Assessing Census and Resighting of Hawaiian Green Sea Turtles in Coastal Waters of Hawai'i Island

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Abstract

Mark-resight studies are important for proper ecosystem-based management, providing crucial information to understand population trends. In 2023, 33 Hawaiian green sea turtles were captured, tagged, and released at three locations on Hawai'i Island, USA (Punalu'u beach on March 31, n=15; Puako on April 17, n=12; and Hualalai Beach Resort on May 2, 2023, n=6). A Dremel moto tool was used to etch unique ID numbers 1-2 mm deep on the lateral scutes of the carapace, and filled in with a white epoxy paint. Snorkel surveys were conducted bi-weekly, starting no less than 4 days after the tagging event, with triplicate 30-minute in-water surveys were conducted followed by three replicate 15 minute on-shore beach surveys to account for basking sea turtles. Aerial drone surveys with a DJI Air 2 drone were concurrently conducted with snorkel surveys at the Punalu'u and Puako sites. Using a GoPro 11 camera, turtles were photographed and tag visibility scores were assessed, along with behavior and size. Of the primary study sites, tag retention was highest at Puako, with a visibility score of 1.33 ±0.47 at 345 days. Results indicate a significant difference in the average number of sea turtle sightings per location with 12.74 ±5.14 at Punalu'u, 13.19 ±6.94 at Puako, and 0.75 ±1.14 at Hualalai per survey ($F = 100.22$, $p < 0.001$). Population abundance model estimates using the Lincoln-Peterson Index predicted a significantly higher resident population at Puako (142.16 ±63.65) compared to Punalu'u (53.46 ±19.49) and Hualalai (7.17 ±2.32). Finally, this study found an underestimate of almost 4 sea turtles per survey occurred when using drones (8.91 ± 3.36) as opposed to traditional snorkel surveys (12.86 ± 5.57). This study exemplifies the critical role of mark-resight techniques and innovative technologies in understanding and conserving the Hawaiian green sea turtle population. These findings also provide valuable insights into sea turtle population dynamics and habitat use, emphasizing the need for continued monitoring and conservation efforts to protect these sentinel marine species and the ecosystems they inhabit.

Key words
Punalu'u, Puako, Hualalai, size class, snorkel survey, drone survey

Introduction

In coastal marine environments, which are frequently impacted by anthropogenic stressors, sentinel species play an important part in evaluating potential ecological consequences (Lutz et al. 2003). The green sea turtle (*Chelonia mydas*) is widely prevalent throughout the Hawaiian archipelago (Aguirre & Lutz 2004). Green sea turtles, as large air-breathing marine vertebrates with high site fidelity, are vulnerable to biological and chemical exposures, offering valuable insights into both biological and chemical stressors (Aguirre & Lutz 2004). The absence of these large herbivorous marine animals could lead to significant changes in the ecology of reef systems, as they remove excess seagrass and algae, and release nitrogen-rich fecal matter that may activate productivity (Burkholder et al. 2011).Mark-recapture studies are crucial for recovery planning, as they can offer valuable demographic information necessary to understanding population trends and population abundance estimates (Balazs & Chaloupka 2004).

Juvenile (35-83 cm) and adult (>83 cm) Hawaiian green sea turtles can be found foraging across the Hawaiian archipelago, inhabiting coastal regions after six or more years of pelagic development (<35 cm in size) in the Pacific Ocean (Balazs et al 1987; Balazs & Chaloupka 2004; Seminoff & Shanker 2008). These shallow waters along open coastlines and bays become a permanent location for immature turtles, as they show high site fidelity to foraging grounds that are comprised of intertidal marine algae and accessible shorelines that can be utilized to thermoregulate (Balazs 1976; Balazs & Chaloupka 2004; McDermid et al 2007). Sexually-mature adults of this distinct population utilize the French Frigate Shoal (FFS) for breeding when sexually mature, and return back to their respective coastline (Balazs 1976; Balazs & Chaloupka 2004; McDermid et al 2007; Balazs et al 2015).

Site fidelity is an important factor in conservation efforts, habitat use, including feeding ecology and thermoregulation in the form of basking, are also needed to understand the importance of a survey location (Chassagneux et al. 2013; Van Houtan et al. 2015; Arthur & Balazs 2008). Immature green sea turtles forage inshore, where their diet shifts from that of an omnivore during pelagic years to that of an herbivore diet, with high site fidelity to foraging grounds and where the quality of food can impact growth rates and sexual maturity (Balazs 1976; Arthur & Balazs 2008, McDermid et al 2007). A delay in maturation rates can impact survivorship to adulthood, and ultimately play a role in reproduction output and population growth (Arthur & Balazs 2008). Basking behavior predominantly found in green sea turtles is not only utilized for thermoregulation but is also believed to aid in vitamin D synthesis, digestion, and predator avoidance (Maxwell et al. 2014; Van Houtan et al. 2015).

Mark-recapture studies, when combined with population modeling, offer a valuable approach for estimating population abundance, recruitment, and understanding growth rates (Lettnik & Armstrong, 2003). Conducting multiple capture sessions over a designated period of time can lead to more precise estimates of population trends and abundance (Lettnik & Armstrong 2003). However, bias can be introduced as animals may become "trap happy" or "trap shy," leading to inaccurate abundance estimates (Lettnik & Armstrong, 2003; McClintock & White 2009). Mark-resight studies, proven beneficial for addressing the financial costs and stress on endangered species in long-term population monitoring studies, involve marking individual animals in a population using a specific tagging system, with subsequent recaptures achieved by sighting the animals in a series of surveys rather than physically recapturing them from their natural habitat (McClintock & White 2009; Magle et al 2007). With minimal disturbance of the animal, accurate behavioral patterns can be observed, as well as the assessment of other factors, such as age and sex (Lettnik & Armstrong 2003; McClintock & White 2009).

Unmanned aerial vehicles (UAVs) offer distinct advantages over manned aircraft for monitoring animals in their natural habitats (Kelaher et al. 2020; Scarpa & Pina 2019). UAV aerial surveys are cost-effective, repeatable, and offer flexibility while on location (Scarpa & Pina 2019). Operating at lower elevations, drones capture detailed photographs and video footage, enabling flexible timing and frequency of observations (Joyce et al. 2019). This approach expands sighting surveys beyond human visual limits, providing a comprehensive aerial perspective for individual animal counting and population abundance verification (Scarpa & Pina 2019). By enabling post-survey video analyses, drones offer more reliable sampling counts for marine fauna surveys (Kelaher et al. 2020). Moreover, when weather conditions or inaccessibility limit in-water surveys, drones present a safe and effective alternative (Joyce et al. 2019).

This study has three primary objectives. Firstly, to evaluate sea turtle abundance through turtle counts, size class distributions, observed behaviors, and population estimation models. Secondly, to assess the longevity of tags using etched markings on the carapace scutes, aiming to determine the viability of using these markings for long-term mark-resight studies. Finally, to compare the effectiveness of drone-based surveys with traditional in-water snorkel surveys at three sites on Hawai'i Island.

Methods and Materials

Hawaiian green sea turtles were tagged as part of a long-term health assessment program at three locations on Hawai’i Island (Punalu’u beach, n=15, Puako area 92, n=12, and Hualalai Beach Resort, n=6) across three sampling days in 2023 (March 31, April 17, and May 2, respectively). Turtles were captured by hand, measured to determine straight carapace length (SCL), weighed, and assessed for body condition. A marking method utilizing an etching technique filled with enamel paint was established as an effective means to identify sea turtles with minimal disturbance (Balazs 1995). The use of a moto tool elicited minimal response from the sea turtle during the engraving process and took less than 30 seconds to complete (Balazs 1995). During these health assessments, turtles were marked with a unique ID number with etchings on the right lateral scutes (Punalu’u, Puako) or the left lateral scutes (Hualalai Resort) of the carapace 1-2 mm deep and highlighted with a white non-toxic epoxy paint prior to being released.

Punalu’u Bay, located on the southeast side of Hawai’i Island, HI, is comprised of a small coastal algal habitat in a rocky substrate where population abundance has increased since the 1980s (Balazs & Chaloupka 2004; Rice et al. 2000). Puako Bay, found on the northwest side of Hawai’i Island, is a 4.8 km long coast comprised of sand and a lava rock substrate that creates shallow tidepools providing both foraging grounds and basking locations ideal for Hawaiian green sea turtles (Davis et al. 2000). Due to the size of this coastline, this study focused on the area referred to area 92, covering approximately 1.6 km. Hualalai beach resort, located within the Ka'upulehu marine reserve sits in front of the Four Season’s Resort in Kailua-Kona, Hawai’i Island, HI. Within this boundary, the take or possession of any aquatic life from the shoreline seaward to the 20-fathom depth contour is prohibited (DAR 2016) (Fig. 1).

To determine site fidelity and moto tool tag longevity, a total of 55 surveys were completed at Punalu’u and 56 surveys were conducted at both Puako and Hualalai from April 2, 2023 through March 31, 2024. Snorkel surveys were conducted biweekly, starting within 4 days of the initial tagging event through present time. Biweekly sampling trips consisted of triplicate 30-minute snorkel surveys and triplicate15-minute beach surveys (for basking turtles) conducted between snorkel surveys. Snorkel surveys were conducted mid-morning, starting at approximately 0800 hrs. to ensure optimal light conditions and high tag visibility (Zubik & Fraley 1988). The use of a Gak waterproof stone paper notebook was used to document the following: tags present, tag visibility scores, relative size classes of sea turtles present (post-oceanic juvenile < 35 cm, juvenile 35-83 cm, adult > 83 cm), and observed behavior (feeding, basking, etc.). All turtles observed during surveys were also photographed using a GoPro 11 underwater camera for photographic documentation of tag visibility (if present).

During each survey, tag ID numbers were documented and assigned a tag visibility score ranging from 5-0. Tag visibility was scored on a rolling scale, with all tags receiving a score of 5 on day zero of tagging. As time progressed, tag visibility changed in response to environmental conditions. A score of 5 had a visibility of 100%, with no algal coverage. A score of 4 is a tag with less than 25% algal coverage, a score with 3 is a tag with greater than 25%, a score of 2 is less than 50%, a 1 is greater than 75% coverage, and a zero is unreadable (Fig. 2). Turtles were only scored with a zero if they had a mark with an ID that was deemed unreadable and had a new metal flipper tag, indicative of a turtle tagged from the most recent health assessment. Metal tags were not used to identify individual animals in this study, as this was not a mark-recapture study, and tags were unreadable from snorkel survey distance to each turtle.

At the beginning of each survey DJI Air 2 drone was flown in conjunction with each snorkel and beach survey to compare sea turtle counts from an aerial view. The drone was launched from the shoreline, elevated to approximately 30 m (wind permitting), hovered in one position with the camera angle set at 40˚. Video footage captured the movement of green sea turtles entering and departing the survey area. Post survey, videos were analyzed, and sea turtles were counted and size estimation were recorded. Drone surveys were not conducted at the Hualalai location due to logistical restrictions at that site.

To estimate population abundance at each location, the Lincoln-Peterson method was used and the formula: $\hat{N} = \frac{nK}{k}$. N = population abundance, n = marked turtles, K = total captured, and k = recaptured tagged. This equation was applied to two resight occasions to provide estimated population abundance (Lettink & Armstrong 2003). Differences in the average number of turtles per site were tested using an Analysis of Variance (ANOVA) with subsequent post-hoc (Tukey) tests. Differences between turtle size classes and locations were tested using a two-way ANOVA with subsequent post-hoc (Tukey) tests. A paired t-test was run to test the mean difference in sea turtle counts between snorkel and drone surveys. Statistical analysis was performed using Minitab 21.1.10 with an alpha of 0.05.

Figure 1: Map of three survey sites across Hawai'i Island, Hawai'i, USA. The inset shows the location of Hawai'i Island.

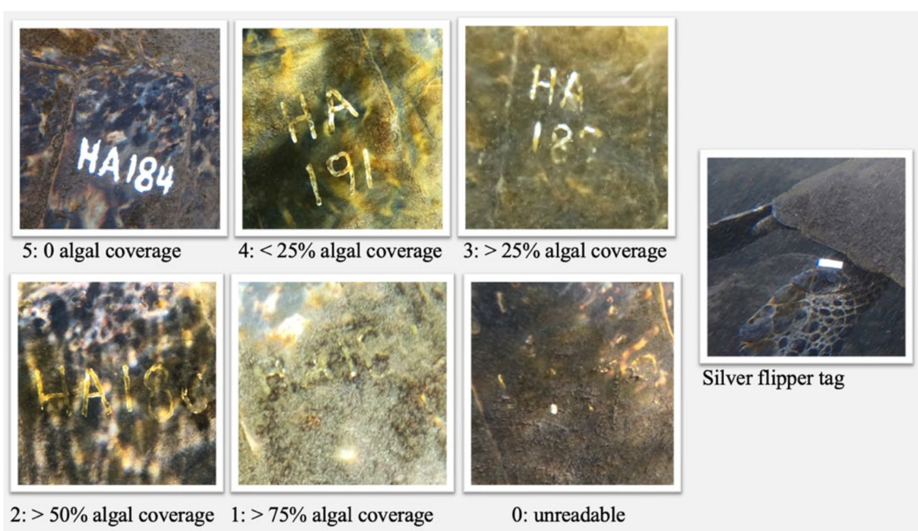

Figure 2: Tag visibility scores based on algal coverage observed at all three survey sites across Hawai'i Island, Hawai'i, USA.

Results

Turtle Counts

During in-water snorkel surveys, turtle counts were taken of both tagged and untagged sea turtles. There was a significant difference in the number of sea turtles counted at Hualalai compared to Punalu'u beach and Puako. Hualalai averaged 0.75 ±1.14 while the number of turtles at Punalu'u and Puako observed were 12.74 ±5.14 and 13.19 ±6.94 respectively ($F = 100.22$, $p < 0.001$) (Fig. 3).

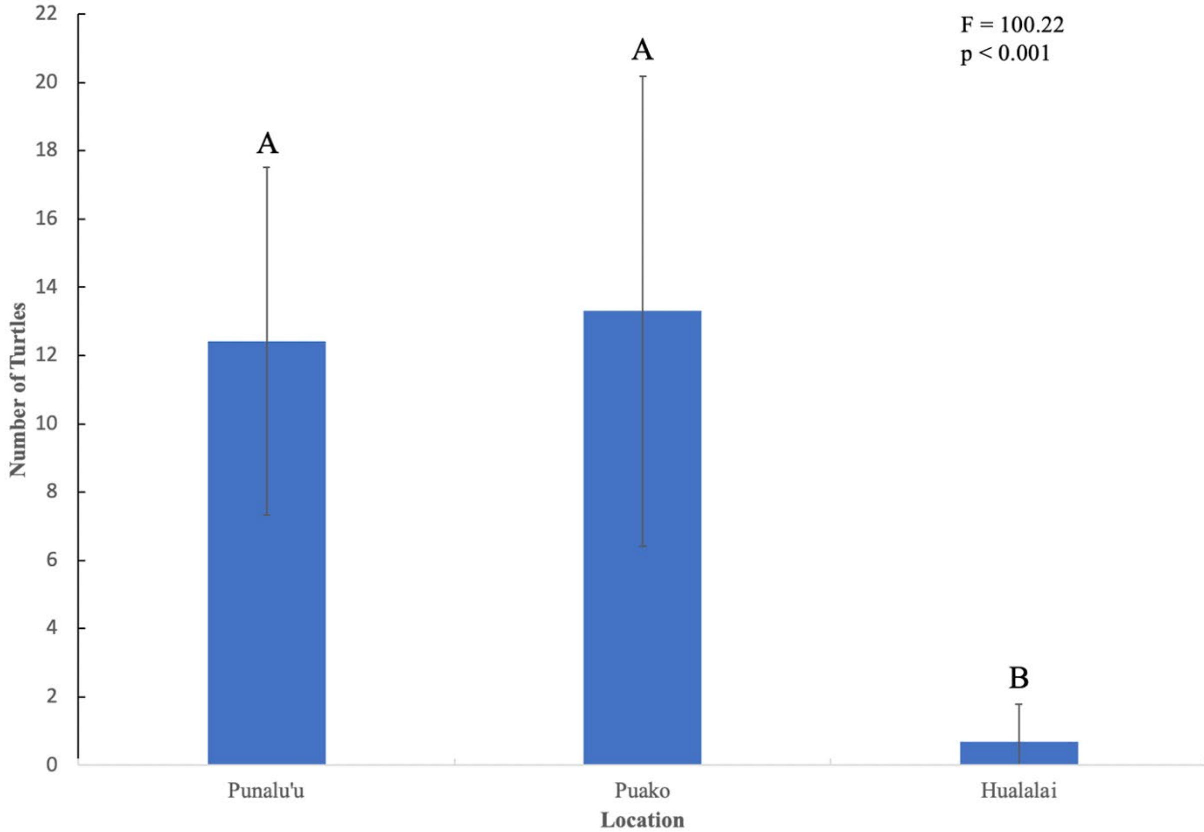

Figure 3: Average number of sea turtles (±SD) observed per survey at Punalu'u beach, Puako, and Hualalai, Hawai'i Island, HI. Results from ANOVA and Tukey test are shown in the figure ($\alpha = 0.05$).

During each survey day, the number of tagged turtles observed were documented. After the initial tagging event, no location showed the presence of all tagged turtles during one survey day. At Punalu'u, the tag counts ranged from 1 tagged individual to 11 tagged individuals (Fig. 4). At Puako, the tag counts ranged from 0 to 4 tagged individuals, with seven survey days presenting zero tagged individuals (Fig. 5). At Hualalai, the number of tagged individuals ranged from 0 to 2, with 18 survey days having zero tags present (Fig. 6).

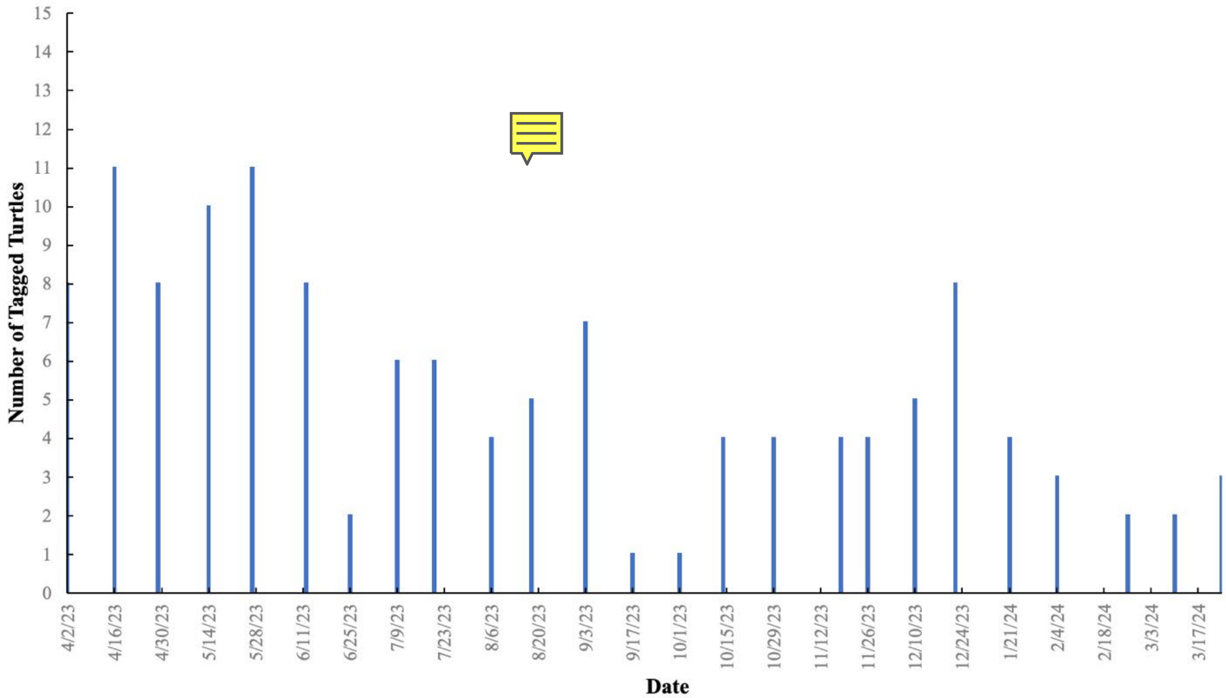

Figure 4: Number of tagged sea turtles counted at Punalu'u beach, Hawai'i Island, HI from April 2, 2023 to March 24, 2024.

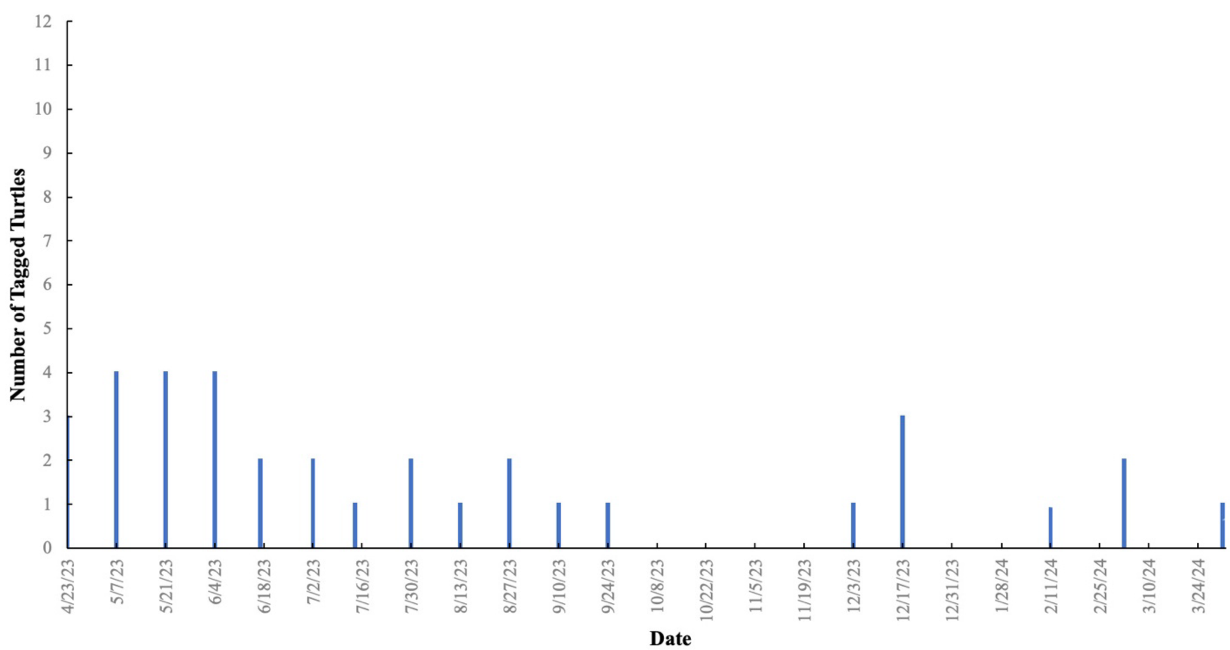

Figure 5: Number of tagged sea turtles counted at Puako, Hawai'i Island, HI from April 23, 2023 to March 31, 2024.

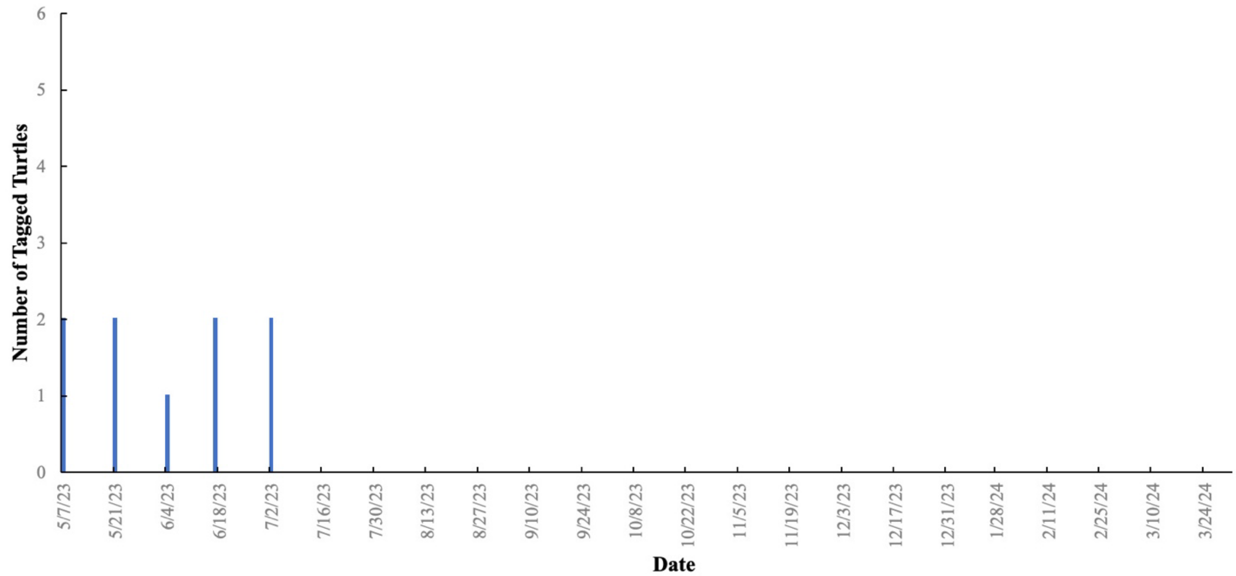

Figure 6: Number of tagged sea turtles counted at Hualalai, Hawai'i Island, HI from May 7, 2023 to March 31, 2024.

Tag Longevity

Individual HA-179, found at Punalu'u was observed during every survey conducted at Punalu'u except for once on September 15, 2023. The progression of tag deterioration from April 2023 through March 2004 has been documented, where the tag visibility had actually shown improvement between the months of October to November 2023. This may be due to an aggressive Acanthuridae population present at Punalu'u beach (Fig. 7).

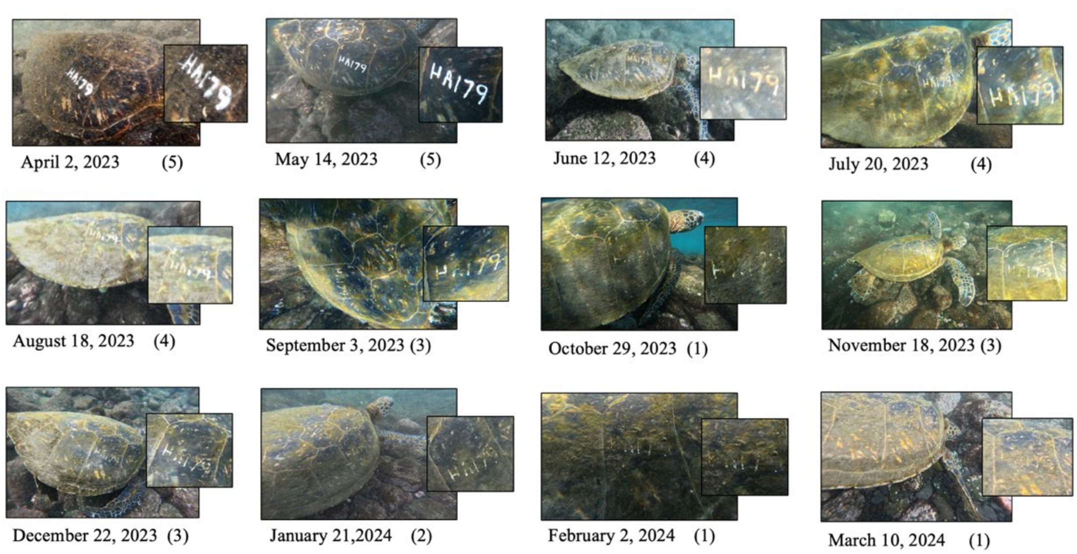

Figure 7: Progression of moto-tag deterioration from April 2, 2023 through March 10, 2024 observed at Punalu'u beach, Hawai'i Island, HI, USA. The inset image is the tag visibility score assigned during snorkel surveys.

After 90 days, tag retention visibility scores across all three sites averaged 4.60 ±0.42 with Puako having the highest visibility score of 5 ±0, followed by Hualalai with 4.75 ±0.43, and Punalu'u at 4.05 ±1.01 (Fig. 8). However, after this time, no tagged turtles were found present at Hualalai. After 180 days, tag visibility averaged 2.56 ±2.04, with Puako still showing a score of 5 ±0, compared to Punalu'u 2.69 ±1.59, and no data available for Hualalai. At 240 days, no tag data was available for Puako or Hualalai, and the tag visibility score at Punalu'u 2.2 ±0.98. Tags were again noted at Puako at the 270 and 345 day mark, with scores of 1 ±0 and 1.33 ±0.47 respectively. Punalu'u presented scores of 2.2 ±0.48 and 1.2 ± 0.40 for the same time periods.

Among the primary study sites, tag retention was highest at Puako, with a visibility score of 1.33 ±0.47 at 345 days, compared to Punalu'u with a visibility score of 1.20 ±0.40 and Hualalai with a score of zero. However, tag visibility scores were recorded for each time period at Punalu'u, compared to the Puako and Hualalai (Fig. 8).

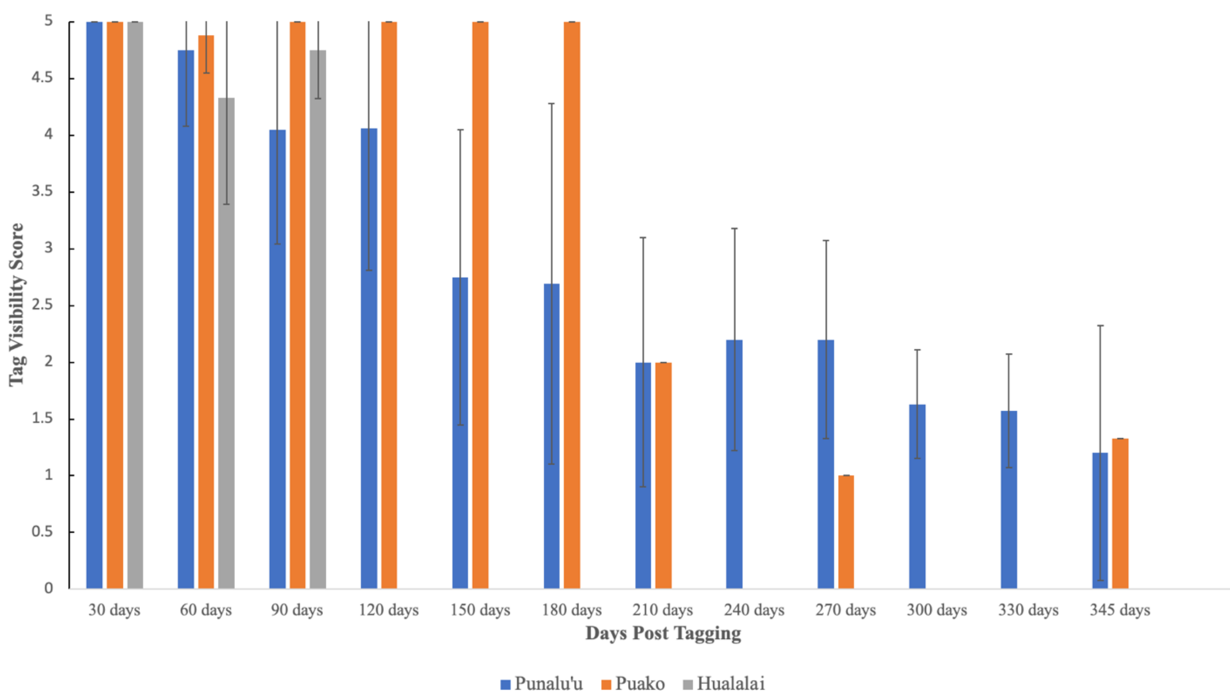

Figure 8: Average tag visibility scores (±SD) at Punalu'u beach, Puako, and Hualalai, Hawai'i Island, HI.

Site Fidelity

There was a significant difference in the percentage of tagged sea turtles identified at each location, with an average of 37.62% ± 22.63 identified at Punalu'u, 16.03% ± 20.24 at Puako, and 10.38% ± 22.42 tagged turtles at Hualalai (Fig. 9).

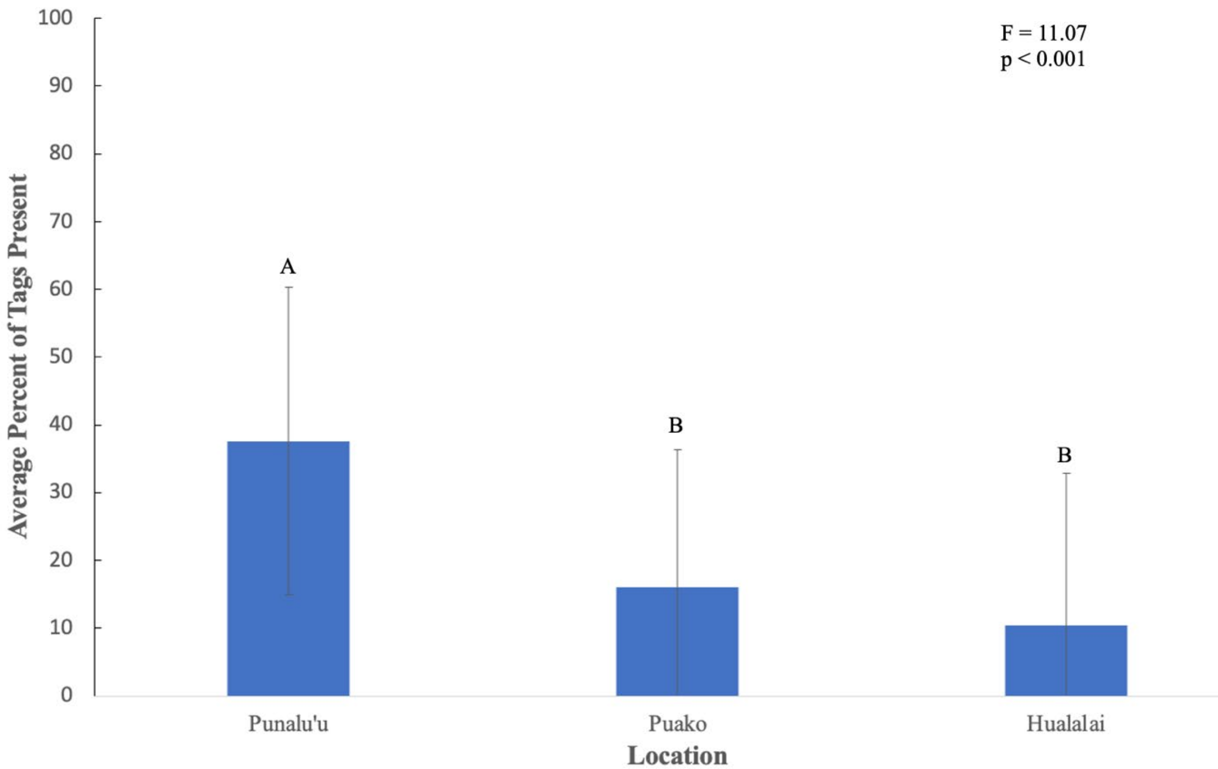

Figure 9: Average Percentage of tagged sea turtles (±SD) present at Punalu'u, Puako, and Hualalai, Hawai'i Island, HI. Results of ANOVA and Tukey test are shown in the figure (α = 0.05).

Site fidelity was tracked using individually tagged sea turtles, with Punalu'u exhibiting higher site fidelity compared to Puako and Hualalai. At Punalu'u beach, 93.33% of tagged sea turtles have shown site fidelity, as 14 of the 15 tagged individuals have returned back to this location over the duration of the study. Over the 26 bi-weekly surveys, tagged individual HA-190 was never observed after the initial health assessment, while HA-179 has been present 24 of the 26 bi-weekly surveys, while several other individuals (HA-178, HA-184, HA-185, HA-188, and HA-189) have been observed at least ten times for the duration of the survey (Table 1).

At Puako, 66.67% of the tagged sea turtles returned back to this location over the duration of the study, with 8 of the 12 of the individuals returning. Individuals HA-199 and HA-200 were observed at least ten times in the area, while four individuals, HA-194, HA-198, HA-120, and HA-126, were not observed after the initial health assessment (Table 2). HA-120 and HA-126 were noted re-tagged individuals from a previous health assessment, conducted prior to April 17, 2023.

At Hualalai, 50% of tagged sea turtles have returned back to this location, with 3 of the 6 individuals returning back. Individual HA-203 was observed five of the 26 bi-weekly surveys, while HA-205, HA-206, and HA-207 were not observed after the initial health assessment on May 2, 2023. HA-113 was also noted to be a recapture from a previous health assessment prior to May 2, 2023 (Table 3).

Table 1: Site fidelity and tag visibility score deterioration observed at Punalu'u, Hawai'i Island, HI from April 2, 2023 to March 24, 2024.

Days	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192
0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
2	5	5					5	5	5			5		5	5
16	5	5	5	2			5	5		3	5	5		5	
29	5	5					4	5		5	5	5		4	
44	4	4	3	4		5	4	3	4	4	5			3	
57	4	5		3			5	5	5	5	5	4		3	
73		5		3		3	2				5	5		5	
86		2		5											
100	2	3	2	5				3			3				
112	2	4			2			1			3			4	
129	1	5		1			1								
142		5			2		2			4	2				
157	1	2	4	4			2	1		4					
171								1							
185		2													
198		2					1	2						4	
212		1		2						2	2				
231		3			3			2			3				
240		1	3									2			1
254			2							1	1	1			
266	1	2					2			1	2	2		2	2
295		2					1				1	2			
309		1									1	3			
330		1	4								3				
344		1									1				
358		1	2							1					
Total:	11	24	9	10	4	3	13	12	4	11	17	11	1	10	4

Table 2: Site fidelity and tag visibility score deterioration observed at Puako, Hawai'i Island, HI from April 16, 2023 to March 31, 2024.

Days	193	194	195	196	197	198	199	200	201	19	120	126
0	5	5	5	5	5	5	5	5	5	5	5	5
6	5						5	5				
20			5	5			5	5				
34				4				5	5	5		
48							5	5	5	5		
61							5	5				
76							5	5				
88	5											
104								5		4		
118	5											
132	5						5					
146								5				
160												
174							5					
187												
201												
216												
230												
244					1		2	1				
258												
286												
300							1	1				
321			1				1					
336												
349												
Total:	5	1	3	3	2	1	11	11	3	4	1	1

Table 3: Site fidelity and tag visibility score deterioration observed at Hualalai, Hawai'i Island, HI from May 7, 2023 to March 31, 2024.

Days	203	204	205	206	207	113
0	5	5	5	5	5	5
5	5		5			
19	5					5
33	5					
46	5		3			
61	5					4
73						
89						
103						
117						
131						
145						
159						
172						
186						
201						
215						
229						
243						
271						
284						
305						
320						
333						
Total:	6	1	2	1	1	3

Behavior Patterns

Feeding and basking behaviors were recorded while conducting surveys at all three locations. Punalu'u and Puako were assessed to compare the amount of percentage of sea turtles observed feeding and basking at each location. At Punalu'u 79.14 ±28.27% sea turtles were observed feeding while at Puako 45.12 ±25.52% sea turtles were observed feeding ($F=43.88$, $p <0.001$). At Punalu'u, 5.56 ±11.61% were observed basking and 21.39 ±21.39% were found to be basking at Puako ($F =48.75$, $p < 0.001$). Zero turtles were observed feeding or basking at Hualalai (Fig. 10).

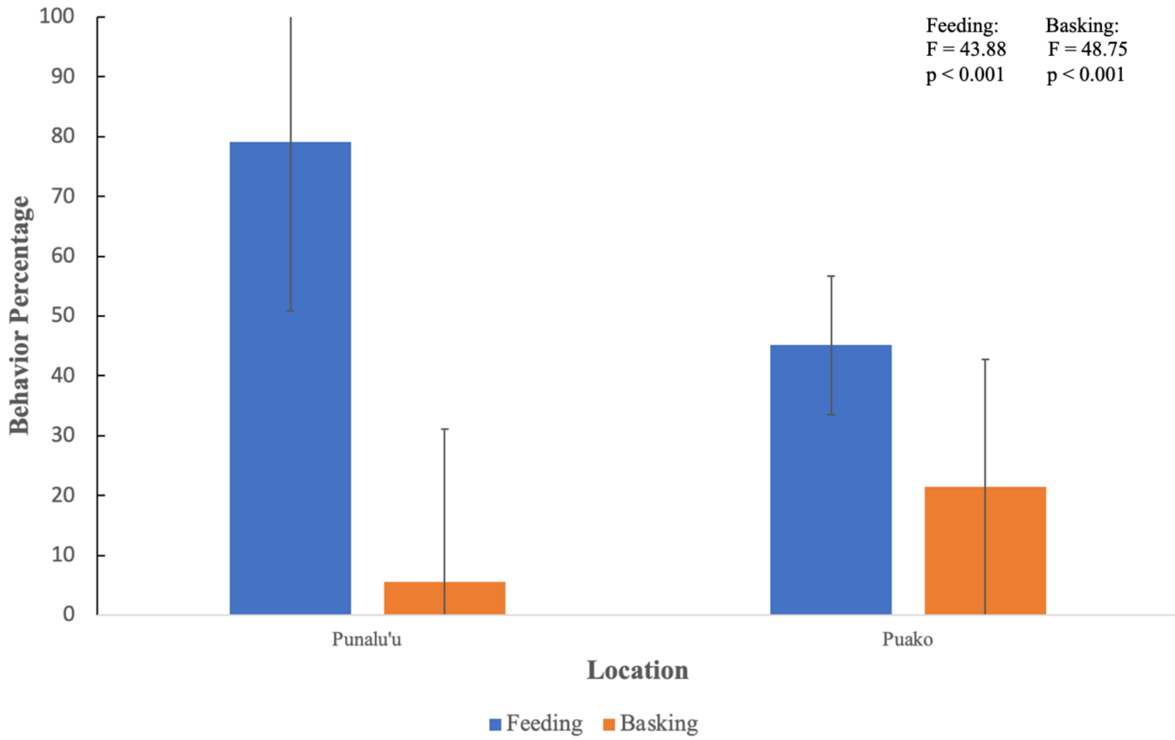

Figure 10: Percentage of sea turtles (± SD) observed feeding and basking at Punalu'u and Puako, Hawai'i Island, HI, USA. Results from a One-way ANOVA are shown in the figure ($\alpha = 0.05$).

The behaviors of sea turtles were also assessed at Punalu'u beach and Puako by month, showing variation over time. There was a significant difference in feeding behavior over the duration of the study at Punalu'u, as feeding behavior was observed ranging from 0.5 ±0.5 (November 2023), to 16 (May 2023). There was not a significant difference in basking behavior observed at Punalu'u beach. Zero basking behavior was observed in May, November, and December 2023, along with January 2024, with the highest amount observed basking of 3.4 ±2.15 in September 2023 ($F = 2.31$, $p < 0.025$) (Fig. 11).

At Puako, there was a significant difference in both feeding and basking behavior over time. Feeding behavior ranged from 2.8 ±2.64 (December 2023) to 13.17 ±7.24 (May 2023) ($F = 4.44$, $p < 0.001$). A higher number of basking sea turtles were present at Puako, ranging from 0.20 ±0.4 (December 2023) to 8.67 ±4.47 (May 2023) ($F = 4.44$, $p < 0.01$) (Fig. 12).

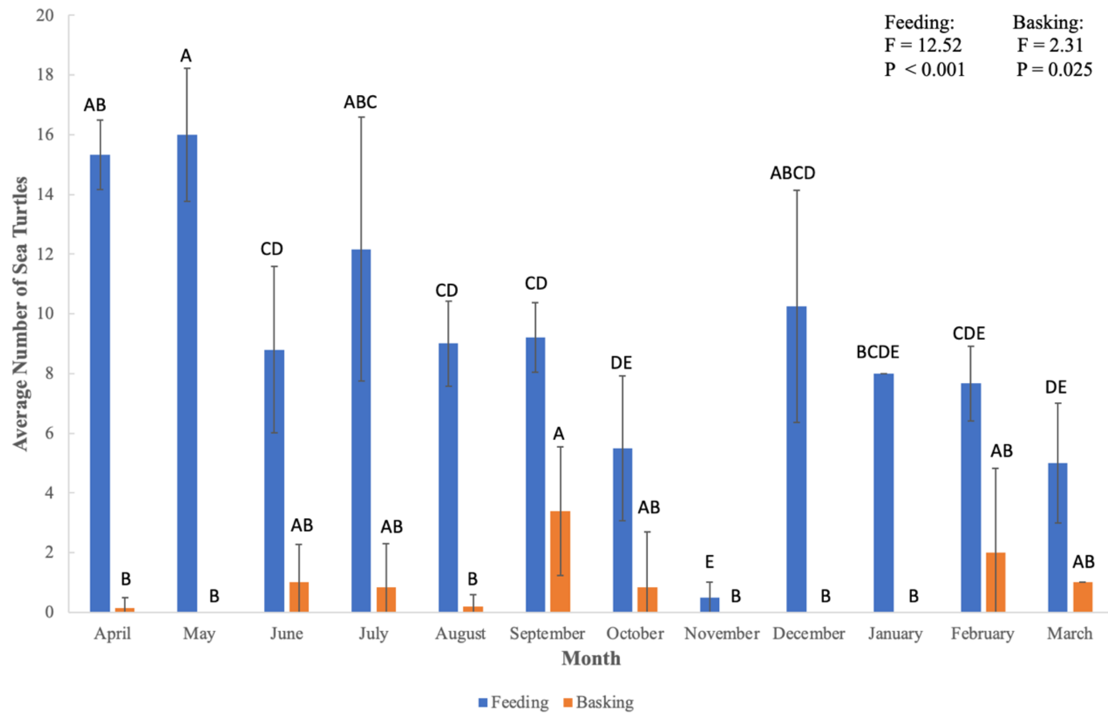

Figure 11: Average number of sea turtles (± SD) observed feeding and basking at Punalu'u beach, Hawai'i Island, HI, from April 2, 2023 to March 24, 2024. Results from a One-way ANOVA and Tukey test are shown in the figure (α = 0.05).

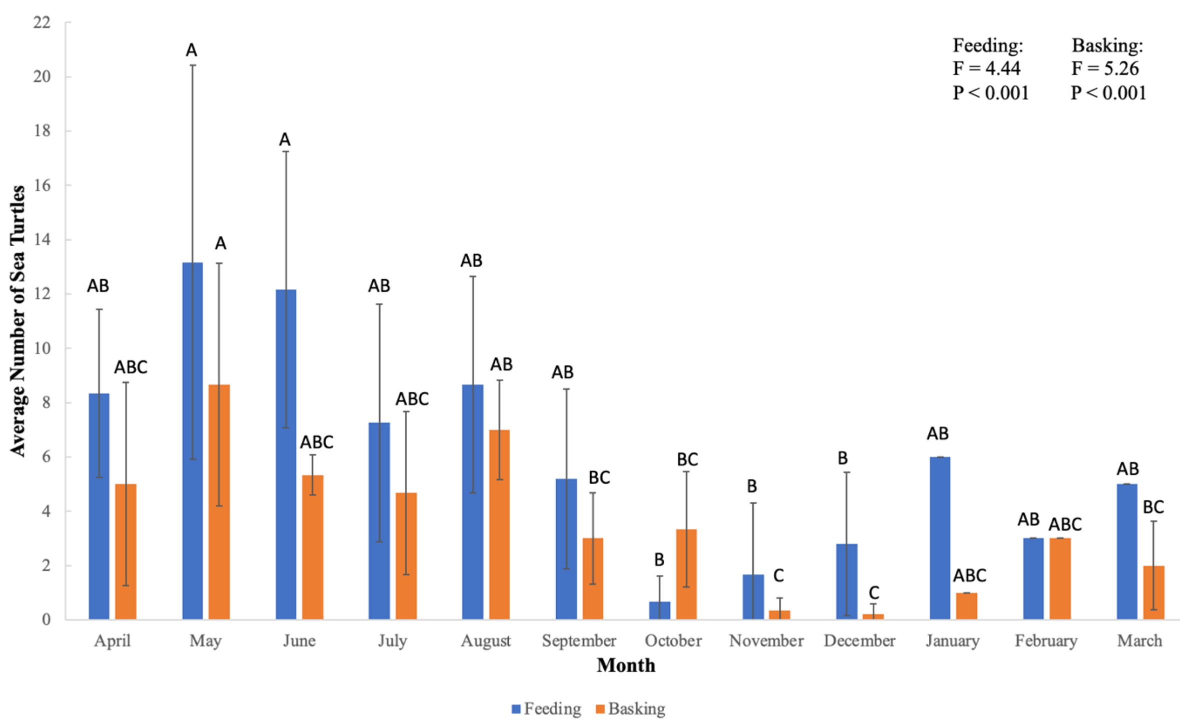

Figure 12: Average number of sea turtles (± SD) observed feeding and basking at Puako, Hawai'i Island, HI from April 17, 2023 to March 31, 2024. Results from a One-way ANOVA and Tukey test are shown in the figure (α = 0.05).

Turtle sizes

At the time of the initial health assessments, the straight carapace length (SCL) of the tagged sea turtles were documented. SCL values have been used as an estimation for sea turtle age classes, and have been assigned the categories of post-oceanic juveniles (<35 cm), juveniles (35 cm to 83 cm), and adults (>83 cm). During snorkel surveys, untagged sea turtle sizes were estimated based on the known sizes of the tagged turtles. There was a significant difference in the size/ages of sea turtles present, with juvenile sea turtles (6.30 ±6.21) being the predominant class per survey, compared to both adults (1.45 ±2.27) and post-oceanic juveniles (0.33 ±0.82) turtles (F=115.70, p <0.001) (Fig. 13).

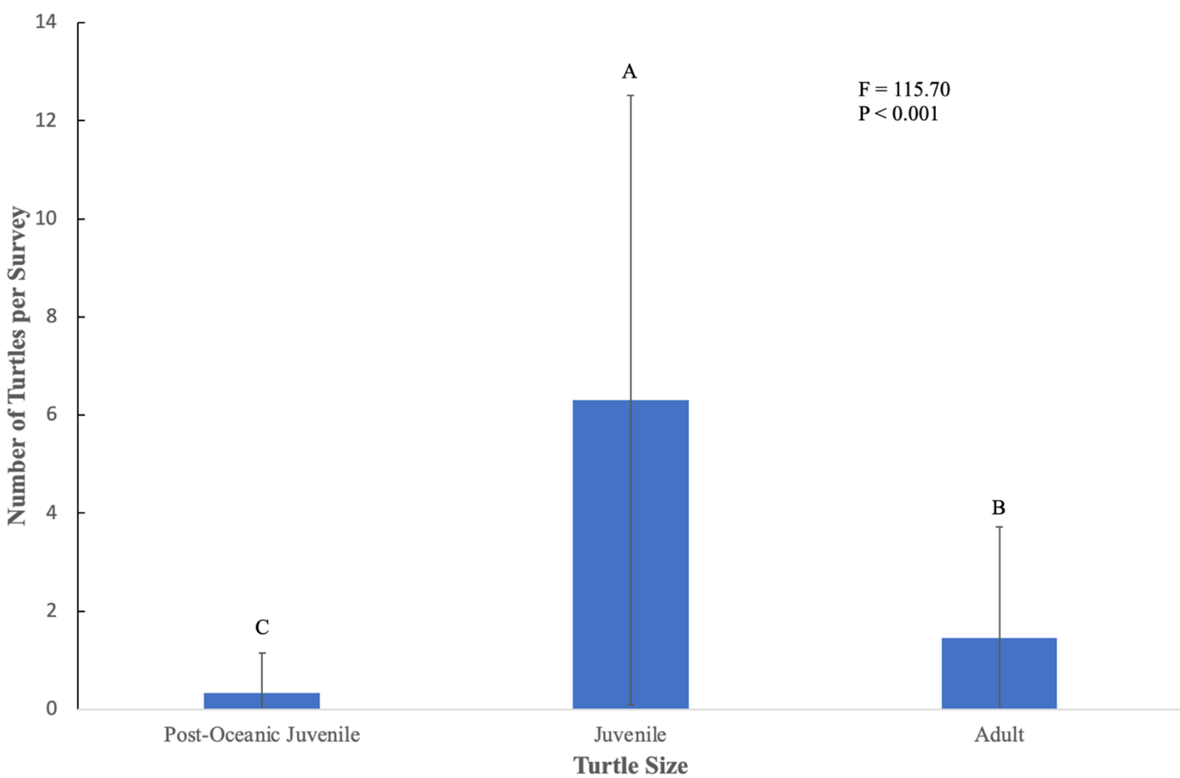

Figure 13: Average number of sea turtles (± SD) counted in each size class, Post-Oceanic Juvenile (<35 cm), Juvenile (35 cm to 83 cm), Adult (>83 cm) of sea turtles observed across Punalu'u beach, Puako, and Hualalai, Hawai'i Island, HI. Results from a One-way ANOVA and Tukey test are shown in the figure (α = 0.05).

Sizes were also compared at each location over the duration of the study, showing a difference between the sizes classes and locations. Juvenile sea turtles at Punalu'u (10.85 ±4.26) and Puako

(9.30 ±5.91) were significantly different from Hualalai (0.55 ± 0.97). There was not a significant difference of post-oceanic juveniles at Punalu'u (0.21 ±0.44), Puako (0.75 ±1.26), however there was a difference at Hualalai (0.06 ±0.23). Adults between Punalu'u (1.35 ±1.4) and Puako (3.32 ±2.89) were not significantly different, compared to none found at Hualalai (Fig. 14).

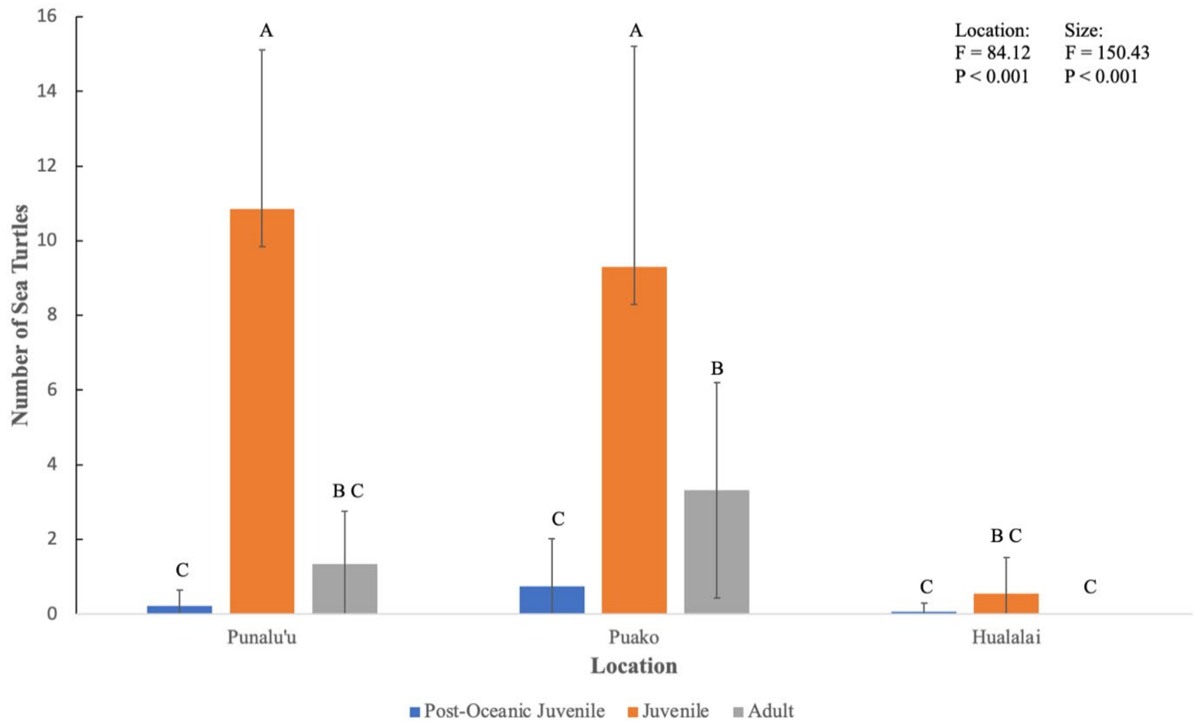

Figure 14: Average size, Post-Oceanic Juvenile (< 35 cm), Juvenile (35 cm to 83 cm), Adult (> 83 cm) of sea turtles (±SD) observed at each location (Punalu'u, Puako, and Hualalai) Hawai'i Island, HI. Results from a Two-way ANOVA and Tukey test are shown in the figure (α = 0.05).

Sexually mature adult green sea turtles are known to emigrate to FFS (May through September) to breed, returning back to their residential foraging grounds when complete (Balazs et al. 2015). For this reason, adult turtles were assessed to determine if there was a change in the number of adults due to this emigration. At Punalu'u beach, the average number of adult sea turtles ranged from 0.25 ± 04.3 to 3.29 ± 1.67, with the lowest number seen in November 2023 and the highest number seen in April 2023 (Fig. 15). At Puako, average adult sea turtles ranged from 0 to 6.33 ± 4.32, with the lowest number of adults present in January (Fig. 15), and highest number present in August. Zero adult sea turtles were observed at Hualalai (Fig. 15).

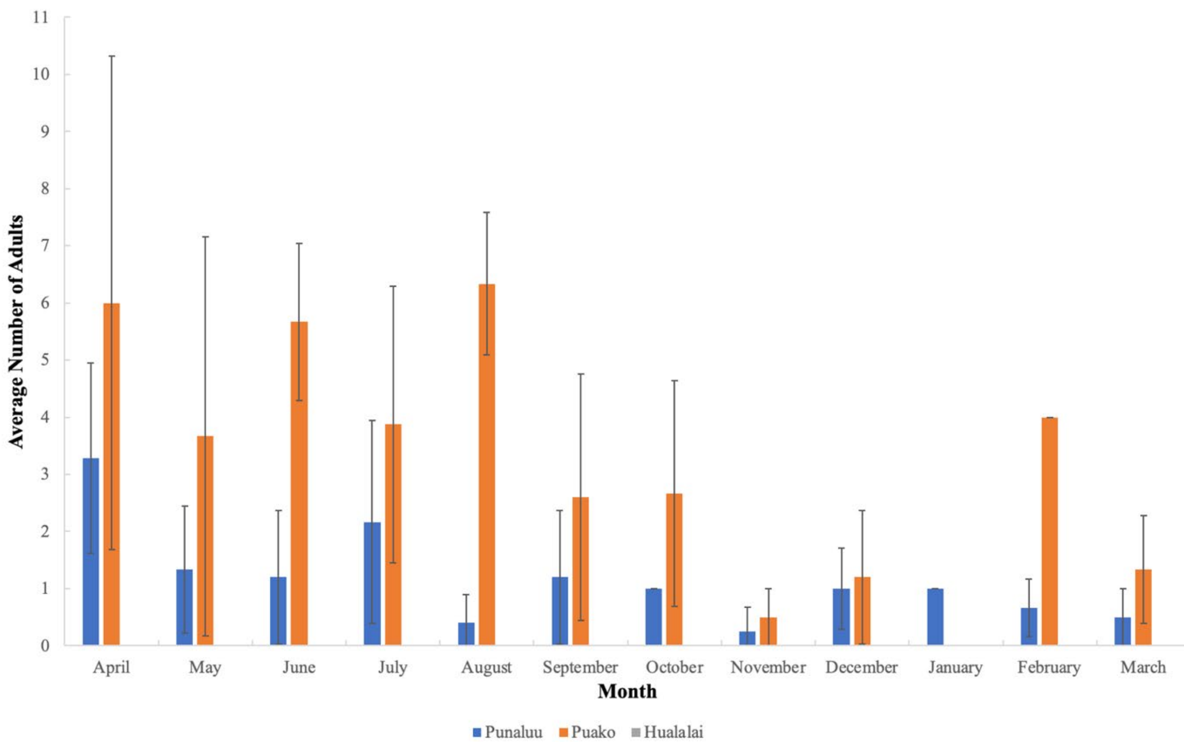

Figure 15: The average number (± SD) of adult (> 83 cm) Hawaiian green sea turtles present per month from April 02, 2023 to March 31, 2024 at Punalu'u beach, Puako, and Hualalai, Hawai'i Island, HI, USA. Results from a One-way ANOVA are shown in the figure ($\alpha = 0.05$).

Population Abundance

Population abundance estimates were calculated using the Lincoln-Peterson model. At Punalu'u beach, 55 surveys were completed over the duration of the study, with 54 surveys having at least one tagged individual present, allowing for calculation. The abundance estimates ranged from 18.75 sea turtles on November 18, 2023 to 120 sea turtles estimated on February 25, 2024, with an population abundance average of 53.45 ±19.49. At Puako, 25 of the 56 surveys had tagged individuals present, with population abundance estimates ranging from 48 sea turtles on March 3, 2024 to 288 sea turtles on August 13, 2023, and an average population abundance estimate of 142.16 ±63.65. Hualalai only had enough data to calculate 15 estimates, ranging from 5 sea turtles on May 7, 2023 to 12.5 on July 2, 2023, and an average abundance estimation of 7.17 ±2.32 sea turtles (Fig. 16).

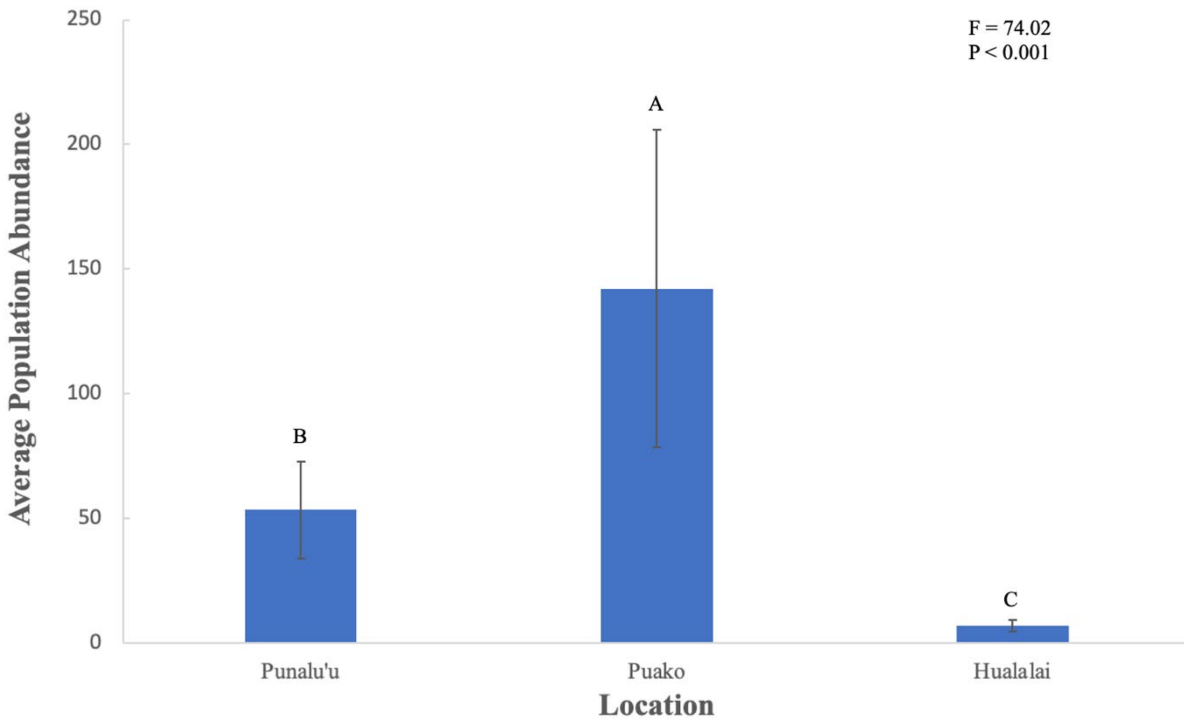

Figure 16: Average population abundance estimates (±SD) using the Lincoln-Peterson index taken at Punalu'u, Puako, and Hualalai, Hawai'i Island, HI.

Concurrent Snorkel and Drone Surveys

A total of 36 concurrent snorkel and drone surveys were conducted during the first survey every week. There was a significant difference in the use of drones compared to in-water snorkel surveys, making in water snorkel surveys more effective with a yield of three sea turtles. Snorkel surveys (12.86 ± 5.57) yielded a higher number of observed sea turtles compared to drones (8.91 ± 3.35). Results from a paired-T Test are shown ($T=5.63$, $p <0.001$) (Fig. 17).

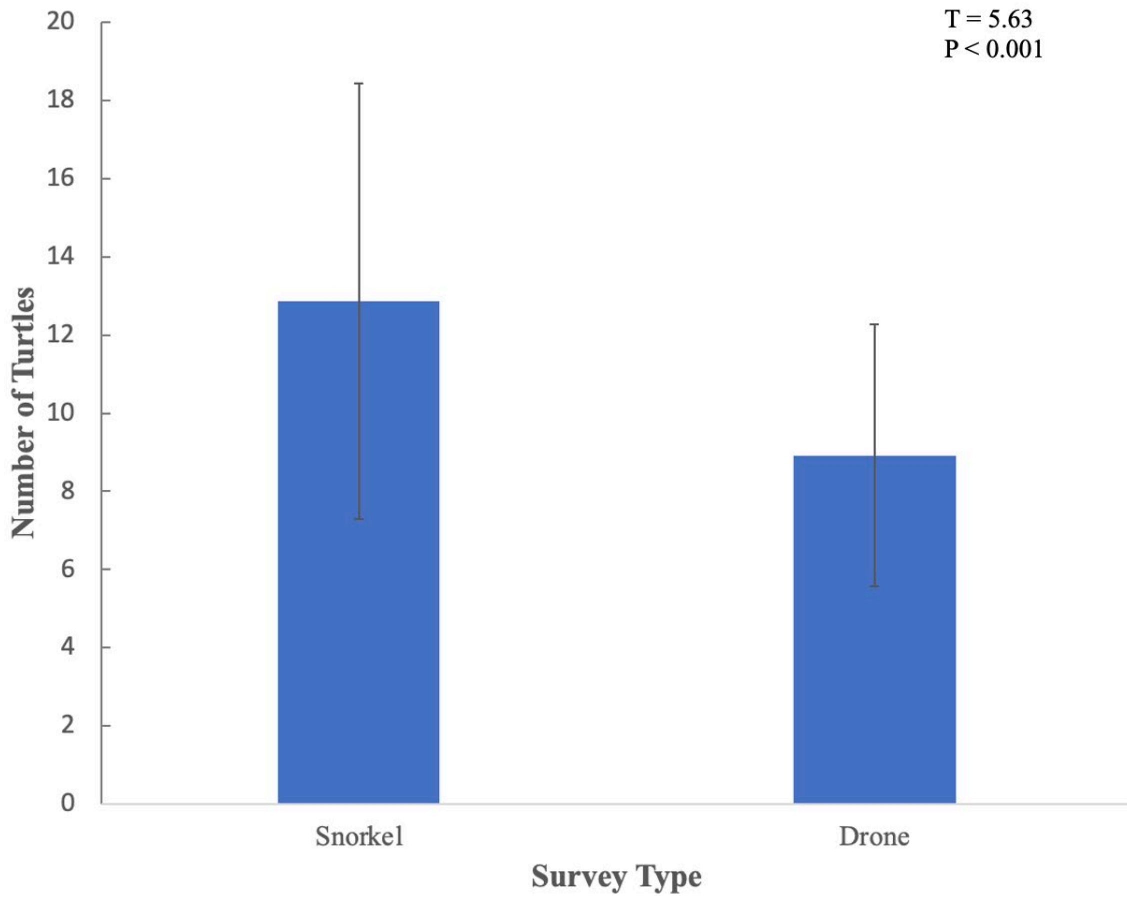

Figure 17: Average number of sea turtles (±SD) observed using snorkel surveys compared to drone surveys conducted on Hawai'i Island, HI, USA. Results from a paired T-Test are shown in the figure ($\alpha = 0.05$).

Discussion

In-water census surveys were utilized to accurately count the number of Hawaiian green sea turtles found across all three locations on Hawai'i Island. The average number of sea turtles observed during each snorkel survey displayed variation across different locations with Hualalai exhibiting a notably lower count of sea turtles compared to both Punalu'u and Puako. The count difference between Puako and Punalu'u was approximately one sea turtle higher at Puako.

Tags remained visible at both Punalu'u and Puako for the duration of the one-year study, even with algal growth coverage. During snorkel surveys, a tag visibility score was assigned based on the amount of algae covering the etched tags. These scores served as an indicator of tag longevity and were an essential component of population abundance estimates. The longevity of the moto tag markings on the sea turtles exceeded expectations, with tag visibility scores remaining high throughout the twelve-month study period at Punalu'u and Puako. This finding suggests that the marking method using the etching technique filled with enamel paint is a viable option for short-term mark-resight studies. Understanding tag longevity is essential for ensuring the accuracy and reliability of mark-resight data, which is used to estimate population abundance and monitor individual movements over time.

Previous field testing at the French Frigate Shoals completed in 1990 and 1991 with the same moto tool etching technique showed that marks usually disappear within six to twelve months. Prior to the completion of this study, it was assumed that the enamel paint would only be visible for weeks to months due to algal coverage across the carapace at Punalu'u Beach (Balazs 1995). However, this was not the observed result. Tag retention visibility remained legible throughout the duration of the twelve-month period study.

One concern associated with moto tool etching is the duration of visibility due to the growth of the keratin layers of the carapace. The carapace of a juvenile green sea turtle is composed of 2-4 cell layers of keratin, which increases to 5-6 layers as the sea turtle ages into adulthood (Solomon et al. 1986). Due to the low protein intake and digestibility in juvenile Hawaiian green sea turtles, somatic growth is extremely slow, with carapace length increasing by approximately 2 cm per year (Bjorndal 1980; Balazs & Chaloupka 2004). Given the slow somatic growth rates of green sea turtles found in Hawai'i, moto tool etched tags have been demonstrated to be a viable option for population surveys.

With no tagged sea turtles found outside of their initial location, site fidelity was found to be highest at Punalu'u beach, followed by Puako area 92, and Hualalai beach. The high site fidelity observed at Punalu'u, with 93.33% of tagged individuals returning to the site over the study period, calls attention to the importance of this location for green sea turtles. Since 1976, site fidelity at Punalu'u has been consistently observed and from 1990-1993, health assessment captures recorded 12 to 26 green sea turtles, with observers noting twenty or more sea turtles actively foraging during surveys, comparable to present numbers (Balazs & Hallacher 1994). The high site fidelity observed at Punalu'u highlights the need for continued protection of this area, while the variation in population abundance estimates between sites emphasizes the importance of habitat diversity and quality.

The study also examined the habitat use and behavior of green sea turtles, focusing on feeding and basking activities. A higher percentage of turtles were observed feeding at Punalu'u compared to Puako, suggesting the presence of richer intertidal red algae (*Pterocladia capillacea*), which is the primary food source found at Punalu'u (Rice et al 2000; Arthur & Balazs 2008). During surveys conducted at Punalu'u, sea turtles were predominantly found to be foraging at the start of observation (approximately 0800 hrs.), with no prior basking activity recorded. A prior study conducted on one green sea turtle over a course of 249 days showed similar foraging behaviors at Punalu'u, with foraging beginning from 0600 hrs. and continued throughout the day (Rice et al 2000).

At Puako, sea turtles were found to be basking prior to the start of surveys (approximately 0800 hrs.), and feeding as a secondary behavior. During low tides at Puako, the rocky composition provided ample space for sea turtles to bask, with at times up to seven sea turtles were seen in one location. Sea turtles can easily move freely through conjoined tide pools when tides are both low and high, as this area can accommodate a larger number of sea turtles compared to Punalu'u and Hualalai. Part of a marine reserve, Hualalai is surrounded by the Four Seasons Resort and comprised of white sandy beaches along with the presence of lava rock. No sea turtles were found to be feeding at this location, which may be the reason for such a small population abundance compared to Punalu'u beach and Puako area 92. With a majority of surveys only recording the presence of zero to one turtle present, behavior patterns were not able to be assessed, however zero turtles were observed to be basking at this location. This information is valuable for habitat management and conservation efforts, as it highlights the importance of protecting areas that support key behaviors such as feeding and basking.

While in situ, known measured turtles were used as a reference to assign size classes to unmarked turtles that were observed during in-water survey counts. With sea turtles broken down into three size classes, juveniles ranging in size from 35 cm to 83 cm were the predominant size class, compared to post-oceanic juveniles and adults. While this does highlight the importance of foraging grounds and growth rates, it is important to note the few adults that were observed at Punalu'u and Puako, which will be discussed with relation to population abundance.

Post-oceanic juvenile, estimated to be 6 years for Hawaiian stock, return to neritic habitats and grow slowly into sexually mature adults (Balazs & Chaloupka 2004). While most studies have focused on long-term nesting females, there is a need for stage-based population models to highlight mortality rates in subadults and adults affected by natural and anthropogenic activities (Siegwalt et al. 2020). Species with long generation times have recovery times dependent on age of maturity and population abundance estimates, making use of demographic indicators an important aspect of population modeling (Piacenza et al 2016).

The study revealed significant differences in population abundance estimates between the three study sites. Due to the minimal data obtained from Hualalai, a focus on Puako showed three times the number of sea turtles compared to Punalu'u, even though approximately the same number of sea turtles were observed during surveys conducted at these two locations. This variation could be attributed to differences in habitat quality, food availability, or other environmental factors.

Sea turtles are a long-lived species, who recruit to a feeding environment as post-oceanic juveniles and have shown strong site fidelity throughout their life history, leaving only to reproduce (Balazs & Chaloupka 2004). Two assumptions of the Lincoln-Peterson model is that of a closed system and minimal mortality. If sea turtles were observed leaving these habitats and appearing at other regions across the archipelago, it would not be a fair assumption of a closed system, and abundance models such as the Lincoln-Peterson population model may not be a viable option. However, as seen with the lack of movement of adults at Punalu'u and Puako during breeding months, which may be due to lack of sexual maturity, the parameters of this study can be applied to this modeling technique. The second assumption of a closed system is little mortality. A shift in daytime foraging noted since the early 1990s can be an indicator of reduced mortality, as hunting pressures from humans are no longer and the lack of observed interactions with large sharks in the bay have been documented (Balazs & Hallacher 1994).

A limitation of this method is the occasional absence of tag recordings on several days, which renders it impossible to calculate population abundance for those surveys, as the presence of tags is necessary for such calculations. This issue was particularly notable at Hualalai, where no tags were found after 90 days, rendering several months of data unusable for calculation. However, this data does highlight the scarcity of sea turtles in the area, suggesting the presence of a very small population.

Anthropogenic factors are increasingly impacting marine life, threatening population size and growth, necessitating population abundance estimates to assess the conservation status of species listed on the IUCN Red List of Threatened Species (Hammond et al. 2021). Two encounters observed during surveys with entangled sea turtles in fishing line underscore the impact of anthropogenic activities on sea turtle populations. While these incidents may seem small in number compared to the total observed population, they highlight the need for continued efforts to reduce negative interactions between sea turtles and human activities, such as implementing measures to reduce incidental catch and promoting responsible fishing practices.

The last component of this study compared the efficacy of drone-based surveys with traditional in-water snorkel surveys for monitoring sea turtle populations. While drones offer a cost-effective and non-invasive method for data collection, the study found that in-water snorkel surveys yielded higher numbers of observed sea turtles. This suggests that a combination of both methods may provide the most comprehensive data for population monitoring and conservation management.

Aerial surveys offer a valuable method for estimating sea turtle populations at foraging grounds. However, due to the species' behavior, with more than 90% of their time spent underwater, accounting for this lack of surface time is crucial (Katsanevakis et al. 2012). Snorkeling surveys provide a complementary approach, enabling the assessment of abundance as well as additional characteristics such as size, sex, the presence of fibropapillomatosis (FP) tumors, and potential entanglement, which may be overlooked from an elevated observation point (Roos et al. 2005).

Punalu'u Beach is characterized by a sheltered bay where sea turtles frequently move into shallower waters to feed and use the shoreline for basking (Rice et al. 2000). The Puako Bay shoreline extends approximately 5 km, with area 92 being its central point. Surveys were conducted during daylight hours, as this provided the clearest visibility for both snorkel and drone surveys. Additionally, cloudy overcast conditions helped reduce glare from the sun (Tait et al. 2021). During concurrent in-water snorkel and aerial drone surveys, it was observed that snorkel surveys yielded higher counts of sea turtles compared to drone video footage.

A limitation observed with snorkel surveys is the challenge posed by water quality and turbidity, particularly evident at Punalu'u Beach. The influx of freshwater into Punalu'u occasionally led to compromised visibility due to brackish water and excessive debris, necessitating the use of drones to accurately assess sea turtle counts under such conditions (Colefax et al. 2017). There were also times when wave heights and currents may have been considered unsafe, resulting in reduced survey times conducted that week. Another issue identified was the limited coverage range for a single surveyor, which was insufficient for effectively monitoring the entire shoreline (O'Neal 2007). The movement of sea turtles beyond the survey area before being sighted could have resulted in missed sightings and inaccurate counts. To address this, the involvement of multiple surveyors, each responsible for a specific area of the coastline, may improve the accuracy of counts and reduce the likelihood of missed sightings (O'Neal 2007).

Human presence can introduce a potential bias in snorkel survey data, as sea turtles may perceive humans as a threat. While this behavior was not evident at tourist-rich beaches like Punalu'u, where sea turtles are accustomed to human activity in the water, it could be more pronounced in less frequented areas such as Puako, which is not a typical tourist destination. During surveys, Punalu'u often experienced high tourist traffic, with visitors exploring the black sand beach and attempting snorkeling to observe sea turtles in their natural habitat. In contrast, Puako had minimal human presence in the water, with rare sightings of spear fishers or small SCUBA dive groups consisting of three to four divers.

One challenge associated with using aerial footage at Punalu'u Beach is the composition of the sand. The beach is made up of black sand basalt, which is reflective, often causing the coloration of Hawaiian green sea turtle carapaces to blend into the environment (Colefax et al. 2017). Even with a polarizer attached to the camera lens, detecting the presence of sea turtles was sometimes difficult. Moreover, the coastline exceeded the camera's field of view when hovering at 30 meters above, making complete coverage of the entire bay unfeasible and allowing sea turtles to maneuver undetected.

While the sand composition cannot be altered, advancements in technology that lead to higher-quality video footage could allow surveys to be conducted for longer periods throughout the day, regardless of sun glare and positioning (Colefax et al. 2017). To address the limited field of view, an additional drone could be flown further down the shoreline, overlapping the field of view of the first drone to ensure complete coverage of the entire site. As drone technology improves and the costs of commercial drones decrease, the coverage of samples could significantly increase, potentially reducing the need for multiple drones (Colefax et al. 2017).

Conclusions

Overall, the findings of this study provide a basis for informed conservation strategies and highlight the importance of continued research and monitoring efforts to ensure the long-term survival of endangered species. The use of moto tool etching is shown to be an effective tool in observing sea turtles to gain valuable information on their site fidelity and ecology on Hawai'i Island, HI. This study also highlights the sensitivity of certain sites, such as Punalu'u in comparison to Puako where even minor impacts on these areas could have significant repercussions on the broader population.

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