Heeding the History of Kahu Manō*:* Developing and Validating a Pono Photo-Identification Methodology for Tiger Sharks (*Galeocerdo cuvier*) in Hawaiʻi

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Abstract

Amidst concurrent global declines in shark populations and advancements in camera technology, underwater photo-identification (photo-ID) is increasingly being used to unobtrusively gather data on potentially sensitive species. Tiger sharks (*Galeocerdo cuvier*) are prime photo-ID candidates, particularly in places where population data is scarce and they hold a significant role in customary practices and beliefs, such as Hawaiʻi. This study emulates traditional Hawaiian practices of kahu manō, i.e., shark keepers, through implementation of non-intrusive contemporary approaches to develop, assess, and validate photo-ID methodology as a pono, or respectfully appropriate, technique for tiger shark research in Hawaiʻi. An identification system reliant on chronologically subdividing the dataset based on sex and caudal fin condition and then using 14 identifiable traits to match unknown tiger sharks to a database of previously sighted individuals was developed. This identification system complements Native Hawaiian approaches of observation and anaylsis, such as kilo and the papakū makawalu process developed by the Edith Kanakaʻole Foundation. Volunteers with varying experience with tiger sharks and photo-ID, were trained to use this identification system and exhibited > 90% agreement in tiger shark ID with each other and the method developer. The time taken by an observer to identify an individual negatively influenced the probability of agreement with other observers, including the expert observer. In contrast, observer-reported certainty positively influenced the probability of agreement. This validated method was used to ID individual tiger sharks (n=69) in West Hawaiʻi during 2005-2021, including the observation of 1 male shark and 1 female shark across 16 years. This study identifies important parameters of photo-ID that can aid future photo-ID experimental design and demonstrates the capacity for safe and respectful research methods that parallel Native Hawaiian cultural practices. The validation of underwater

photo-ID methodology contributes an important non-invasive approach to research and inform management in Hawai‘i, and its continued implementation and accompanying analyses as pono scientific techniques have the potential to obtain meaningful life-history information on an important ecological and cultural species.

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1. **Introduction**

1.1 Photo-Identification

Photo-identification, i.e., photo-ID, is the process of capturing imagery of an organism and using unique natural marks to identify and differentiate between individuals of a population, which can be used in lieu of more traditional mark-recapture or mark-resight approaches (Otis et al. 1978). This approach differs from typical mark-recapture studies in that target species need not be captured or handled to obtain data (Marshall & Pierce 2012). Prime candidate species for photo-ID tend to be large-bodied, long-lived, mobile vertebrates with a high proportion of identifiable individuals that can be re-identified over time (Würsig et al. 1990, Marshall & Pierce 2012). Species with phenotypic patterns that are highly variable among individuals are preferred; however, photo-ID has been utilized on elasmobranchs, such as nurse sharks (*Ginglymostoma cirratum)*, where only 46% of recorded individuals exhibited unique and distinguishable characteristics (Castro & Rosa 2005). In cases where the targeted species lacks unique and readily distinguishable characteristics, photo-ID can still be applied by focusing attention on scars or artificial marker tags (Kohler & Turner 2001, Castro & Rosa 2005). However, artifical marker tags can be shed or obscured by biofouling, while the healing of temporary marks, such as wounds and scars, can lead to re-sight errors and limit reliability of photo-ID data dependent upon such features (Rowat et al. 2009). Using natural marks, such as coloration patterns, in photo-ID can alleviate many of these issues, but only for species with stable and unique marks.

As photo-ID has gained popularity as a surrogate for tagging or otherwise physically marking individuals, the analytical methods using photo-ID data to extract meaningful information about the behavior, biology, and ecology of the targeted species have also become increasingly varied and complex (Castro & Rosa 2005, Marshall & Pierce 2012). Population models are increasingly capable of handling valid photo-ID-based mark-resight data to estimate population size and demographic patterns; however, these applications require a number of assumptions about photo-ID data that are comparable to those made with more traditional mark-recapture data (Hammond 2009, Marshall & Pierce 2012, Choo et al. 2020). Mark-recapture and photo-ID assumptions include the use of marks that are unique enough to reliably distingush individuals without error and are retained so that individuals can be re-identified for the duration of the study (Hammond 2009, Marshall & Pierce 2012). Despite the uncertainty about the degree to which photo-ID data satisfies these assumptions, far less attention is spent on preliminary validation and standardization of the multitude of photo-ID methodologies implemented by various research studies (Urian et al. 2015). Therefore, there is a need to understand the types and sources of error involved in the nuanced process of photo-ID analysis techniques to ensure data products are valid and accurate and can be appropriately applied to various ecological research questions (Yoshizaki et al. 2009, Urian et al. 2015).

Photo-ID assumptions can be violated due to errors that impair the accuracy of their methods. These errors include evolving natural tag errors, i.e., a change in an individual's pattern; non-evolving natural tag errors, i.e., insufficient image quality to make an ID; misidentification due to false positive errors, i.e., an observer incorrectly matches an image to a different individual; and misidentification due to false negative errors, i.e., an observer incorrectly determines an image as a new individual when it matches an individual in the known database (Stevick et al. 2001, Yoshizaki et al. 2009, Choo et al. 2020). False positive errors can negatively bias abundance estimates, while false negative errors can postively bias abundance estimates (Yoshizaki et al. 2009, Urian et al. 2015). Even though the impact of ID errors is relatively small compared to the variability typically seen in modeled estimates of population parameters (Stevick et al. 2001), these errors can undermine the confidence of resource managers and the public in the utility of such models to forecast changes in population size (Urian et al. 2015, Choo et al. 2020). Biases associated with potential ID errors can be reduced by validating approaches, standardizing photography and image match making methods, and by screening images to ensure only high-quality images are used (Stevick et al. 2001, Hammond 2009, Marshall & Pierce 2012, Urian et al. 2015).

1.2 Elasmobranchs and the Relevance of Photo-ID

The use of photo-ID in elasmobranch research dates back the 1970s (Myrberg & Gruber 1974) and has been used to estimate population parameters for several species, including white sharks (*Carcharodon carcharias*) for over 22 years (Anderson et al. 2011) and reef mantas (*Manta alfredi*) for over 30 years (Couturier et al. 2014). While photo-ID approaches have inherent limitations, the minimal impact that this approach has on targeted species compared to tagging and other mark-recapture methods coupled with advances in digital photography have led to increased integration of this method for monitoring elasmobranch species as populations have declined globally. Approximately 25% of all elasmobranch species are currently facing extinction, and as a taxonomic grouping, elasmobranchs have the highest fraction of species of concern among all vertebrate groups currently studied (Dulvy et al. 2014). Thus, application of photo-ID approaches to study elasmobranch populations is increasingly common due to being inexpensive and non-invasive relative to conventional tagging methods (Manire & Gruber 1991, Barrowman & Myers 1996, Dicken et al. 2006, Wilson & McMahon 2006). Traditional tagging methods are often invasive, frequently requiring the capture and restraint of the target species, which can lead to mortality or result in short-term negative impacts (Kohler & Turner 2001), and long-term negative impacts that potentially affect fitness, such as reduced growth or reproductive rates (Dicken et al. 2006, Lewin et al. 2006).

Photo-ID is a visual survey technique that is therefore also subjected to potential biases during the image capture process. Observational biases can differ depending on behavioral or environmental variability of the studied organism (Cagua et al. 2015), as well as the skill of the photographer in properly capturing their unique traits (Davies et al. 2012). Many shark and cetacean photo-ID studies employ above-water photography to exclusively capture images of dorsal or caudal fins for photo-ID, and rely on scars, tears, and notches to differentiate individuals (Anderson et al. 2011, Sims et al. 2000, Würsig et al. 1990). The use of underwater photo-ID for elasmobranchs allows for the use of additional traits such as pigment patterns, and additional fins and surfaces to be included (Domeier & Nasby-Lucas 2007). The utilization of multiple unique areas and traits can improve accuracy of identifying re-sighted individuals by providing additional features to validate repeated identification (Domeier & Nasby-Lucas 2007, Dureuil et al. 2015). Consequently, elasmobranch photo-ID studies are viable for species with uniquely identifiable traits that are approachable so that observers can safely and readily photograph them (Marshall & Pierce 2012).

1.3 Tiger Sharks

Tiger sharks *Galeocerdo cuvier* are large elasmobranch apex-predators found in tropical and temperate oceans worldwide (Randall 1992, Castro 2010). They are listed as near threatened by the International Union for Conservation of Nature (IUCN) primarily due to unsustainable fishing pressure (Ferreira & Simpfendorfer 2019, Simpfendorfer 2009). Tiger sharks have the potential for long-distance movement and oceanic dispersal, yet most tagged tiger sharks exhibit some degree of site fidelity (Hazin et al. 2013, Holmes et al. 2014, Werry et al. 2014, Acuña-Marrero et al. 2017), including those in the Hawaiian Archipelago (Tricas et al. 1981; Holland et al. 1999; Meyer et al. 2009, 2018; Papastamatiou et al. 2010, 2013; Holmes et al. 2017).

The home ranges of tiger sharks in the Hawaiian Archipelago are primarily focused on a core use area consisting of a single island and even though individuals exhibit frequent long distance inter-island movements, they make repeated returns to this core use area (Holland et al. 1999; Lowe et al. 2006; Papastamatiou et al. 2013). The population in Hawai‘i exhibits lower genetic diversity relative to other Pacific populations (Bernard et al. 2016), which can potentially be attributed to limited connectivity and isolation of the Hawaiian Archipelago. The lower genetic diversity of the tiger shark population in Hawai‘i was exacerbated by culling efforts that killed at least 554 tiger sharks in the Main Hawaiian Islands (MHI) during 1959 – 1976 (Wetherbee et al. 1994). These shark culling efforts combined with heavy fishing pressure have reduced overall apex-predator biomass in the MHI relative to that in the adjacent yet protected Northwestern Hawaiian Islands (NWHI; Friedlander & Demartini 2002), despite the potential for sharks and other large predators to move between islands.

The impact of the loss of apex predators, such as tiger sharks, from the nearshore habitats in the MHI can cascade through the ecosystem and lead to detrimental changes in fish assemblage structure, nutrient dynamics, and coral reef resilience (Sandin et al. 2008; Barley et al. 2017). Ensuring healthy populations of tiger sharks and other apex predators is important to maintain the ecological integrity of nearshore habitats in the MHI, particularly following human-induced trophic shifts of fish assemblages and the recent unprecedented bleaching of coral in Hawai‘i (Friedlander & Demartini 2002; Couch et al. 2017). Previous fishing and culling efforts and the subsequent reduction in MHI apex predator biomass and tiger shark genetic diversity in Hawai‘i strongly highlight the need for current and future tiger shark studies to minimize mortality and negative impacts, and to promote non-intrusive research.

1.4 Hawaiian Beliefs and Sharks

In Hawai‘i, sharks in general are among the most universally worshipped individuals as ‘aumakua, or ancestral family deities (Emerson 1892, Puniwai 2020). Based on written and oral descriptions, tiger sharks likely represented one of the prevalent species of potential ‘aumakua sharks (Beckwith 1917). Sharks also feature prominently in Hawaiian mo‘olelo, or stories and oral histories, and are associated with many different places, deities, and practices (Pukui & Johnson 1971, Puniwai 2020). It is important to note that within Hawaiian beliefs and in Hawaiian epistemology, the land and sea as well as all its non-human inhabitants are believed to have existed and been born before humans (Johnson 2000). Hawaiians are and were born as children of the land, and as told in mo‘olelo, or history, are the younger relatives of these islands, its inhabitants, and its elemental deitites. Therefore, Hawaiians believe and act with an understanding of reciprocity between human and natural systems and treat natural systems with the respect and reverence given to an elder relative (Anderson-Fung & Maly 2002, Andrade 2013, Kurashima et al. 2018).

The cultural importance of sharks to Native Hawaiians is further highlighted by the existence of kahu manō, or shark keepers, whose kuleana, or responsibility, included the care, observation, and worship of patron sharks (Emerson 1892, Beckwith 1917). Hawaiian practices of kilo, or methodology of conscious and analytical observation (Morishige et al. 2018), and papakū makawalu, or the outlook and methodology of deconstructing layers of embedded meaning of natural systems through dynamic observation and images (Huaman 2019, Wilson-Hokowhitu 2019, Kanahele-Mossman & Karides 2021) complement photo-ID techniques to non-invasively study individually identify and name sharks and to study their biology, demography, communal function/role and genealogy. The results of the practice of kahu manō can be seen in the historical description of each coastal locality in Hawaiʻi having named sharks whose history, appearance, and home range were well known by the people (Emerson 1892, Beckwith 1917).

This potential for elevated significance in Hawaiian cultural and spiritual beliefs entails pono, or proper, behavior while seeking to interact with sharks to ensure no harm or negative impacts may come to sharks or the Hawaiian community and their practices. Contemporary science methods, particularly invasive tagging, can be viewed as problematic and a source of conflict considering these aspects of Hawaiian beliefs and epistemology. As such, the creative development and use of appropriate and pono methods to observe and assess sharks are necessary to respectfully conduct research in Hawaiʻi. These same techniques can be applied to shark research elsewhere to ensure responsible methods are used to study sharks that minimize impact or disturbance of these important predators.

Considering the cultural and ecological history of tiger sharks in Hawaiʻi, there is a responsibility and benefit to use non-invasive research techniques. As large-bodied, long-lived, mobile vertebrates with variable stripe patterns that are easily approachable and photographable, tiger sharks are prime candidates for photo-ID. Additionally, photo-ID derived from underwater photography allows for a tiger shark's bilaterally asymmetrical pigment patterns and collection of fins to be incorporated into the photo-ID methodology. Therefore, the objective of this study is to incorporate traditional Hawaiian knowledge tools and practices of kahu manō with non-intrusive contemporary approaches to develop, assess, and validate underwater photo-ID methodology for tiger sharks that can respectfully be used to conduct research in Hawai‘i.

2. Methods

2.1 Dive Surveys

Surveys were conducted at sites (n = 3) along the west, or leeward, coast of Hawai‘i Island (Figure 1). Exact locations have been withheld due to the cultural importance of the locations and concerns of potential commercial exploitation voiced by members of the local communities. Sites were chosen in part for their historic and cultural significance, as places having traditional practices involving sharks, and therefore have a fair reliability of encountering sharks, particularly tiger sharks. Sites were located ≤ 500 m from shore at a depth range of 5 - 30 m. Habitats were similar across sites and were characterized by well-developed fringing reefs at shallower depths (0-10m) transitioning to ledges at 10-25m and dropping to deeper patch reefs surrounded by sand (>25m).

Images of sharks were collected by volunteer divers using open-circuit SCUBA during 2005 - 2021. Divers would capture images of sharks opportunistically while conducting dives with the non-profit organization, Mālama Manō. Image collection was opportunistic and relied on the availability of volunteers and sighting of sharks during their dives; therefore, effort was not uniformly distributed between years or locations. Dives were not conducted under the auspices of the University of Hawai‘i, but, and all divers were volunteers of Mālama Manō. The volunteers that contributed imagery that was used for this study possessed extensive dive experience, an understanding of shark behavior, and working knowledge of Hawaiian culture. Divers also conducted themselves in accordance with local laws and with respect to the wishes of the culture and communities of the study area. Images were only obtained from this non-profit, as public solicitation would not have ensured diver safety, as well as the safety and respect of the sharks being observed, and working with Mālama Manō assured the image collection does not impact the sharks or the cultural practices of local communities associated with the sites.

No set search patterns or specific methodology to photograph sharks were employed on the dives; however, the same general areas were visited. When a tiger shark was encountered, the divers collected images at the same depth as the shark to obtain pictures and/or videos of the shark from a perpendicular angle. This ensured that the following features could potentially be captured on both sides of each tiger shark: body stripe pattern, head and body countershading delineation, profile and pigment patterns of fins, and pelvic region for determining sex (Figure 2). Immediately following the dives, the non-profit volunteers would record the number and sex of tiger sharks seen for their own records, as well as other initial kilo such as obvious unique traits, behavior, and environmental conditions.

2.2 Images

For consistency, the term 'images' will be used henceforth to refer to both digital photographs and still frames captured from digital video files. Images were obtained using a variety of high resolution ≥ 1080p HD video or ≥ 12 megapixels still image digital cameras in underwater housings equipped with wide angle lenses. False negative ID errors are known to increase with low image quality (Stevick et al. 2001), so this study used only high-quality images that clearly captured more than one identifiable trait of a shark for subsequent ID analysis. Diver notes were referenced while examining the images to compare and discern between images and captured traits of every individual from a single day. Image files were renamed to include date, location, and a temporary designation to denote the chronological order of recorded individuals, e.g., Temp1-TempN, where N is the total number of tiger sharks seen at that location on that date. The selected and renamed images may then be compared across survey days to photo-ID them.

2.3 Tiger Shark Photo-ID Traits

This study identified tiger sharks as having seven unique and identifiable traits on each side: the countershading delineations on the head and body; the size, shape, and margins of the pectoral, dorsal, caudal, and rear (i.e., secondary dorsal, pelvic, and anal) fins, and the body stripe pattern (Figure 2) which results in a total of 14 potential unique and identifiable traits per individual tiger shark.

2.3.1 Stripe Pattern

Tiger shark stripe patterns consist of dark pigmented bars over lighter pigmented skin on their dorsal surfaces that start from their gills and extending along both lateral surfaces of their bodies onto their flanks and tails (Randall 1992, Castro 2010). These bilaterally asymmetrical stripe patterns were subjected to visual examination comparing the grouping and distance between stripes, the size and shape of unique stripes, and the location of unique stripes in proximity to reference points, such as gill slits, fin bases, fin insertion points, and fin rear tips (Figure 3). While many describe juvenile tiger shark patterns as being more spot-like before lengthening and fusing into vertical stripes as they grow, images of an estimated 55-cm neonate tiger shark show a vibrant and distinct stripe pattern (Cambra et al. 2021). There are anecdotal accounts of patterns fading in vibrancy with age, but no evidence suggests the pattern changes or fades beyond recognition.

2.3.2 Countershading Delineation

Countershading delineation is the abrupt transition in coloration between the darker dorsal surfaces and lighter ventral surfaces (Cott 1940, Wilson & Martin 2003). The head region forward of the pectoral fin and the body region flanking the pectoral fin were used as separate photo-ID traits. The head countershading delineation was visually examined by comparing intruding pieces of contrasted pigments, and the complexity, pattern, and amplitude/breadth of height of the delineation in relation to reference points that include the labial furrow, jaw, eye, spiracle, gills, and pectoral fin of a tiger shark's head region (Figure 4). The body countershading delineation also was visually examined by comparing intruding pieces of contrasted pigments, and the complexity, pattern, and breadth of amplitude/height of the delineation in relation to reference points that include the pectoral fin, dorsal fin, unique stripe pattern, and pelvic fin of a tiger shark's lateral surface (Figure 5).

2.3.3 Dorsal Fin

The dorsal fin and its bilaterally asymmetrical stripe pattern extending onto either side allowed the dorsal fin to be identified as a tiger shark photo-ID trait for each side of the shark. A tiger shark's dorsal fin was visually examined by comparing height, width, shape, and condition of its profile, as well its stripe pattern and the depth and location of notches or tears in relation to reference points that include the dorsal fin's base, apex, insertion point, and rear tip (Figure 6). Previous elasmobranch photo-ID studies highlight the potential for fin profiles to change (Anderson et al. 2011, Domeier & Nasby-Lucas 2007, Dureuil et al. 2015). Observers were therefore trained to recognize lower trait stability when comparing this trait, and the importance to incorporate more stable traits to confirm ID.

2.3.4 Pectoral Fin

The pectoral fins and their bilaterally asymetrical pigment pattern and uneven wear allowed the pectoral fins to be identified as a tiger sharks photo-ID trait for each side of the shark. A tiger shark's pectoral fin was visually examined by comparing height, width, shape, and condition of its profile, as well its pigmentation pattern and the depth and location of notches or tears in relation to reference points that include the pectoral fin's base, lateral tip, insertion point, and rear tip (Figure 7). Like with the dorsal fin, observers were trained to recognize lower trait stability when comparing these fin traits, and the importance to incorporate more stable traits to confirm ID.

2.3.5 Rear Fins

The rear fins (i.e., secondary dorsal fin, pelvic fins, and anal fin) and their bilaterally asymetrical pigment pattern and uneven wear allowed them to be identified as a tiger sharks photo-ID trait for each side of the shark. A tiger shark's rear fins were visually examined by comparing height, width, shape, and condition of each fin's profile, as well the stripe pattern, countershading delineation, and the depth and location of notches or tears in relation to reference points that include the keel, caudal pit, and base, tips, and insertion points of each rear fin (Figure 8). Like the other fins, observers were trained to recognize lower trait stability when comparing these fin traits, and the importance to incorporate more stable traits to confirm ID.

2.3.6 Caudal Fin

Similar to the other fins, the tail or caudal fin and its bilaterally asymmetrical stripe pattern extending onto either side allowed it to be identified as a tiger shark photo-ID trait for each side of the shark. A tiger shark's caudal fin was visually examined by comparing height, width, shape, and condition of the profile of both the upper and lower lobe, the presence and condition of the terminal lobe and subterminal notch, as well its stripe pattern and the depth and location of notches or tears in relation to reference points that include the caudal pit, caudal keel, caudal fork, and upper and lower tip of each tail lobe (Figure 9). Like the other fins, observers were trained to recognize lower trait stability when comparing these fin traits, and the importance to incorporate more stable traits to confirm ID.

2.4 Naming Individuals

Traditionally, Hawaiian names of individual sharks honored their appearance, territory, demeanor, and geneology (Emerson 1892, Beckwith 1917). These names illustrate a rich history that acknowledge named sharks as community members and represent a cultural identity to the sharks and to Hawaiians that acknowledge them (Kikiloi 2010, Puniwai 2020). For this purpose, names or nicknames of tiger sharks were avoided and an alpha-numerical system was created to name individuals in a simple and respecftul sense for the purpose of the study. The alpha-numerical designation of individuals was done chronologically by sex, i.e. presence/absence of claspers, with a WM to designate wahine manō, or female shark, and KM to designate kane manō, or male shark, and the number to designate the chronological order seen (e.g., the 1st female shark photographed was designated WM1 and the Nth number male shark photographed was designated KMN). After being given an alpha-numeric designation, a known individual was added to the official catalogue only if both sides have captured images that each contain at minimum 3 traits on either side. Individuals with only 1 side were not added into the official catalogue, but were kept in the known database since their single captured side was distinguished from the catalogued individuals. If they are re-sighted with both sides being captured on a single survey day then can be added into the catalogue.

2.5 Photo-ID Method Validation

2.5.1 First Iteration Method Validation

The first iteration test of validating tiger shark photo-ID methodology was conducted with a group of 5 volunteers that were provided with training material describing each of the tiger shark's unique traits and providing several images over time as examples. Each volunteer was asked to compare 18 images against those contained within a reference database of 30 previously identified tiger sharks (26 females, 4 males). Every individual in the reference database had images that depicted all traits from both sides shark's body. The 18 images to photo-ID were more recent than the images in the known database and comprised both male and female sharks that matched individuals in the known database and male and female sharks that did not match individuals in the known database, i.e., new individuals. Observers compared traits and assigned IDs to each file to their selected match or new individual if they were unable to determine a match.

2.5.2 Second Iteration Method Validation

The photo-ID methodology and training was improved and further refined for the second iteration validation testing based on volunteer feedback. The second iteration methodology incorporated an initial classification step focused on the sex and caudal fin shape of the shark to reduce the number of potential matches from the reference data set and attempt to increase accuracy and decrease time of identification (Marshall et al. 2011). The revised initial classification step assigns a clasper-caudal code to specify the presence or absence of claspers, i.e. sex, and the presence or absence of a terminal lobe in the caudal fin (Figure 10). The clasper-caudal code thereby adds to the naming process of a shark with the 0/1 code being inserting between the W/K designation and M to denote the presence or absence of the terminal lobe for the specific # individual of the specified sex. It is possible for a named individual (#N) to experience a code change from W/K1MN to W/K0N after captured images reveal the loss of the terminal lobe during the interval between re-sightings. This requires the identifier to still compare images of putative new sharks coded as W/K0 to W/K1 individuals in the known database if a match cannot be made by comparing to W/K0 individuals in the known database (Figure 11).

A total of 16 volunteers were given a 45-minute training video and tasked with analyzing 15 images capturing one side of a tiger shark to be identified. These 15 images were different from the 18 images used for the first validation iteration. Volunteers were asked to code the 15 images and record the time to make a match, which was defined for the validation test as a minimum of 3 identical traits. If the target individual cannot match with any sharks of any code in the known database, it is classified as a new individual (Figure 11). In addition to adding the clasper-caudal code in the second iteration, each observer recorded the time in minutes required to make an ID for each image and 'certainty' was scored as the number of traits (0-7) used to make the ID.

After evaluating the ID submissions of the second iteration method validation test, I reached out to participants to convene and gather feedback. Whenever an ID was made that was incorrect (i.e., did not agree with my ID) I sent a detailed description of my ID and all the traits used to confirm the individual. All observers were able to correct their IDs and revise the associated matching traits after reviewing my notes, and at the end there were no disagreements on Ids among all volunteers. These corrections were used to evaluate the accuracy and effectiveness of the volunteer's IDs.

2.6 Repeated Measures Mixed Effects Logistic Regression

A mixed-effects repeated-measures regression model with a log-link function was used to evaluate the influence of the order of examined tiger shark image files, the time in minutes to examine each image file, and the observer certainty score (fixed effects) on the probability of an observer (n = 15) to make a correct ID. An observer's specified answer for ID was considered correct when it agreed with the author's experienced designation. The probability of correctly identifying a file was the response variable and coded 0 for incorrect ID and 1 for correct ID. The 15 specific files were treated as repeated effects and grouped by each of the 15 observers, which was treated as a random effect. The mixed-effects model was designed and assessed using the GLIMMIX procedure in SAS 9.4 (SAS Institute Inc., Cary, NC, USA). The model was also applied to a simulated data set of 51,000 entries with randomized values assigned to observers (100), files (100), the order of file examined (0-100), the time (0-120 minutes), and certainty (0-7) to visualize the simulated probability of correct ID under various randomized conditions.

3. **Results**

3.1 Photo-ID Method Validation Tests

In the first iteration method validation test, 5 observers each examined 18 files for a total of 90 entries resulting in 93.3% agreement with the IDs of the method developer. In the second iteration, observers (n = 15) each examined 15 files for a total of 225 entries resulting in 92.4% agreement with my reference IDs. There were 4 observers who participated in both validation tests who averaged 95.8% agreement with my IDs in the first iteration and an average of 100% the same in the second iteration test. Of the 225 ID entries, there were a total of 17 errors – 12 false negative errors or 5.3%, and 5 false positive errors or 2.2% (Figure 15).

3.2 Repeated Measures Mixed-Effects Logistic Regression

Observer ID agreement was a function of the time spent examining a photograph and the certainty of the observer as measured by the number of traits matched. The probability of an observer making a correct ID decreased the more time they took making a match (Table 1, F = 10.90, $df_1 = 1$, $df_2 = 220$, p-value < 0.01). Time varied from 1 minute to 104 minutes, with a general increase in time resulting in a lower probability of making a correct ID (Figures 12, 13, and 16). Certainty was found to have a positive effect on the probability of a reader making a correct identification (Table 1, F-value = 8.96, $df_1 = 1$, $df_2 = 220$, p-value < 0.01). Certainty was defined as the number of traits an observer used to make an ID, with 0 to denote no traits matching any of the individuals in the known database, and a minimum of 3 traits required to make an ID, and up to a total of 7 potential matching traits. Some observers mistakenly entered this value as the number of traits they could clearly see on the tiger shark of the image file they were comparing, instead of the number of traits they were able to match to their entered ID. In both the simulated and observed data it can be concluded that an observer is most likely to make a correct ID when they are quickly able to make a match with high certainty (Figure 16).

3.3 West Hawai'i Tiger Shark Photo-ID

Utilizing this method of photo-ID a total of 69 tiger sharks (59 females; 10 males) were identified across sites in West Hawaiʻi from 2005 to 2021. Of the 59 females, 41 had their terminal lobe intact (Clasper-caudal-code W1) and 17 did not have their terminal lobe intact (Clasper-caudal-code W0) and 1 could not be determined (Clasper-caudal-code WX). Of the 10 males, 6 had their terminal lobe intact (Clasper-caudal-code K1) and 4 did not have their terminal lobe intact (Clasper-caudal-code K0). Only 2 individuals were observed to have a change in the clasper-caudal-code and both were females (Table 3). A total of 46 females and 7 males had images capturing both sides (Tables 2, 3, 4, and 5) and therefore a total of 53 tiger sharks in the official catalogue of this study. There were 9 individuals with only the right side captured, and 7 individuals with only the left side captured (Tables 4 and 5).

A total of 27 sharks or 39% were not re-sighted (Table 5), while 37 females and 5 males for a total of 42, or 61%, were re-sighted at least once (Tables 2, 3, and 4). Of the 16 individuals with only one side captured, 15 were only sighted once, and one was only sighted twice. Of the 42 individuals re-sighted, 25 were re-sighted over ≥5 years, 11 were re-sighted over ≥10 years, and 2 were re-sighted over ≥15 years (Tables 2, 3, and 4). The total observed time of an individual reached 16 years in two individuals, one male and one female, and the number of days between individual sightings varied from 1 day to 2174 days (Tables 2, 3, and 4). There were 7 females and 1 male that were seen at more than 1 site in West Hawaiʻi at least once.

4. **Discussion**

The underwater photo-ID methodology developed to identify Hawaiian tiger sharks produced repeatable identifications by observers who receive minimal training suggesting that it may be a useful approach for monitoring tiger shark populations in other locations. Despite tiger shark having many of the characteristics that make them good candidates for photo-ID studies, photo-ID does not seem to be a tool widely applied to study this species. Only a single, peer-reviewed study on tiger shark photo-ID appears in the literature and its authors do not fully describe or validate methods. Instead, Begue et al. (2020) focus on employing photo-ID data to examine the prevalence of hooking injuries in Tahitian tiger sharks. While photo-ID is an accepted research technique, the complete method of photo-ID needs to be validated and reported with photographic evidence before additional analyses are considered, particularly when applied to a novel species (Choo et al. 2020). Validation ensures that photo-ID data does not violate any assumptions or are subjected to potential errors that would bias supplementary modeling or analyses (Stevick et al. 2001, Yoshizaki et al. 2009). While proper descriptions of the methodology and photographic evidence of individual identification are less likely to be used in unintended adverse practices they are not nearly as widely published as location and abundance data are (Choo et al. 2020). It is important to validate methods and to ensure reported results benefit studied populations and host culture more than they can potentially harm or alter them. By focusing on aligning non-intrusive methods with cultural values and knowledge systems and clearly defining the photo-ID methods while consciously reporting results this study has validated underwater photo-ID methods of tiger sharks that can be built upon to continue respectfully researching tiger sharks in Hawaiʻi.

Development of an effective and easily followed standard operating procedure for photo-ID studies is widely considered to be an important factor to improve the repeatability of results (Choo et al. 2020); therefore, understanding how the behavior of observers influences their performance by collecting observer data, such as time spent, certainty, order, etc., is important to refine procedures and training. Many photo-ID studies display ranked answers to show several candidates of matches ordered by likelihood (Dureuil et al. 2015, Dunbar et al. 2021). This study, even with some novice observers and a binary answer option, i.e., correct or incorrect, still managed to obtain accuracies akin to the secondary, and even tertiary options of those ranked manual and automated ID methods. This demonstrates the power of utilizing multiple traits as well as the importance of photographers clearly capturing target areas. Publicly sourced images of whale sharks in the Maldives could only be used to identify sharks 84% of the time, while all images from researchers in the study could be used (Davies et al. 2012). The findings from this study further highlight the importance of experienced photographers obtaining high quality images for photo-ID with the added responsibility of lawful and respectful methods in Hawaiʻi.

Observer certainty was found to positively influence the probability of a correct ID, however, certainty was not recorded in the same way by all observers. This shows the need for clarification in the training and perhaps including both uses of certainty (the number of traits in the image file being observed and the number of traits successfully matched in making an ID) to be separately recorded in future tests. Multiple traits make natural markings comparable to double marking/tagging, which can increase the accuracy of positive identifications (Domeier & Nasby-Lucas 2007, Marshall et al. 2011, Dureuil et al. 2015). Being limited to a single, less stable trait, increases the likelihood of a higher rate of false negative errors unless coupled with double-marking with the use of physical marker tags or genetic sampling (Dudgeon et al. 2008, Gubili et al. 2009, Stevick et al. 2001). Marks have the potential to change subtly or even completely over varying periods of time for some cetacean and elasmobranch species (Domeier & Nasby-Lucas 2007, Baird et al. 2008, Aschettino et al. 2012, Bassos-Hull et al. 2014, Dureuil et al. 2015), although ID was still possible with remaining stable marks of the same trait or use of an additional trait. The findings of this study show that the stable traits of stripe pattern, head and body countershading delineations did not change for tiger sharks, even over the longest span for an individual of 16 years. While all natural marks have the potential to be covered or lost if a serious enough injury occurs, this study also supports that the likelihood of a false ID due to variable stability of traits can be ameliorated with the use of multiple traits to increase observer certainty.

While the order that the files were observed did not produce a statistically significant result in the model, there was a general trend of lower probability occurring in the later observed files (Table 1, Figure 12). Since the order was chronological and therefore the same among all 15 observers for the second iteration, there are confounding effects that prevent determining whether this trend was a result of the files being of individuals more likely to be misidentified or from potential fatigue of prolonged visual comparisons. There is evidence of altered accuracy of tasks based on the previous and subsequent order of classification due to sequence effects (Stewart et al. 2002). Therefore, the randomization of images by observers would allow the determination of order influencing accuracy based on aspects of an individual file or the captured traits of the shark, or due to prolonged visual comparisons. Most elasmobranch photo-ID studies attribute errors to lower quality images or those with less suitable angles and exposures (Marshall & Pierce 2012). Another potential way to further improve photo-ID methods would be to continue to communicate with observers afterwards to get additional feedback on trait and image elements and include scoring of images and/or traits to assign values to these elements in the photo-ID process to better understand them and how they influence observer accuracy (Urian et al. 2015).

As an observer spent more time attempting to make a match, the probability of making a correct match decreased with 20-40 minutes being about the ideal amount of time when there were 3 traits available. However, there are several factors that can influence this “ideal” time, such as the size of the known database being compared to. Nevertheless, this finding can benefit future photo-ID standard operating procedures for observers to either take a break, move on, or seek consultation for a file if an ID cannot be confidently made after a reasonable amount of time such as 30 minutes. There is an established benefit for indexing or assigning phenotypic metadata and/or categorizing files to better organize them for use in photo-ID (Dureuil et al. 2015, Kumar & Singh 2017). The clasper-caudal-code appears to be a novel and effective way to organize images, however the experimental design of iterations did not allow proper examination of potential time-saving benefits of the clasper-caudal-code. Time becomes increasingly important as photo-ID databases grow locally and expand to include international cooperation, which has led to increased use of automated software (Van Tienhoven et al. 2007, Marshall & Pierce 2012).

Automated software is acknowledged to be faster than observer ID and result in fewer false positive and false negative errors (Stevick et al. 2001, Van Tienhoven et al. 2007, Dureuil et al. 2015, Dunbar et al. 2021). However, the algorithms used by these software packages require images of specific regions clearly captured with an emphasis on uniform angle, framing, and exposure, which can dramatically reduce the number of usable images and therefore the number of resulting potential matches (Van Tienhoven et al. 2007, Dureuil et al. 2015, Kumar &

Singh 2017). While it is not certain if tiger shark traits could be used in current software programs, the photo-ID methodology of this study begins to address most drawbacks of observer-led ID due to the added confidence in precision that is gained through underwater photography to capture multiple photo-ID traits. While risk aversion to false positive errors can lead to an increase in false negative errors (Stevick et al. 2001), most of the errors seen in the validation test are likely due to observer inexperience. For example, image 5 contained the only example in the validation test of a code change, which means the caudal fin had observable changes, but ID was still possible with the use of the other 6 traits. Similarly, image 3 saw a change in its dorsal fin compared to images in the known database, which could suggest that inexperienced observers may fixate on differences resulting from a change in a single trait over the less conspicuous remaining traits that potentially match. Therefore the potential exists for sequence effects due to traits, whereby the order in which traits are compared may influence an observer in visuallizing matches or not in the comparisons of the ensuing traits. The improvement seen by repeat observers suggests that training and experience improves accuracy. Even among inexperienced observers this tiger shark methodology was found to have over 90% accuracy. For experienced observers, or cooperative ID, there is potential for 100% accuracy to ID high-quality tiger shark images.

The findings of this study of 61% re-sighting agree with tagging studies demonstrating the potential for residency of tiger sharks in Hawaiʻi (Holland et al. 1999; Lowe et al. 2006; Papastamatiou et al. 2013). Statistical analyses such as Test 2 may be utilized in future research to determine if there is significant heterogeneity in re-sight probability among individual tiger sharks (Burnham et al. 1987, Holmberg et al. 2008). The results of this statistical test would also determine if the tiger shark re-sight data met certain assumptions of potential population estimate models such as the Cormack-Jolly-Seber model. The agreement of photo-ID results with existing tagging data confirms certain ecological data of tiger sharks in Hawai‘i and demonstrates the validity of photo-ID to further analyze ecological data, particularly for aspects that are not feasible or appropriate for invasive tagging methods.

The findings of this study of a nearly 7:1 female to male ratio agrees with fishing studies conducted in Hawai‘i (Papastamatiou et al. 2013, Meyer et al. 2014), as well as tiger shark studies in Tahiti (Begue et al. 2020), and other regions (Simpfendorfer et al. 2001, Holmes et al. 2014). The reason for this female-biased ratio is not known but could be due to sexual segregation as a result of different coastal vs. oceanic habitat preferences (Papastamatiou et al. 2013, Holland et al. 2019). Tiger sharks in Hawai‘i were inferred to have a triennial reproductive status after comparing embryological stages of captured and deceased pregnant sharks based on the time of year they were captured (Whitney & Crow 2007). Initial assessments of re-sighted female sharks in this study provide photographic evidence for potentially determining gravidity that demonstrate examples of biennial and triennial reproductive cycles, as well as reproductive delays surpassing one year potentially due to anthropogenic impacts (Fig. 17). Further analysis of photo-ID data can shed light on reproductive status and anthropogenic impacts as well as other critical ecological and conservation information of tiger sharks. The potential for anthropogenic impacts to delay reproduction and further reduce fecundity (Fig. 17) can be further analyzed and this photo-ID data could then inform appropriate management strategies.

5. Conclusion

Photo-ID is a viable method for collecting mark-resight data for Tiger Sharks in Hawaii and throughout their range in a non-invasive and culturally sensitive manner. The approach developed uses 14 uniquely identifiable traits to differentiate and identify tiger sharks collected through underwater photography and videography and exhibited a high agreement rate both among observers and with expert observers. The probability of agreement was affected by the time an observer spent attempting to identify an individual and the number of traits used. Thus, these factors warrant consideration in the development of operating procedures and training protocols for photo-ID programs. This approach had resulted in the development of a photo-ID database of 69 tiger sharks that have been encountered at sites off West Hawaii during 2005-2021.

Although photo-ID is an accepted research technique, the methods used can vary between studies and this work supports previous findings that urge for the inclusion of more detailed descriptions of methods and their validation (Urian et al. 2015). Not only would this serve to improve the repeatability and confidence in the data collected (Choo et al. 2020), but it would aid in adapting existing photo-ID methods to novel species. For example, the results of the validation studies detailed in this thesis suggest that finding ways to reduce the time necessary to making an identification can improve the accuracy and precision of the photo-ID data. Therefore, the clasper-caudal-code was developed to organize the photo-ID datasets and reduce the number of potential matches that had to be examined. Additional study is required to understand the potential benefits of the clasper-caudal-code. Future research would also benefit from additional ground-truthing by incorporating images of tiger sharks whose ID can be confirmed by either DNA testing or from images of a captive tiger shark, and by randomizing the order of images for each observer to eliminate confounding effects and determine if the order influences correct ID probability due to visual factors of the files or the associated traits captured or from sequence effects.

Now that this photo-ID method has been validated, additional analyses can be confidently conducted on this tiger shark photo-ID data, such as examining survival, residency, and estimating population size. Paired-laser photogrammetry may now also be appropriately implemented to determine morphometric data from photo-ID methods, including growth rates utilizing re-sight data. Further evaluation of images could also allow inferences to be made on movements, seasonality, reproductive cycle, wound healing, and human impacts such as debris entanglement, prevalence of fishhooks, and vessel strikes. While this methodology can certainly be repeated, there is no guarantee that the user respectfully and appropriately obtains images of tiger sharks at any given site to utilize this methodology. Therefore, there is further need for a detailed guideline defining pono methods regarding shark research in Hawaiʻi, ideally determined by the involvement and input of Native Hawaiians, stakeholders, and state and federal agencies. The traditional daily coexistence of kahu manō with sharks allowed the observational study and dissemination of information to the Hawaiian people. By heeding their history and practice with a pono photo-ID methodology we take another step towards regaining the information, identity, and aloha ʻāina, or love of the land, that results from respectfully becoming part of the Hawaiian seascape. Continued applications of respectful ʻāina based research that incorporates traditional practices and involves Hawaiian communities will further strengthen connections to place and allow for informed, culturally-minded conservation.

6. Tables

Table 1 – Results of the test of fixed effects of the mixed-model logistic regression. Parameter estimates (β; ± standard error), degrees of freedom (DF), f value, and p value of the test of fixed effects of the mixed-model logistic regression, which evaluated the influence of a correct clasper-caudal-code, order of image files, time to ID tiger shark (*Galeocerdo cuvier*) image file in minutes, and certainty score on the probability of an observer (n=15) from the second iteration tiger shark photo-ID method validation test of making a correct tiger shark ID. The 15 image files were treated as repeated effects grouped by individual observers (n=15), which was treated as a random effect. *P* values considered significant are indicated with an asterisk.

Fixed Effect	β estimate ± SE	DF	F value	P value
Correct Clasper-Caudal Code	0.35 ± 1.02	220	0.12	0.73
Order	-0.08 ± 0.06	220	1.75	0.19
Time	-0.04 ± 0.01	220	10.90	<0.01*
Certainty	0.28 ± 0.09	220	8.96	<0.01*

Table 2 – Tiger shark W1 photo-ID re-sight data. Re-sight data including sides captured by images (L = left, R = right), total number of sightings, average number of days between sightings ± standard deviation, and total observation span in years between first and last sightings of each wahine/female tiger shark (*Galeocerdo cuvier*)_ with terminal lobes (W1) from West Hawaiʻi during surveys from July 2005 through July 2021.

ID	Sides captured	Total sightings	Ave. days between sightings ± st. dev.	Observation span (years)
W1M1	LR	6	590 ± 372	9
W1M2	LR	19	304 ± 371	16
W1M4	LR	4	243 ± 280	3
W1M6	LR	10	168 ± 157	5
W1M7	LR	21	238 ± 417	14
W1M8	LR	2	14	1
W1M12	LR	13	214 ± 345	8
W1M13	LR	8	468 ± 548	10
W1M15	LR	2	533	2
W1M16	LR	2	56	1
W1M19	LR	21	200 ± 325	12
W1M22	LR	7	527 ± 552	10
W1M24	LR	3	714 ± 396	5
W1M25	LR	5	273 ± 267	4
W1M26	LR	40	111 ± 172	13
W1M27	LR	13	122 ± 272	5
W1M28	LR	11	77 ± 124	3
W1M31	LR	2	3	1
W1M34	LR	6	149 ± 153	3
W1M38	LR	26	101 ± 207	8
W1M41	LR	6	433 ± 372	6
W1M44	LR	2	348	2
W1M52	LR	6	48 ± 47	2
W1M53	LR	7	150 ± 99	3
W1M54	LR	2	54	1
W1M56	LR	3	587 ± 467	4

Table 3 – Tiger shark W0 photo-ID re-sight data. Re-sight data including sides captured by images (L = left, R = right), total number of sightings, average number of days between sightings ± standard deviation, and total observation span in years between first and last sightings of each wahine/female tiger shark (*Galeocerdo cuvier*) without terminal lobes (W0) from West Hawai‘i during surveys from July 2005 through July 2021. An ID with an asterisk denotes a shark observed to have a change of code, i.e. lost its terminal lobe.

ID	Sides captured	Total sightings	Ave. days between sightings ± st. dev.	Observation span (years)
W0M3	LR	21	164 ± 317	10
*W0M10	LR	4	1577 ± 927	14
*W0M20	LR	29	154 ± 249	12
W0M30	LR	5	640 ± 504	8
W0M33	LR	4	482 ± 548	5
W0M35	LR	6	289 ± 371	5
W0M36	LR	7	426 ± 450	8
W0M37	LR	3	696 ± 600	5
W0M40	LR	20	116 ± 183	7
W0M47	LR	4	494 ± 306	5
W0M49	LR	2	78	1

Table 4 – Tiger shark kane/male photo-ID re-sight data. Re-sight data including sides captured by images (L = left, R = right), total number of sightings, average number of days between sightings ± standard deviation, and total observation span in years between first and last sightings of kane/male tiger sharks (*Galeocerdo cuvier*) from West Hawai‘i during surveys from July 2005 through July 2021.

ID	Sides captured	Total sightings	Ave. days between sightings ± st. dev.	Observation span (years)
K0M1	LR	6	653 ± 534	10
K1M2	LR	34	165 ± 372	16
K1M3	L	2	1085	4
K1M4	LR	12	70 ± 120	3
K0M6	LR	2	4	1

Table 5 – List of tiger sharks only sighted once and the sides captured in images.
Sides captured by images (L = left, R = right) of the 27 tiger sharks (*Galeocerdo cuvier)* that were only sighted once in West Hawai‘i during surveys from July 2005 through July 2021.

ID	Sides captured
K1M5	LR
K1M7	R
K1M8	L
K0M9	LR
K1M10	LR
W1M9	LR
W1M11	R
W0M14	LR
W1M17	R
W1M18	L
W1M21	L
W1M29	R
W1M32	L
W1M39	R
W1M42	LR
W1M43	R
W1M45	LR
W0M46	LR
W1M48	R
W0M50	L
W1M51	LR
W0M55	LR
W1M57	LR
W0M58	LR
W1M59	R
W0M60	L
WXM5	R

7. Figures

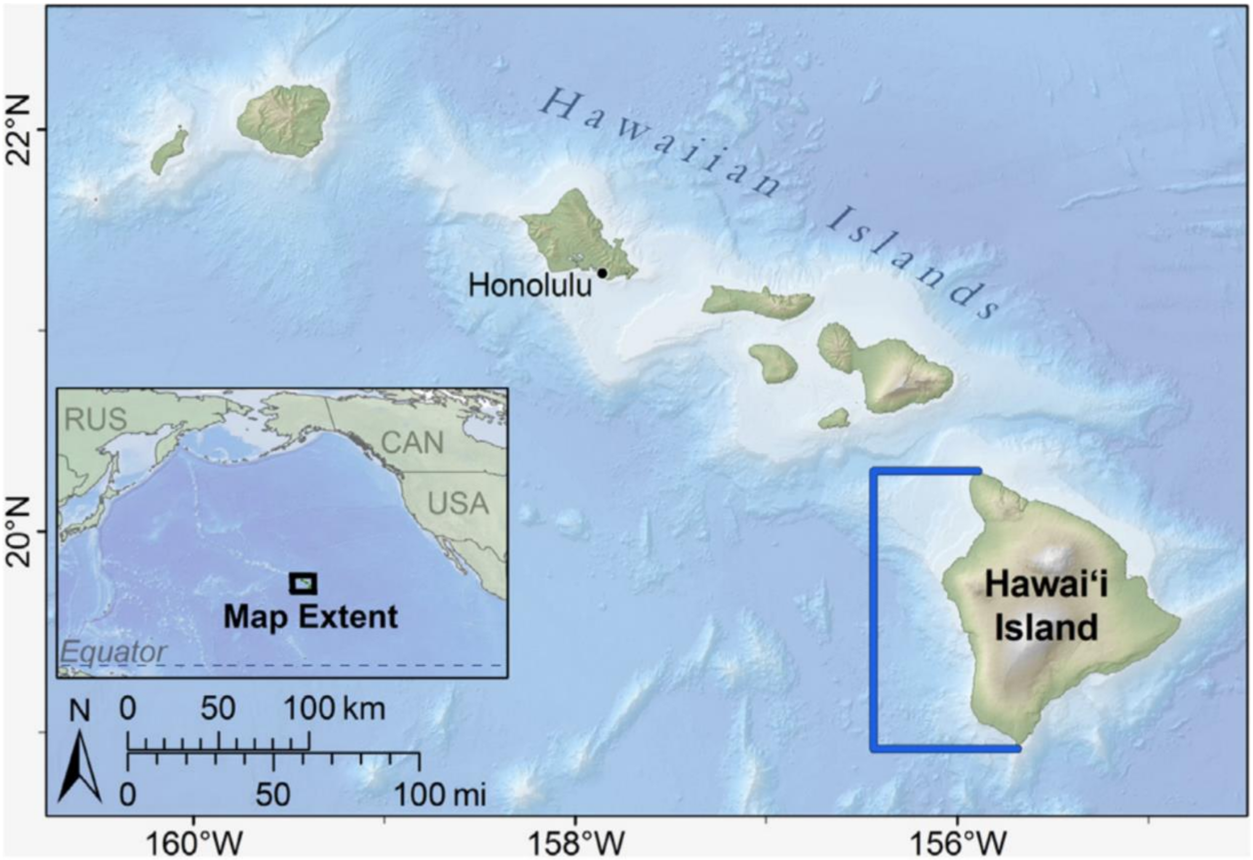

Figure 1 - Map of Hawai'i Island and the Hawaiian Islands (Obtained from Ingram et al. 2018). The blue line denotes West Hawai'i, the general area of this study, with exact tiger shark (*Galeocerdo cuvier*) survey locations being withheld for cultural consideration and to prevent commercial exploitation.

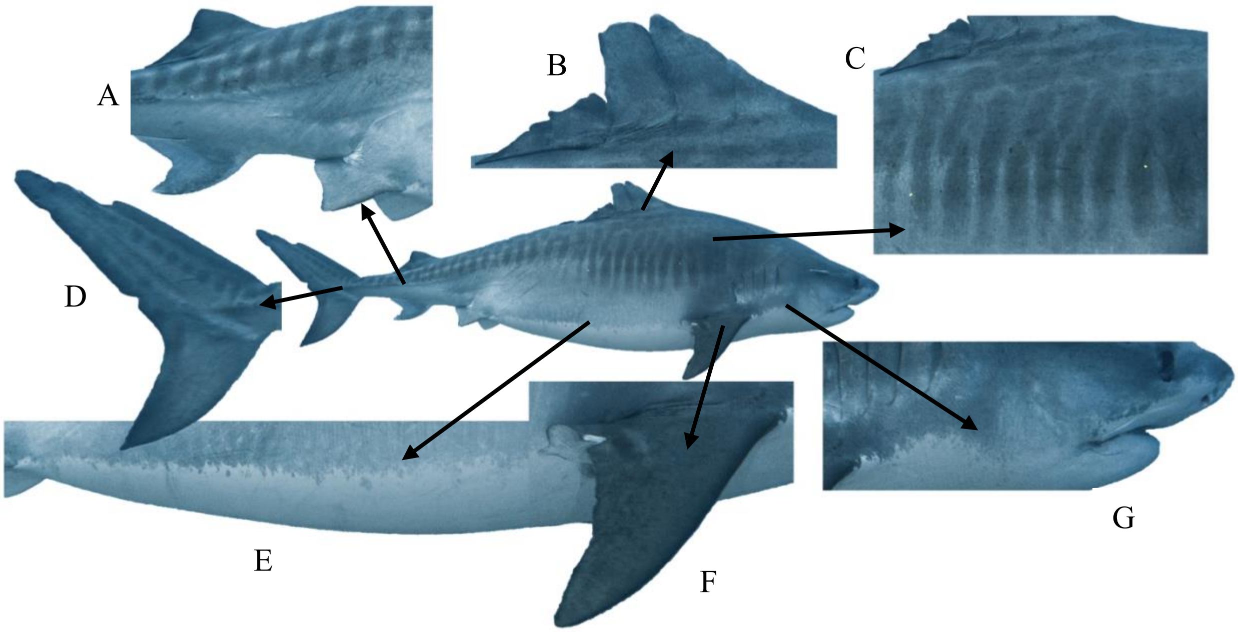

Figure 2 – The 7 potential traits per side of each tiger shark. The 7 unique and identifiable potential traits per side of individual tiger shark (*Galeocerdo cuvier*) including A: rear fins, B: dorsal fin, C: body stripe pattern, D: caudal fin, E: body countershading delineation, f: Pectoral fin, and g: Head countershading delineation, resulting in a total of 14 potential traits per individual.

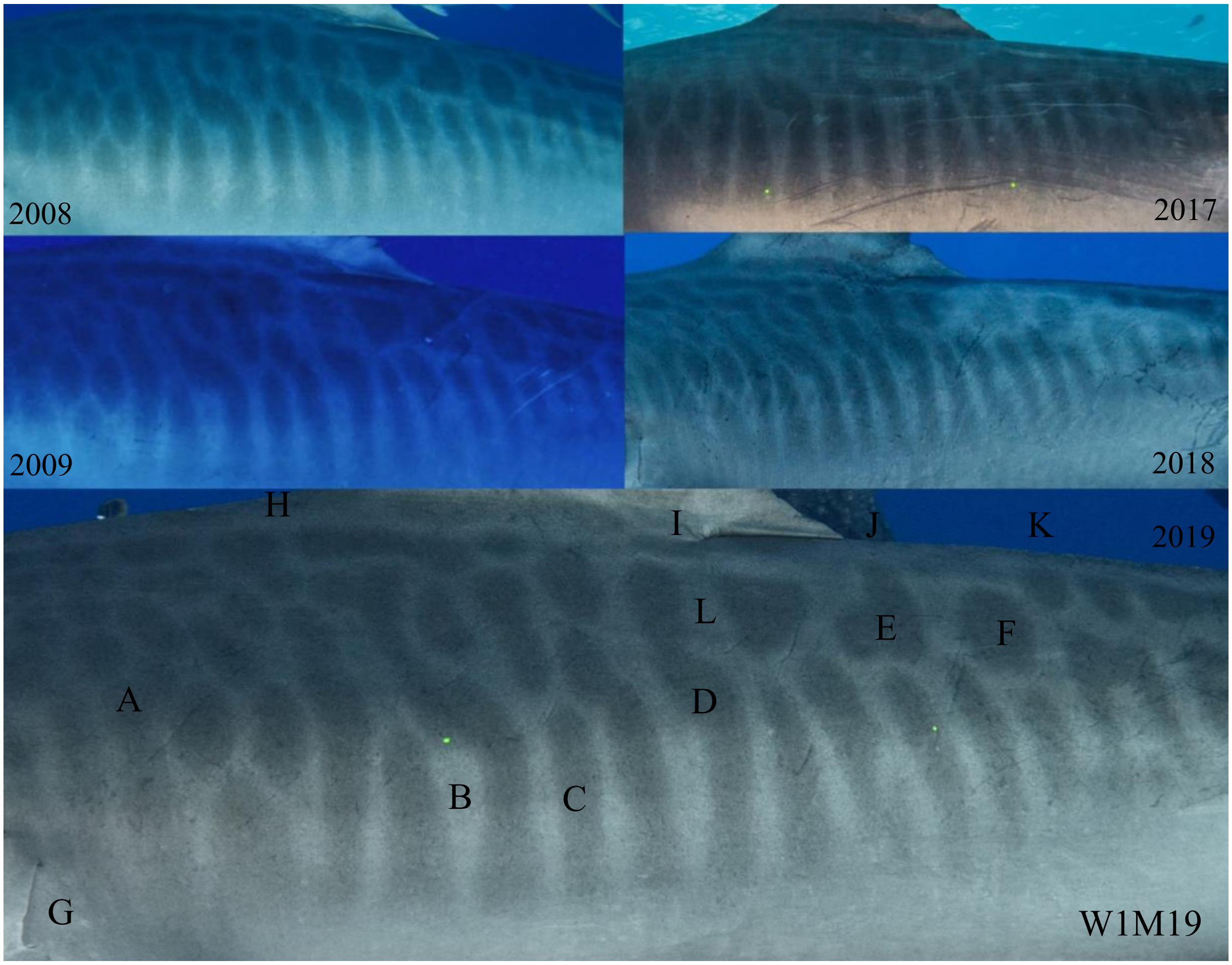

Figure 3 – Tiger shark stripe pattern time series. Images of the left side of tiger shark (*Galeocerdo cuvier*) W1M19 taken from 2008 through 2019 in West Hawai‘i. Unique and identifiable features of this trait seen in this individual include A: areas of tightly packed dark pigment, B: fairly evenly spaced lighter pigmented areas between darker stripe patterns, C: vertical straight stripes, D: long curving stripes, E: uniquely shaped patterns, and F: round spot patterns. Helpful reference points include G: gill slits, H: origin/base of the dorsal fin, I: insertion point of the dorsal fin, J: rear tip of the dorsal fin, K: interdorsal ridge, and L: lateral line.

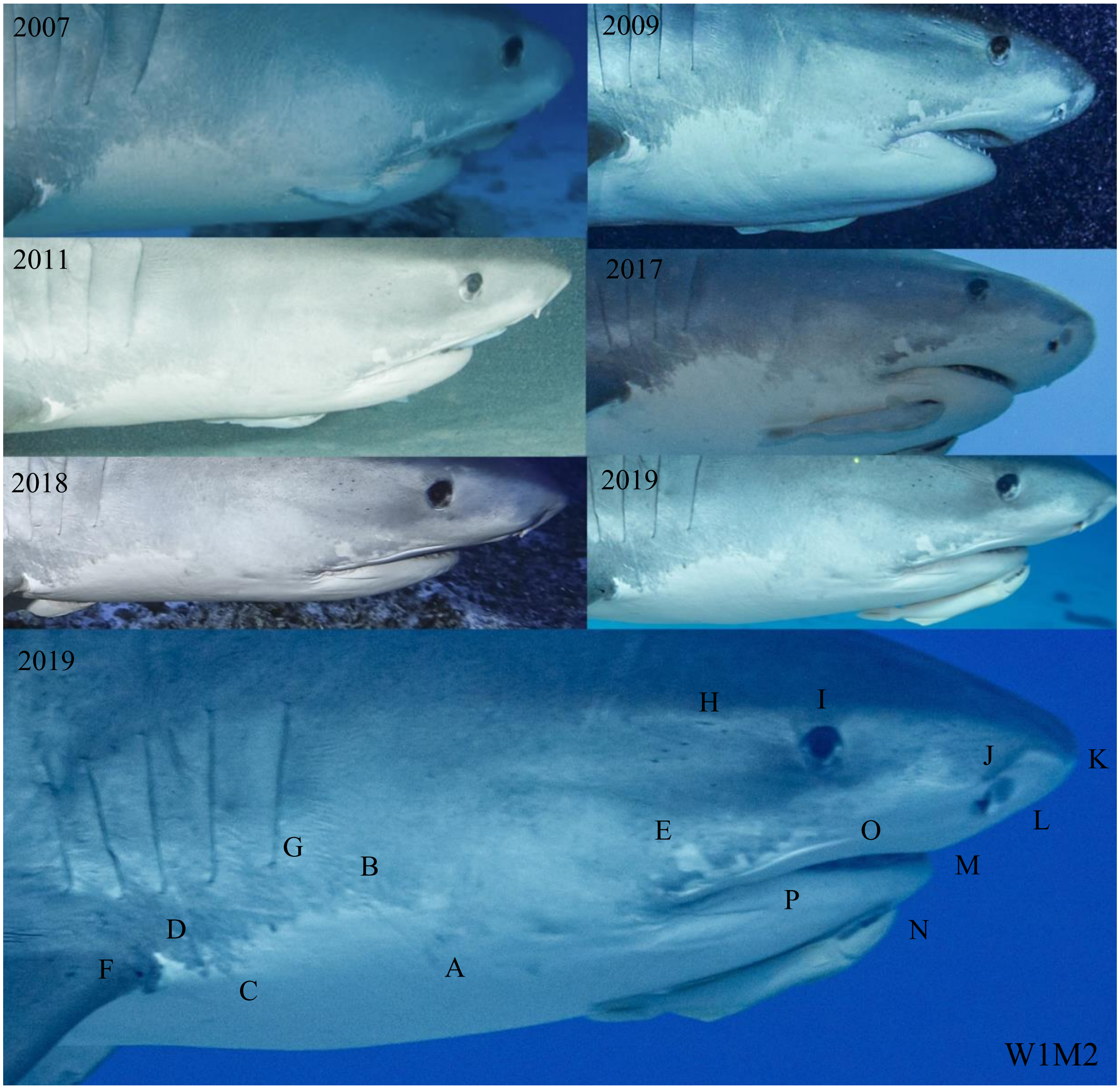

Figure 4 – Tiger shark head countershading delineation time series. Images of the right side head countershading delineation of tiger shark (*Galeocerdo cuvier*) W1M2 taken from 2007 through 2019 in West Hawai'i. Unique and identifying features of this trait for this individual include A: an isolated region of darker pigment in the lighter pigment below the delineation, B: a peak in delineation amplitude of lighter pigment extending upward onto darker pigment, C: a trough in delineation amplitude of darker pigment extending downward onto lighter pigment, D: unique pattern directly anterior of the pectoral fin, and E: unique patterns in the delineation. Helpful reference points include F: base of the pectoral fin, G: gill slits, H: spiracle, I: eye, J: nostril, K: snout, L: fixed upper jaw, M: mouth, N: hinged moveable lower jaw, O: upper labial furrow/fold, and P: lower labial furrow/fold.

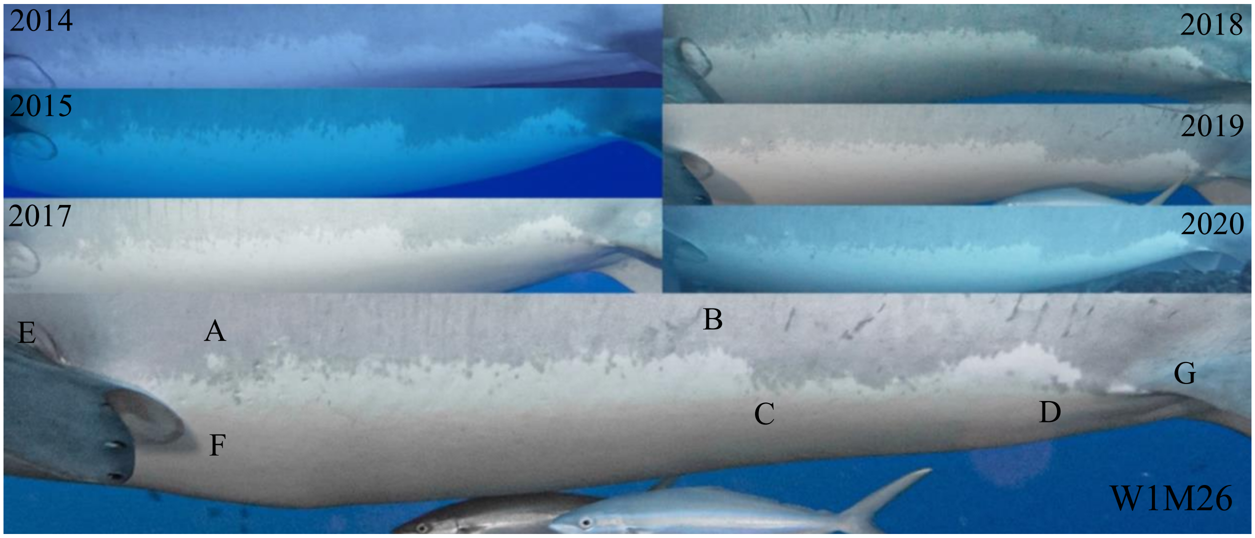

Figure 5 – Tiger shark body countershading delineation time series. Images of the left side countershading delineation of tiger shark (*Galeocerdo cuvier*) W1M26 taken from 2014 through 2020 in West Hawaiʻi. Unique and identifying features of this trait for this individual include A: an isolated region of lighter pigment in the darker pigment above the delineation, B: a peak in delineation amplitude of lighter pigment extending upward onto darker pigment, C: a trough in delineation amplitude of darker pigment extending downward onto lighter pigment, and D: an isolated region of darker pigment in the lighter pigment below the delineation. Helpful reference points include E: the pectoral axil/insertion point, F: the free pectoral fin rear tip, and G: the pelvic fin.

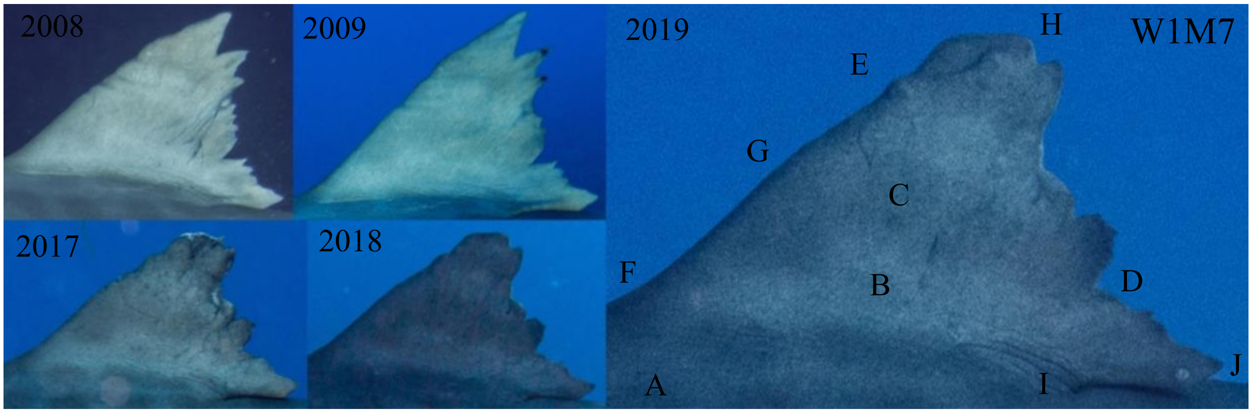

Figure 6 – Tiger shark dorsal fin time series. Images of the left side of tiger shark (*Galeocerdo cuvier*) W1M7 taken from 2008 through 2019 in West Hawai‘i. Unique and identifiable features of this trait for this individual include A: a conspicuous stripe pattern just below the dorsal, B: horizontal lighter pigment patterns on the left lateral surface, C: horizontal darker pigment patterns on the left lateral surface, D: notches or tears in the trailing edge, E: and indents or notches in the leading edge. Helpful reference points include F: origin/base of dorsal fin, G: leading edge of dorsal fin, H: dorsal apex/tip, I: insertion point of the dorsal fin, and J: the free rear tip of dorsal fin.

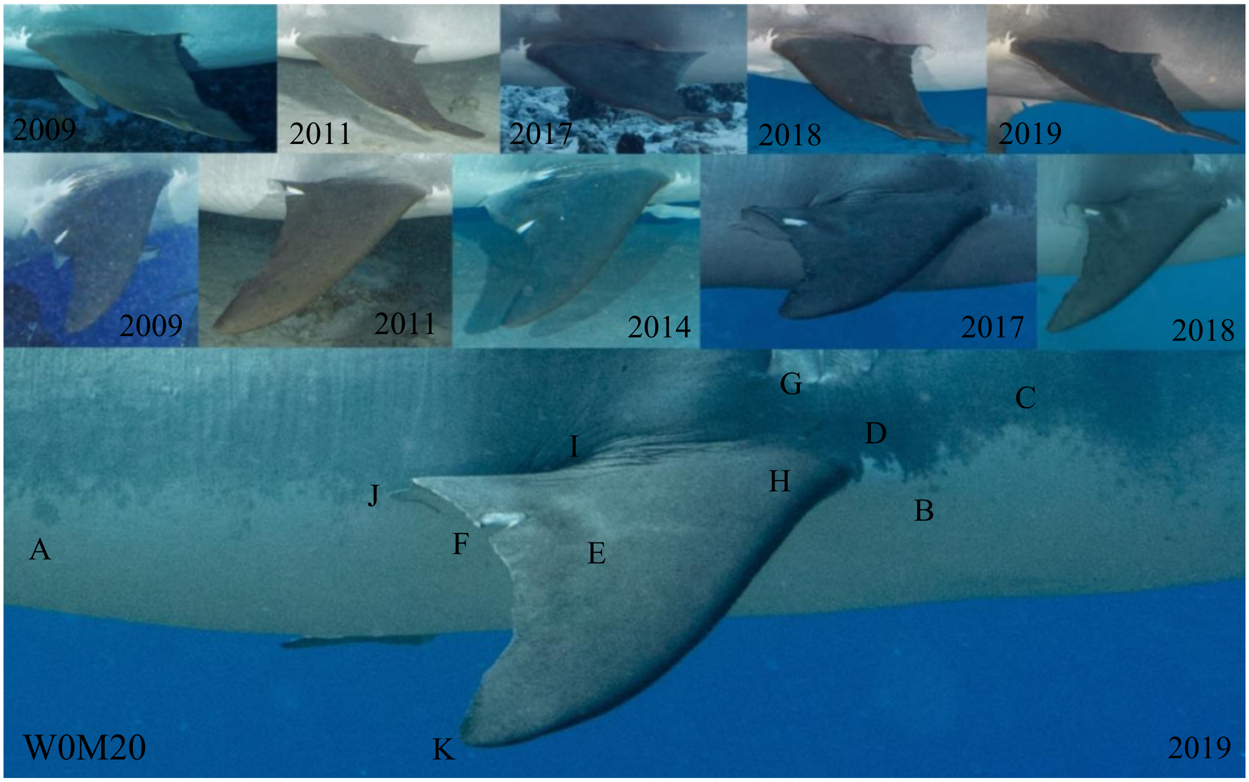

Figure 7 – Tiger shark pectoral fin time series. Images of the left and right side of tiger shark (*Galeocerdo cuvier*) W0M20 taken from 2009 through 2019 in West Hawai‘i. Unique and identifiable features of this trait for this individual include A: an isolated region of darker pigment in the lighter pigment below the delineation, B: a trough in delineation amplitude of darker pigment extending downward onto lighter pigment, C: a peak in delineation amplitude of lighter pigment extending upward onto darker pigment, D: unique patterns directly anterior of the pectoral fin, E: dark and/or light pigment patterns on the dorsal and/or ventral surface of the pectoral fin, and F: notches or tears in the fins. Helpful reference points include G: gill slits, H: origin/base of pectoral fin, I: pectoral axil/insertion points, J: free rear tip of pectoral fins, and K: tips of pectoral fin.

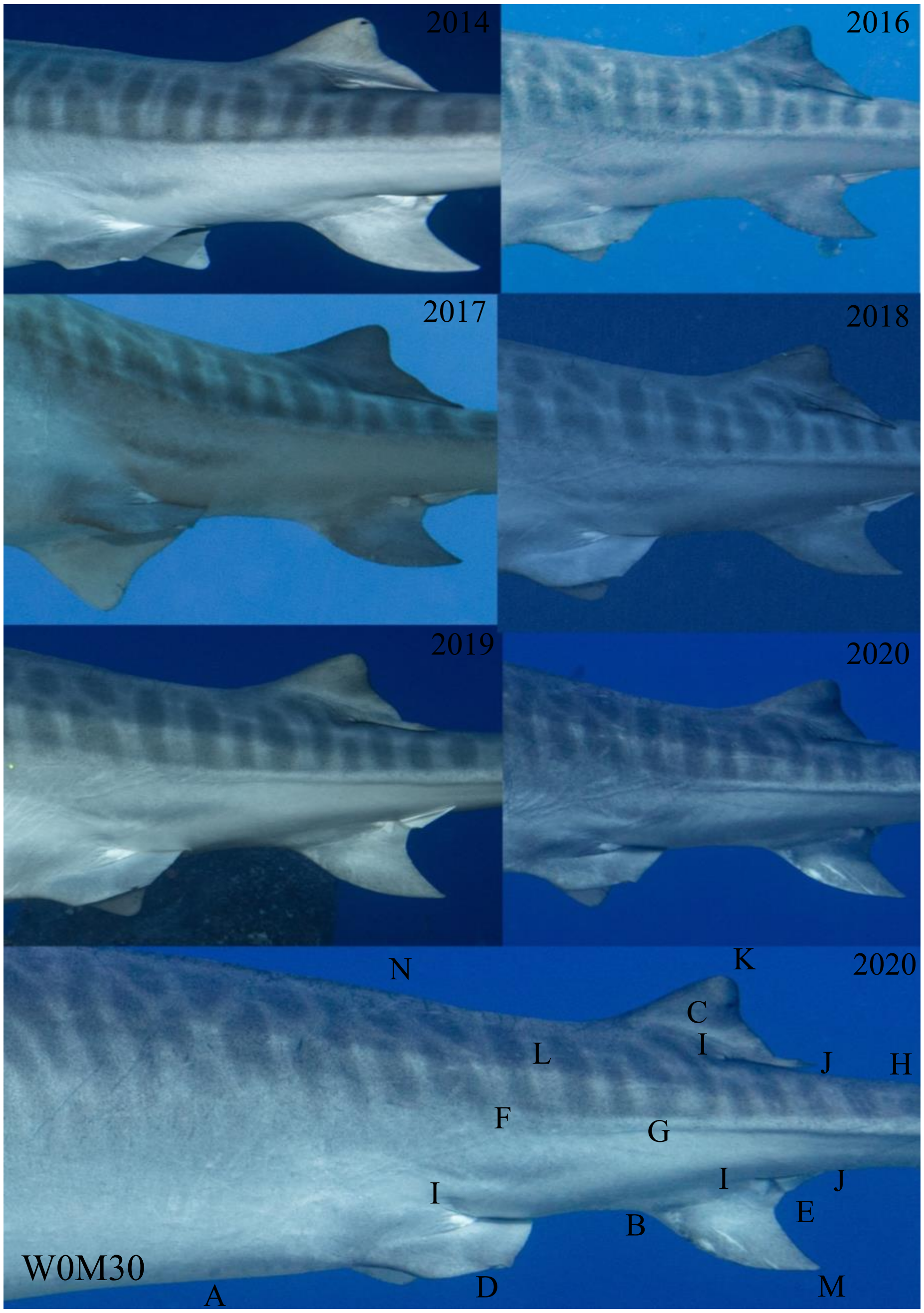

Figure 8 – Tiger shark rear fins time series. Images of the left side of tiger shark (*Galeocerdo cuvier*) W0M30 taken from 2014 through 2020 in West Hawaiʻi. Unique and identifiable features of this trait for this individual include A: an isolated region of darker pigment in the lighter pigment below the delineation, B: unique delineation pattern anterior of anal fin extending down leading edge, C: horizontal pigment pattern on left lateral surface of the 2nd dorsal fin, D: presence/absence of claspers and shape and condition of pelvic fin tips, E: notches or tears in any of the rear fins, F: and stripe pattern above caudal keel continuing forward. Helpful reference points include G: caudal keel, H: caudal peduncle, I: insertion points of each rear fin, J: free rear tips of the secondary dorsal and anal fin, K: apex/tip of secondary dorsal fin, L: lateral line, M: anal fin tip, and N: interdorsal ridge.

Figure 9 – Tiger shark caudal fin time series. Images of the left side of tiger shark (*Galeocerdo cuvier*) W1M20 taken from 2011 through 2019 in West Hawaiʻi depicting the code change to W0M20 between sightings of 2014 and 2017. Unique and identifiable features of this trait for this individual include A: presence/absence of terminal lobe, B: subterminal notch, C: notches or tears in the trailing edge, D: stripe pattern extending onto upper caudal lobe, and E: lighter ventral pigment extending from caudal peduncle onto the lower caudal lobe. Helpful reference points include: F: precaudal pit, G: caudal keel, H: leading edge of the lower caudal lobe, I: lower caudal point, J: caudal fork, K: trailing edge of the upper caudal lobe, and L: caudal tip/apex.

Figure 10 – Clasper-caudal-code visual guide.
Visual guide depicting the clasper-caudal-code developed for tiger shark *Galeocerdo cuvier* photo-ID. Images of tiger sharks were taken in West Hawaiʻi with a K denoting a presence of claspers and a kane/male shark, W denoting an absence of claspers and a wahine/female shark, X denoting an unkown clasper code due to inability to clearly capture pelvic region, 0 denoting an absence of the terminal lobe, 1 denoting the presence of the terminal lobe, and an X denoting an unknown caudal code due to inability to clearly capture caudal fin.

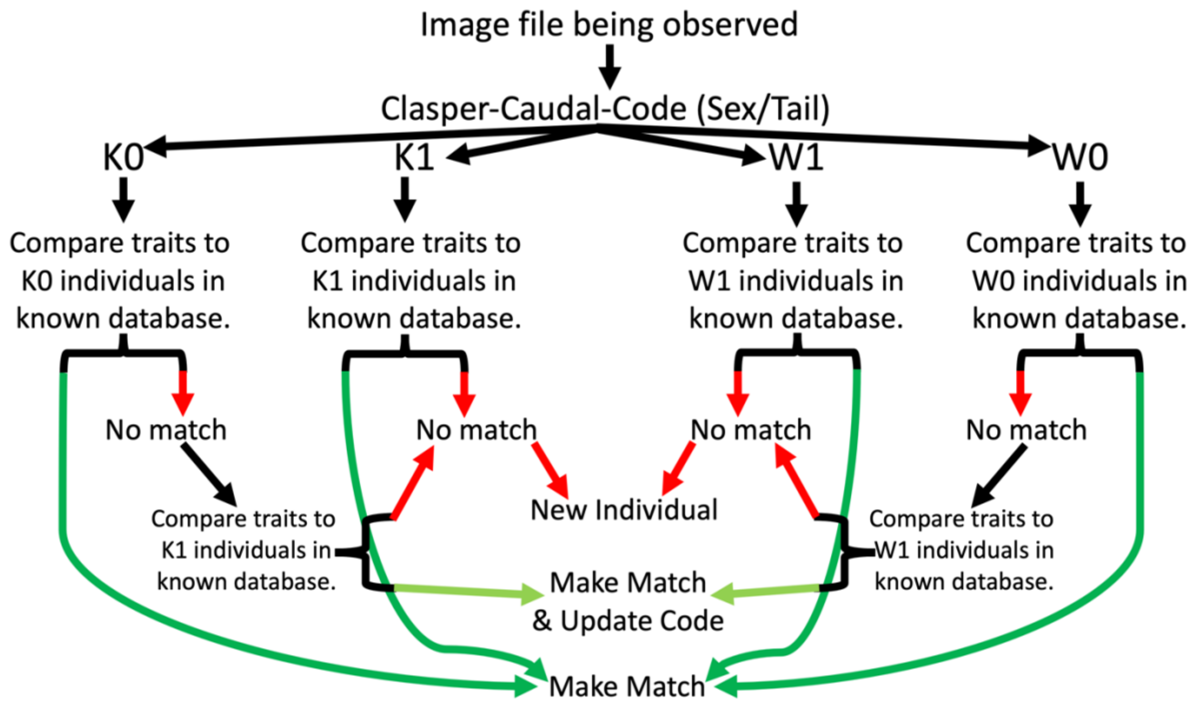

Figure 11 – Clasper-caudal-code photo-ID process steps. Starting from the top with a tiger shark (*Galeocerdo cuvier*) image file being observed, a photo-ID user can assign the file a current clasper-caudal-code, and immediately begin comparisons between the observed image file and pertinently coded individuals in the known database. A minimum of 3 traits on a given side is required to make a match, however, observers should seek to confirm with every available trait.

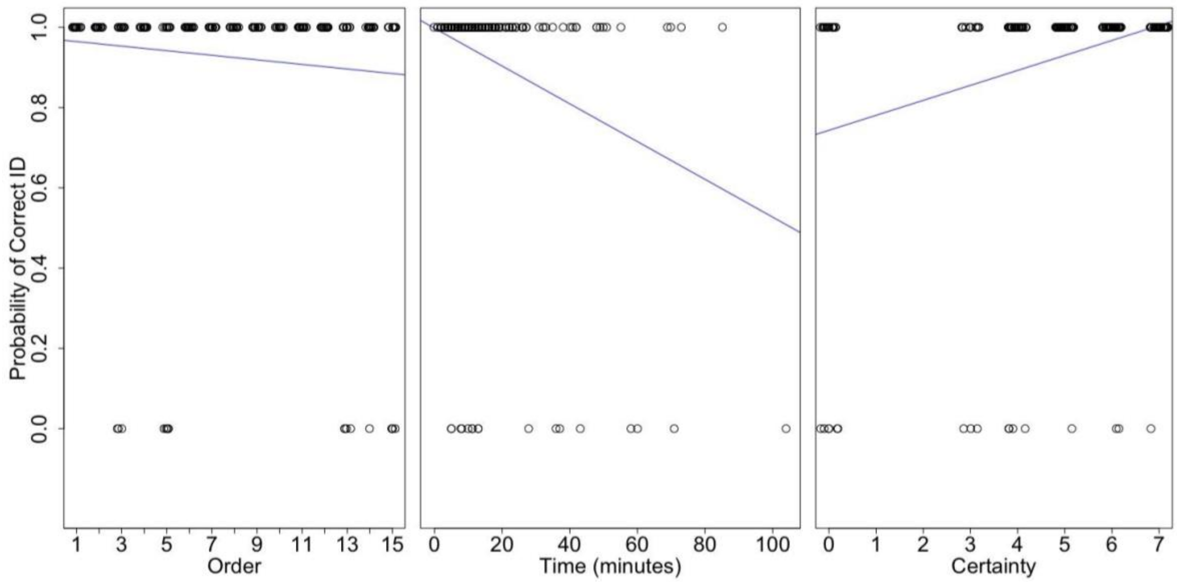

Figure 12 – Probability of correct tiger shark ID by order, time, and certainty. The black circle plot points represent the observed probability of correct ID by the 15 observers of the second iteration tiger shark (*Galeocerdo cuvier*) photo-ID method validation test according to the variables file order, time to ID in minutes, and certainty. The blue line represents a line of best fit of predicted probabilities of correct tiger shark ID as predicted by the mixed effects logistic regression.

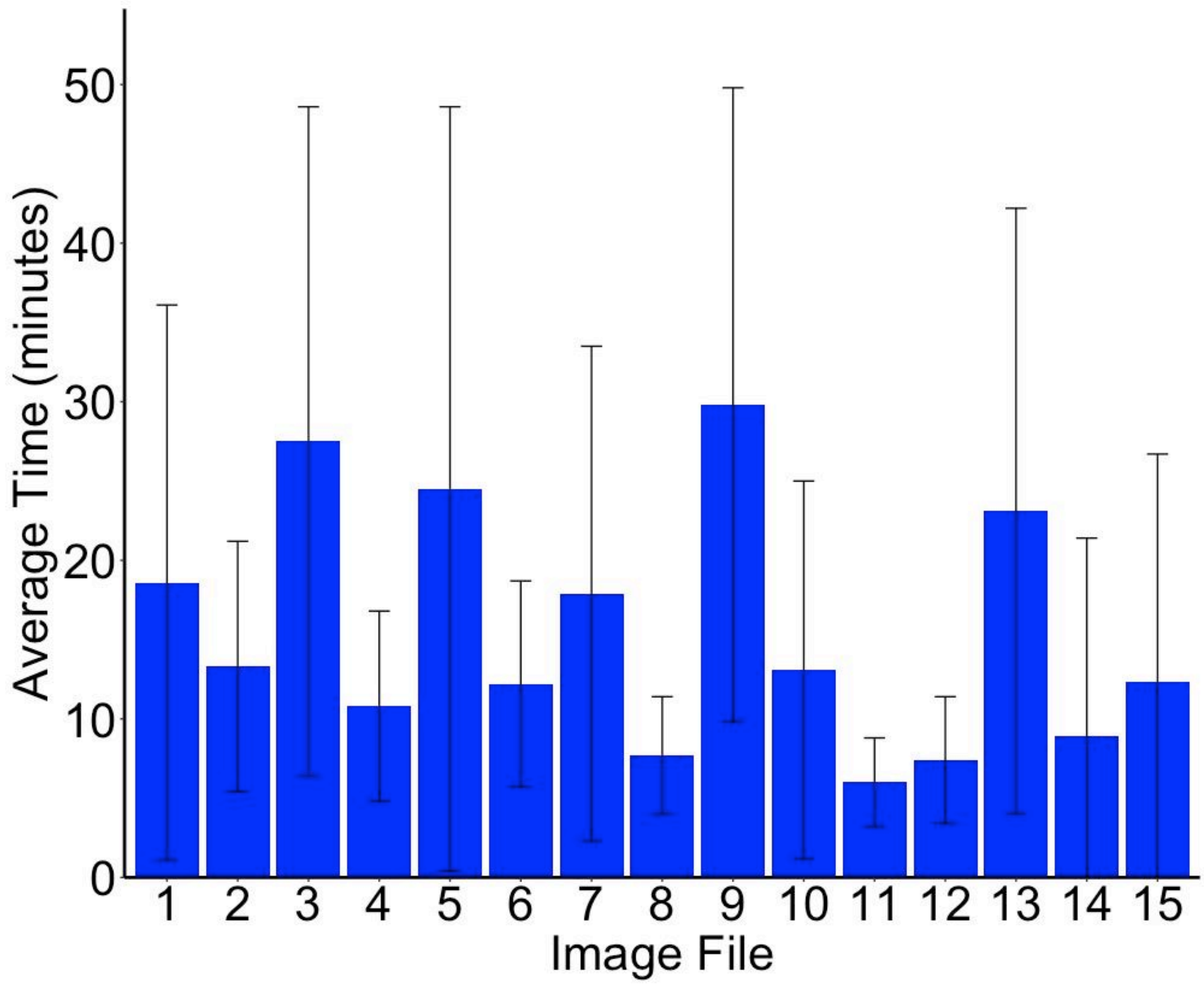

Figure 13 - Average time to ID per image file. The average time in minutes to ID each of the 15 tiger shark (*Galeocerdo cuvier)* images by the 15 observers from the second iteration tiger shark photo-ID method validation test. Error bars depict standard deviation.

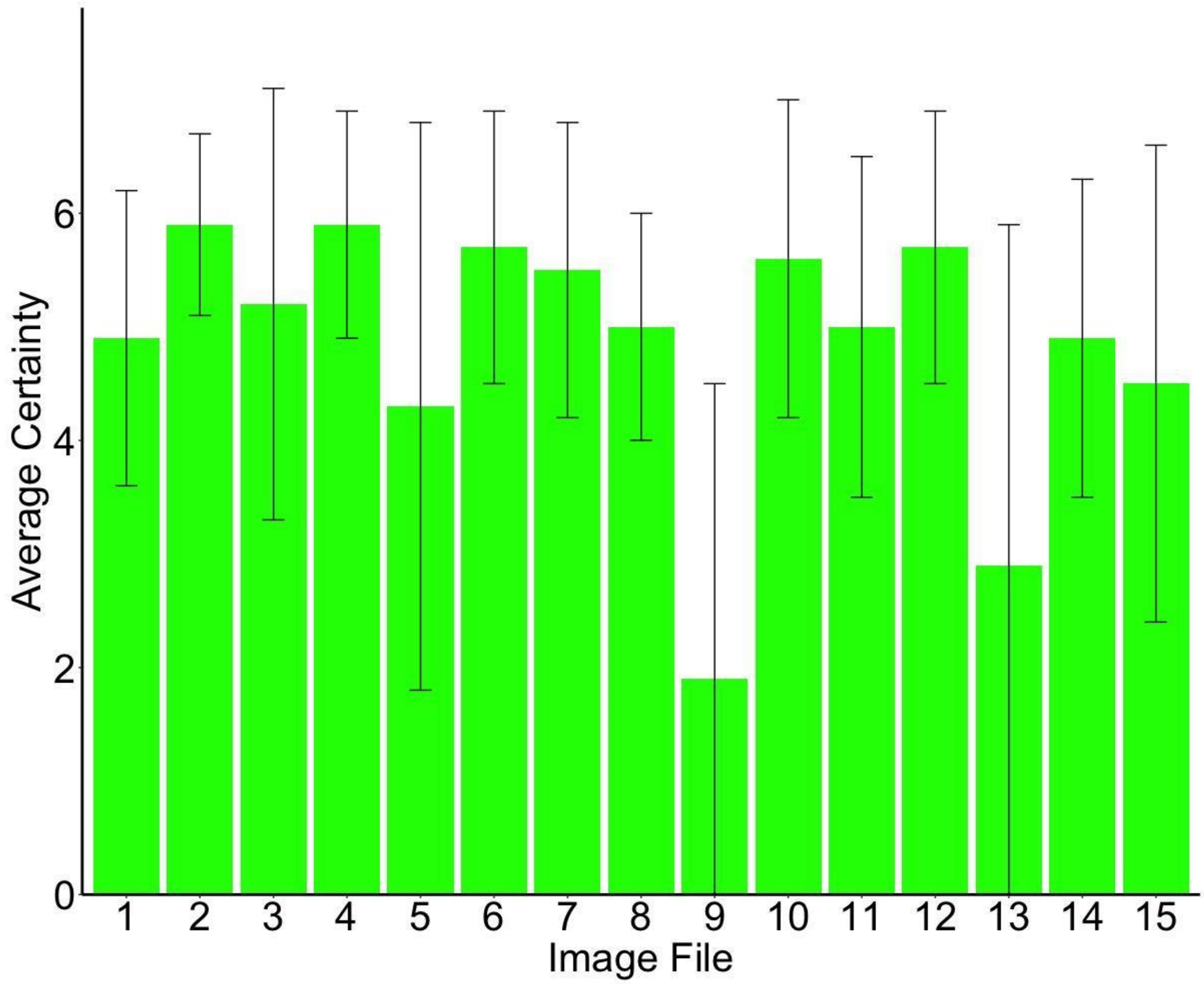

Figure 14 – Average certainty score per image file. The average certainty scores of the 15 tiger shark (*Galeocerdo cuvier*) image files by the 15 observers that participated in the second iteration tiger shark photo-ID method validation test. Error bars depict standard deviation.

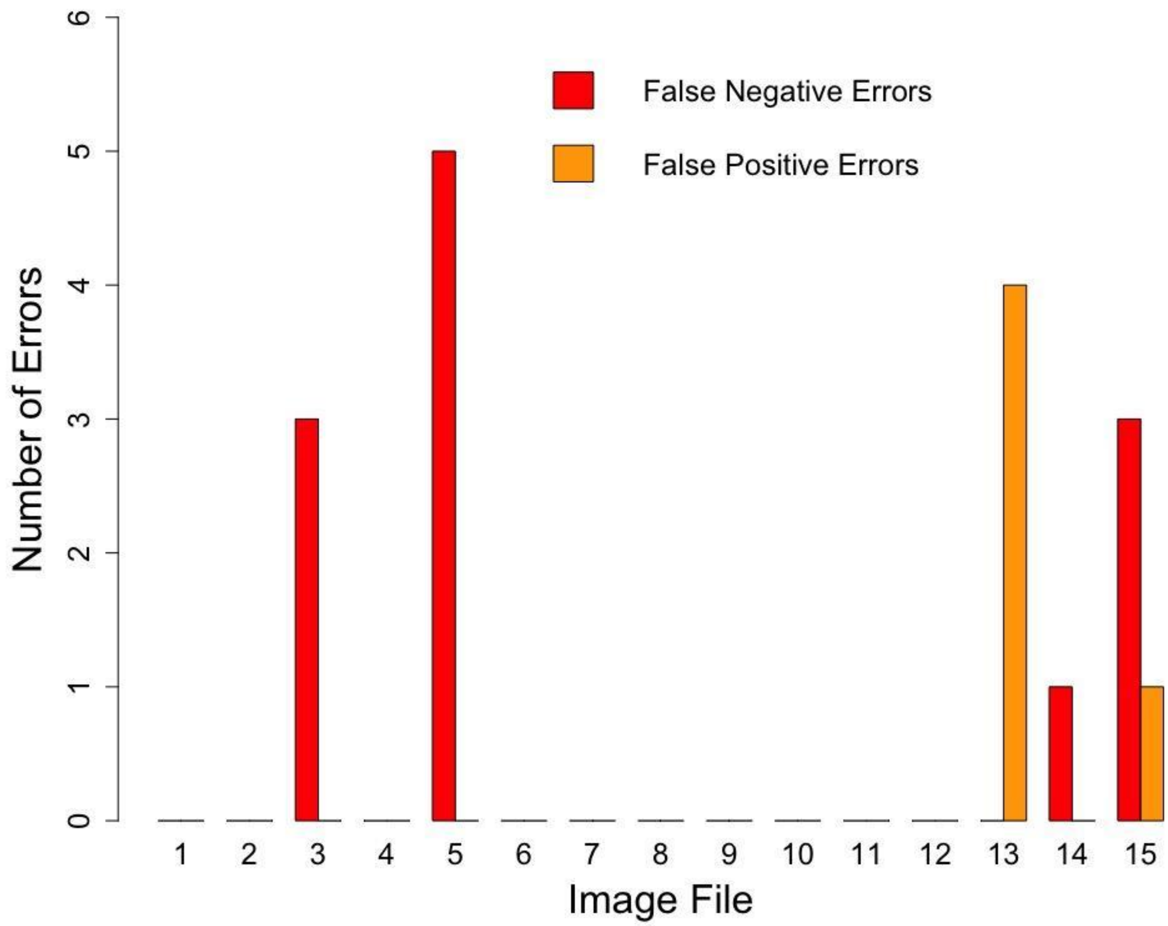

Figure 15 – Type and number of errors per image file. The total number of false negative and false positive errors made on each of the 15 tiger shark (*Galeocerdo cuvier*) image files by the 15 observers that participated in the second iteration tiger shark photo-ID method validation test.

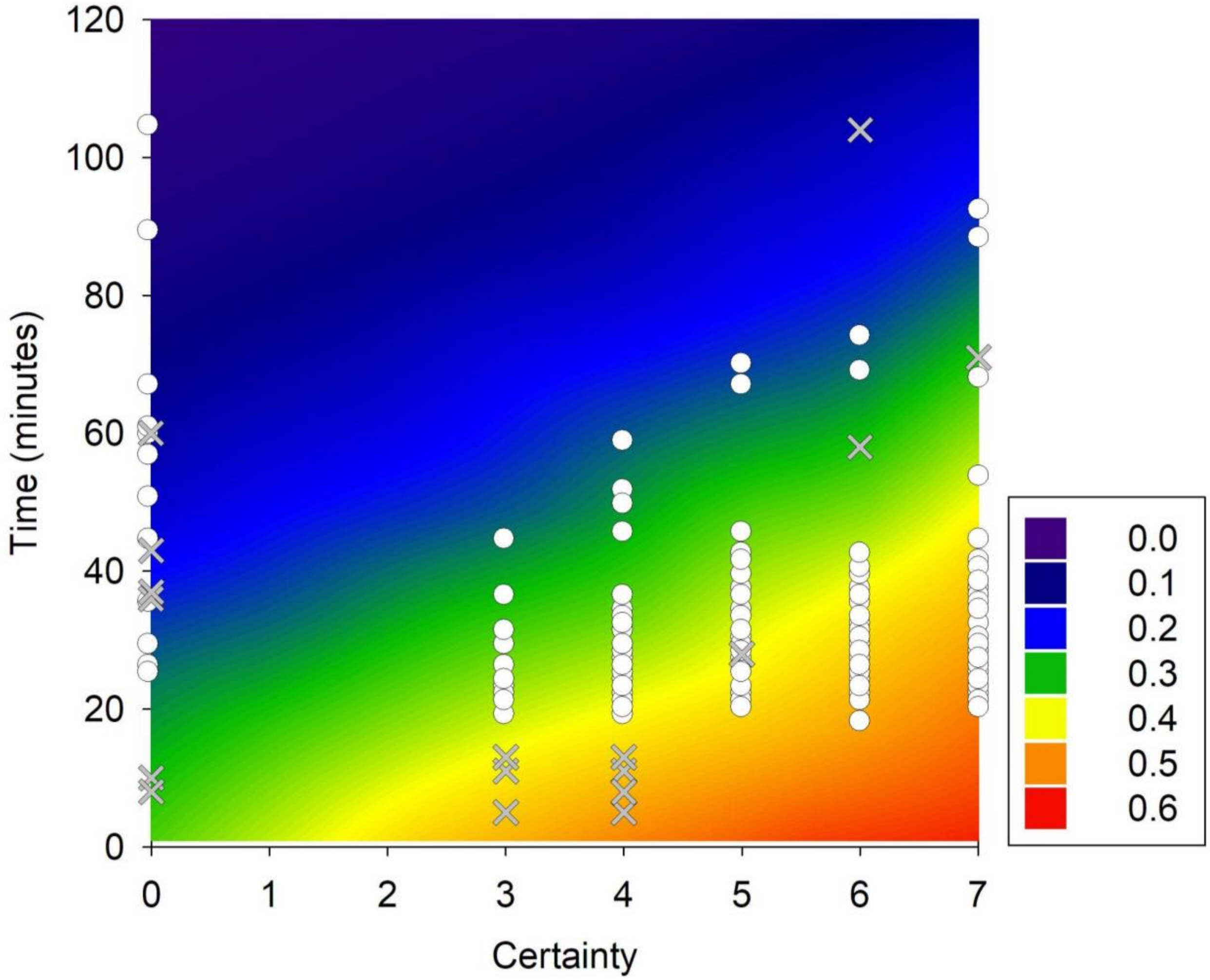

Figure 16 - Observed and simulated probabilities of making a correct ID according to time and certainty. A total of 51,000 simulated entries with randomized variables of time to ID in minutes and certainty from 0 to 7 were entered into the model to produce simulated probabilities of making a correct tiger shark (*Galeocerdo cuvier*) ID, as represented by the colored region. Purple represents a 0 probability of making a correct tiger shark ID with warmer colors increasing in probability up to 0.6 for red. The observed tiger shark IDs of the 15 observers who participated in the second iteration tiger shark photo-ID method validation test are overlaid according to the observer's certainty score and time in minutes to make each tiger shark ID with circles representing correct IDs and Xs representing incorrect IDs.

Figure 17 – Time series of W1M26 in West Hawaii from 2009 – 2020 demonstrating the potential life-history information to be collected using re-sight photo-ID data such as reproductive status, anthropogenic impacts, and hook prevalance.

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