.06436	21.64644
KOM9	-158.06407	21.64642
KOM10	-158.0637	21.64633
KOM11	-158.06451	21.64678
KOM12	-158.06407	21.64678
KOM13	-158.06377	21.64667
KOM14	-158.06424	21.64702

5. Temperature

Temperature is monitored using Onset © data loggers HOBO water temperature Pro V2 data loggers with an accuracy of +/- 0.53°C and range of -20°C to 70°C. Loggers are calibrated prior to placement by immersion in water baths at 0°C and 30°C using a certified thermometer and water bath to standardize loggers during calibration.

Loggers are then attached to inconspicuous concrete substrates, affectionately named “HOBO Houses” (Figure 2) and deployed in the water following the specifications of DAR Special Activity Permit DAR SAP 2026-12 and OCCL SPA OA 24-07. Ensure loggers are adequately secured to HOBO House before deploying in water. Loggers were programmed to record water temperature at 1-hr intervals. On June 19, 2025, a logger was deployed at transects 1 and 4 in the Tidepools and at 1 and 4 in the Cove (Figure 8). Seven more loggers were deployed on July 17, 2025 at transects 2, 6, 7 and 8B in the Tidepools, and at transects 3, 6 and 8 in the Cove. The loggers were removed from the cove before large winter swells arrived on October 2, and kept in the Tidepools to record possible predicted temperatures that would lead to thermal coral bleaching, until being removed on October 30, 2025. The logger at Tidepool transect T8B was also redeployed after 3 days of being removed unknowingly by a visitor.

Figure 4. Deployed temperature logger in HOBO House in the Cove.

Logger Set-up:

1. Open HOBOware software on your device (personal or MPW computer)
2. Use the blue shuttle attachment, attach to the end of the shuttle, and plug in the shuttle to the computer.
3. Insert the logger into the shuttle and press down on the small handle. You should see a green light and the software should display “device detected”
4. If downloading data, select “readout” tab in upper left corner.
5. You will be prompted to stop recording, select continue.
6. Save the files as both a HOBO file and a .csv
7. Either set to relaunch or unplug if finished.

Launching a Logger

1. To launch the loggers open the HOBOware software
2. Follow the same set up instructions as above.
3. Instead of selecting “readout,” select the “launch” tab.
4. Select ℃, and every hour for recording frequency. You will also be able to select when the logger will begin recording temperature.
5. Select done and repeat for all loggers to be deployed.

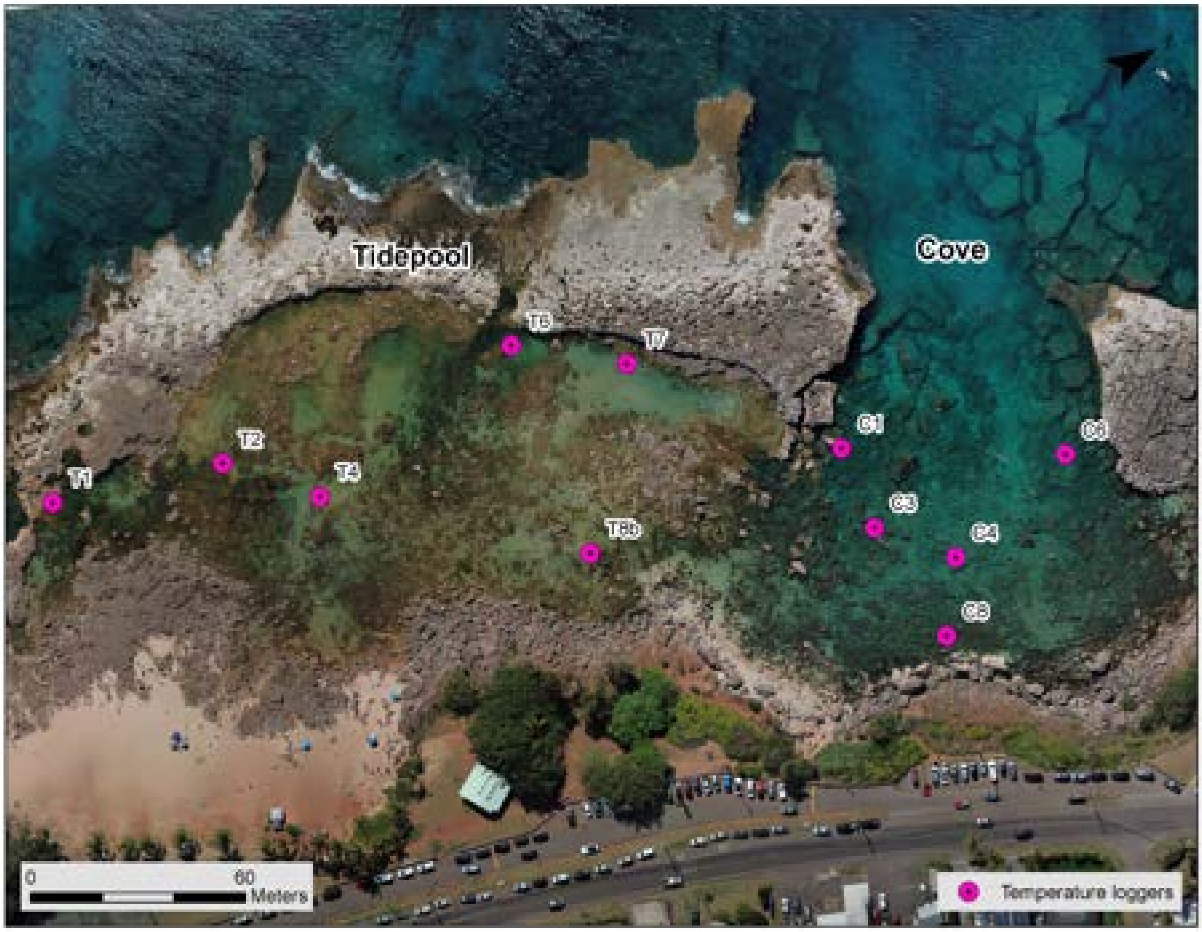

Figure 5. HOBO deployment locations in the Tidepools and Cove in 2025.

6. Drone Surveys

Drone surveys are conducted to understand where hotspots of human use occur within the study area. A total of four unmanned aerial vehicle (UAV) surveys are conducted by Shoreline Conservation Initiative to map human use patterns. Each UAV flight is conducted during high-use times from 10am-5pm and alternates between high and low tide conditions to account for variation in human use based on water depth.

A small UAV, DJI Mavic Pro, is used to conduct low-altitude flights over the study area Kapo‘o Tidepool and Cove. The UAV is 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 is 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, is 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 is 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 is 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 avoid the noon hour to reduce the amount of sunlight reflection in images.

In general, all flights are overseen by an FAA-licensed UAV pilot with additional researchers assisting with flight operations. This allows 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.

Images are compiled into an orthomosaic which can then be analyzed using a GIS software.

Orthomosaic Image Analysis - human use counts:

6. Create new ArcMap project
7. Load shapefiles: Pupukea BCC/Data/Humans/UAV/Shapefiles
    a. Zone_areas.shp
    b. Drone_survey_grid_10m_clip.shp
8. Load drone orthomosaics (.tif files): Pupukea BCC/Data/Humans/UAV/Orthomosaics
9. Create new point shape file for each survey image
    a. Location: Pupukea BCC/Data/Humans/UAV/Shapefiles
    b. Coordinate system: GCS_WGS_84
    c. File name: "Humans_uav_'imageDate'.shp"
        i. Ex: Humans_uav_20220727.shp (matching image filename)
    d. Add field called "Swim"
        i. Short integer format
10. Systematically search the image by grid cell and place a point on each person zooming into (at least) 1:200 scale
11. If floating/swimming (see lower body at the surface) mark a "1" in the "Swim" field, otherwise leave as "0" for standing or sitting individuals
    a. If using donut float assume "1", unless on obvious shallow spot/rock
    b. Often times visitors will be standing and bending over to see underwater so only the upper torso is visible on the surface - these should be marked "0"
    c. If really not possible to determine whether subject is contacting the bottom, input "2" in this field
12. Make sure to double-check the image to ensure that no humans were missed
13. Save project and upload to Pupukea BCC/Data/Humans/UAV/Shapefiles

If using QGIS

14. Create new QGIS project
15. Load shapefiles: Pupukea BCC/Data/Humans/UAV/Shapefiles
    a. QGIS: Data Source Manager - Vector
        i. Zone_areas.shp
        ii. Drone_survey_grid_10m_clip.shp
16. Load drone orthomosaics (.tif files): Pupukea BCC/Data/Humans/UAV/Orthomosaics

    a. QGIS: Data Source Manager - Raster
17. Create new point shape file for each survey image
    a. QGIS: New Shapefile Layer
        i. File name: “Humans_uav_’imageDate’.shp” (date format: yyyymmdd)
            1. Ex: Humans_uav_20220727.shp
        ii. Geometry type: Point
        iii. Coordinate system: GCS_WGS_84
        iv. Add field called “Swim”
            1. Integer format
18. Systematically search the image by grid cell and place a point on each person found in the water zooming into (at least) 1:200 scale
19. If floating/swimming (see lower body at the surface) mark a “1” in the “Swim” field, otherwise leave as “NULL” for standing or sitting individuals
    a. If using donut float assume “1”, unless on obvious shallow spot/rock
    b. Often times visitors will be standing and bending over to see underwater so only the upper torso is visible on the surface - these should be marked “0”
    c. If really not possible to determine whether subject is contacting the bottom, input “2” in this field
20. Make sure to double-check the image to ensure that no humans were missed
21. Save final version to: Pupukea BCC/Data/Humans/UAV/Shapefiles

7. Visitor Impact Survey

A visitor impact survey was also conducted each summer to determine how visitors utilize the area. The study used “secret snorkelers” who follow users and record any contact they have with the substrate. The complete protocol can be found in the 2025 VIS Tourist Tracking Protocol.

8. Additional Environmental Data

Additional environmental data such as tide height and tidal coefficient, transect distance from shore, wave height, wind speed, and wind direction can be obtained through various online sources.

Table 3. Sources for environmental datasets

Dataset	Source
Tide Height	Tides app (7th Gear); Haleiwa, Waialua Bay
Tidal Coefficient	Tides4Fishing
Wave Height	NDBC, PacIOOS Waimea buoy
Wind Speed	NDBC, PacIOOS Waimea buoy
Wind Direction	NDBC, PacIOOS Waimea buoy

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