



Three decades of stranding data reveal insights into endangered hawksbill sea turtles in Hawai'i[†]

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ABSTRACT: Hawksbill sea turtles *Eretmochelys imbricata* inhabiting the Hawaiian Islands are extremely rare and listed as endangered under the US Endangered Species Act. The paucity of data on basic hawksbill ecology continues to hinder effective management of the species. We analyzed stranding data collected between 1984 and 2018 to gain insights into the distribution, demography, and conservation challenges facing hawksbills in Hawai'i. In doing so, we present a comprehensive description of the population across developmental stages and rank threats that may be impeding their successful recovery. Over the >30 yr data set, we recorded a total of only 111 juvenile and adult hawksbill stranding events. Interactions with nearshore recreational fishing gear were documented for a large proportion (48.6%) of stranding events in the Hawaiian Islands, identifying this as the primary management challenge for the species. Stranding events were biased towards females (female to male sex ratio of 4.8:1.0), which may be indicative of the population as a whole. Even though the majority of hawksbills nest on the islands of Hawai'i Moloka'i, and Maui, the greatest number of juvenile to adult strandings was found to be on the island of Oahu (n = 47). Temporal distribution of the majority of adult hawksbill strandings (72.2%) occurred during a 4 mo period between June and September. We discuss these and other findings that help identify future research and conservation efforts to mitigate anthropogenic threats in Hawai'i for this enigmatic population.

KEY WORDS: *Eretmochelys imbricata* · Protected species · Threat assessment · Population monitoring · Coastal fisheries · Sex ratios · Hawai'i

1. INTRODUCTION

The documentation of strandings by marine organisms can lend unique insights into various issues relevant to wildlife management, including population

assessments, identification of habitat, interspecific interactions, and primary threats (Lopez et al. 2002, Jessup et al. 2009). Identifying threats is particularly important for small and highly endangered species, as threat mitigation may ultimately determine the sur-

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[†]This article is dedicated to the memory of the lead author, Shandell Brunson, who passed away unexpectedly shortly before publication. She will be dearly missed by her family, friends, and co-workers.

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vival outcome of populations (Lewison et al. 2004). Sea turtles are a globally distributed and extremely vagile taxon, exposing them to myriad threats and leading to discrete populations often enduring distinct conservation realities (Wallace et al. 2011).

The hawksbill sea turtle *Eretmochelys imbricata* is a highly threatened species that has seen global population declines of >80% during the 20th century (Mortimer & Donnelly 2008). The primary historical threat and cause of population declines has been the unsustainable harvest of hawksbills for their shells (Donnelly 2008), leading to various conservation policies, including protections under the US Endangered Species Act in 1973 and listing in Appendix I of the Convention on International Trade in Endangered Species of Wild Fauna and Flora in 1975.

Both hawksbill and green *Chelonia mydas* sea turtles are the primary nearshore residents around the Hawaiian Islands, yet population estimates for these 2 species in the region contrast markedly, with those for green being several orders of magnitude greater than the hawksbill (Balazs & Chaloupka 2004, Seitz et al. 2012, Gaos et al. 2020). An average (\pm SD) of only 14 ± 4.3 hawksbills have been documented nesting annually on the Hawaiian Islands (Seitz et al. 2012, Gaos et al. 2021), compared to 385 ± 198.6 for green turtles (Balazs & Chaloupka 2004, Pacific Islands Fisheries Science Center (PIFSC) unpubl.), highlighting the precarious state of hawksbills in the region. Historically, hawksbills are believed to have been much more abundant around the Hawaiian Islands, and efforts to recover the population have been cited as an urgent conservation need (Van Houtan et al. 2012). Although the causes for the discrepancy in population sizes for these 2 species remain unclear since both species have been afforded similar protections over time, efforts to identify, quantify, and mitigate threats to hawksbills will be needed to advance recovery efforts of the population.

In this study, we analyzed records of hawksbill strandings between 1984 and 2018 from the Hawaiian Islands to highlight conservation challenges facing the species. We also used informa-

tion on the distribution, size, and sex of stranded individuals to gain further insights and identify future research needs for this data deficient population.

2. MATERIALS AND METHODS

2.1. Study site

This study includes information on hawksbill strandings available for all the islands in the Hawaiian Archipelago, USA, located in the North Central Pacific Ocean and representing the most geographically isolated archipelago on the planet (Juvik et al. 1999). This archipelago includes the Main Hawaiian Islands (MHI) as well as the mostly uninhabited Northwest Hawaiian Islands (NWHI), comprising a chain of small islands and atolls stretching approximately 2000 km to the northwest of the MHI (Fig. 1).

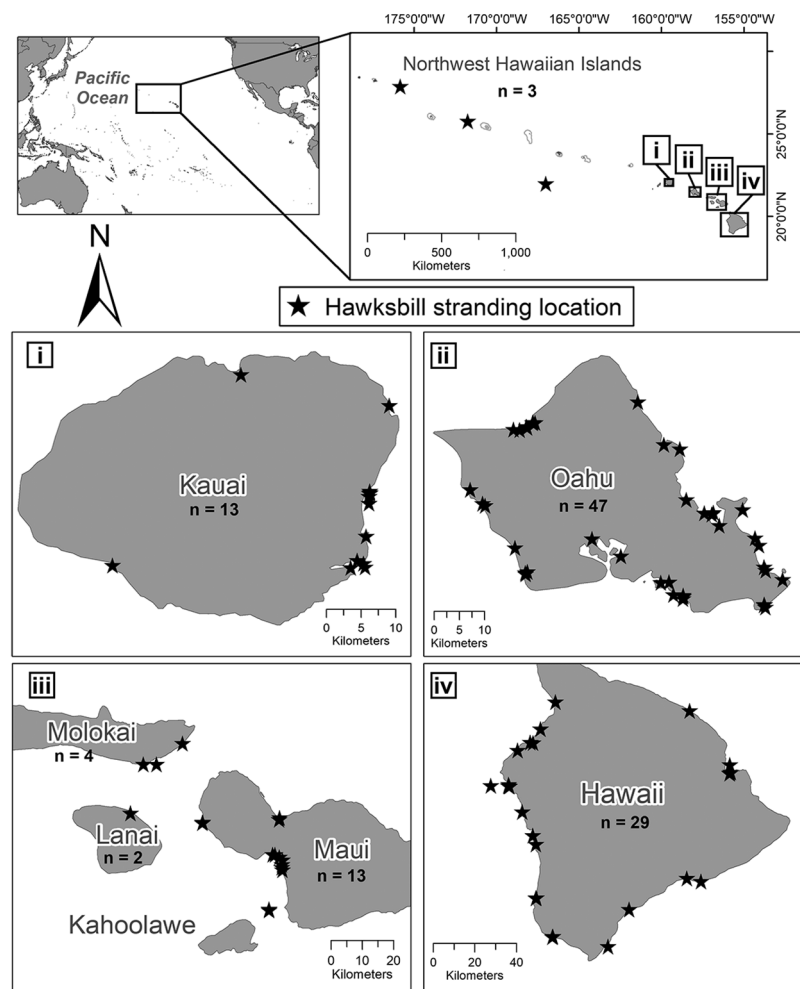


Fig. 1. Study area, depicting stranding events for juvenile–adult (i.e. excluding hatchlings) hawksbill turtles (black stars) in the state of Hawai'i between 1984 and 2018

2.2. Stranding response, data collection, and sample processing

We define a stranding as any instance where a turtle was encountered sick, injured, or dead. Strandings around the Hawaiian islands were reported by the general public as well as collaborating agencies throughout the state to a telephone hotline that has been continuously operated by the NOAA Pacific Islands Fisheries Science Center since 1982 (Work et al. 2004, 2015, Chaloupka et al. 2008). NOAA staff and/or collaborating partners, when possible, visited the site of the stranding to collect data and transport the animal to the NOAA facilities on Oahu for further evaluation. For each turtle, we recorded circumstances of stranding (e.g. how the turtle was found, whether alive or dead, on the beach, or in the water) and any potential impacts (see below), date, time, location, as well as body measurements including curved carapace length (CCL; measured from nuchal notch to posterior-most tip of marginal scutes) and a subjective assessment of emaciation (concave plastron). Adult turtles were also visually assessed to determine sex, with males identified by the presence of a distinctly large tail extending approximately >25 cm from the carapace. Sex was also determined by examination of gonads during necropsy. Turtles were examined for previously applied identification tags such as Inconel (National Band & Tag) and passive integrated transponder (Avid Identification Systems) flipper tags.

If a live turtle was determined to be in good health, identification tags were applied and it was immediately returned to the ocean, while those determined to require additional treatment were evaluated by a veterinarian. Hawksbills requiring extended rehabilitation were retained in aquaria at NOAA's Kewalo Research Facility (1984–2013) or Inouye Regional Center (2013–2018). All captive care practices adhered to US Fish and Wildlife Service guidelines (permit No. TE-72088A-1) and Institutional Animal Care & Use Committee protocols (permit No. SWPI 2013-05R). Captive hawksbills were either released near their initial stranding site if they were judged clinically well enough or euthanized in cases that deteriorated or were in extremely poor health condition (as per Work et al. 2015).

Dead turtles (stranded or euthanized) underwent a systematic external exam, and when possible, necropsies were conducted to gather additional information and samples. Data collected at necropsy included overall (1) post-mortem state, which was a subjective grading of the level of decomposition of

the carcass and involved criteria such as degree of bloating, eye clarity, odor, etc. and (2) body condition, which was a degree of fat content as observed, ranging from emaciated (plastron concave) to obese (coelomic fat observed) (see Work et al. 2015). Turtles were rated as good, fair, or poor for both post-mortem state and body condition. In addition, sex (via examination of gonads), mass (kg), CCL, and any morphological abnormalities were documented (Wyneken 2001, Work et al. 2004, 2015). As appropriate, various tissue samples (skin, stomach contents, humeri, and organs) were examined, collected, and archived for future analysis, and in cases where the post-mortem state of the animal was suitable, representative tissues were collected for histopathology.

2.3. Data analysis

We categorized hawksbills into 3 broad life-stage categories based on CCL: hatch-year (≤ 8 cm), juveniles (>8 –75 cm), and adults (>75 cm). We subsequently categorized juveniles into 4 additional size classes: pelagic-stage juveniles (>8 –20 cm), small juveniles (≥ 20 –40 cm), medium juveniles (≥ 40 –60 cm), and large juveniles (≥ 60 –75 cm) (Balazs 1980, Van Buskirk & Crowder 1994, Monzón-Argüello et al. 2010, Seitz et al. 2012, Balazs et al. 2015, Chacón-Chaverri et al. 2015, Liles et al. 2015, Llamas et al. 2017). Recognizing that hatchling life-stage turtles might have recently emerged from nests deposited in the areas where they were found, we removed hatchling stranding events from our analyses ($n = 50$).

For all non-hatchling life stages (hereon referred to simply as 'juvenile–adult'), we classified strandings into 11 major impact categories based on findings gathered during stranding events, external physical exams, and necropsies (Table 1). If it was not possible to associate any impacts with a stranded turtle, it was categorized as 'unidentified'. We recorded all categories associated with each individual juvenile–adult turtle, i.e. a single turtle could have findings associated with multiple impact categories.

Determination of recorded sex for all individuals was later used to assess sex ratios, which were calculated by dividing the value for the more prevalent sex by the least prevalent. Recognizing that sex ratios could be biased by increased adult female impacts due to nesting behavior on land, we omitted these adult females ($n = 5$) from our sex ratio calculations.

Data were tabulated, analyzed, graphed using Microsoft Excel v.14.16.2, and mapped using ArcGIS v.10.4.1 (ESRI). Mean values, SD, and ranges are

Table 1. Description of impact categories associated with hawksbill turtle stranding events

No.	Stranding impact category	Category description
1	Fishing gear	Signs of direct hooking, entanglement, entrapment, or ingestion of fishing gear (e.g. lines, nets, and traps)
2	Emaciation	Reduced fat reserves resulting in emaciated physical state
3	Predation	Evidence of flipper amputations resulting from predation attempts
4	Internal pathology	Signs of internal pathology (e.g. enteritis, vascular fluke infection, buoyancy issue)
5	Geographic entrapment	Turtle marooned in a natural geographic feature (e.g. crevice)
6	Vessel strike	Evidence of being struck by a boat (i.e. major propeller wounds on the carapace)
7	Automobile strike	Evidence of being run over by an automobile
8	Ingested plastics	Identification of large proportion of plastic debris in the gastrointestinal tract during necropsy
9	Flood (tsunami)	Turtles washed inland during tsunami
10	Physical deformity	Major natural abnormality in the shape of the spine or carapace
11	Unidentified	Unable to identify any impacts

reported throughout this paper. All data used in this study are continuously updated and publicly available via the NOAA web portal at the Pacific Islands Fisheries Science Center (www.pifsc.noaa.gov/psd/).

Fishing gear in Hawai'i is defined as either non-commercial (recreational and subsistence) or commercial. Since it is not currently possible to assign types of fishing gear recovered from stranded turtles to either of these types, we defined the type of gear (hook, fishing line, gill/rawl net, lobster/crab trap) as those types used by fisherman in nearshore coastal waters occurring in Hawai'i state waters within 3 nautical miles from shore.

3. RESULTS

Between October 1982 and December 2018, we recorded a total of 111 hawksbill stranding events in the Hawaiian Islands (Table 2): 3 post-hatchlings (>8–20 cm), 75 juveniles (≥20–75 cm), 18 adults

(≥75 cm), and 15 cases where the size was not documented. Of the 111 stranding events, 89 (80.2%) resulted in mortalities and 22 (19.8%) resulted in cases where the turtle was released alive. A total of 31 juvenile–adult hawksbills were initially found alive, of which 12 died shortly thereafter and 1 was euthanized. An additional 12 individuals were released immediately on-site and 7 were released after receiving treatment by a veterinarian. Two (of the 3) post-hatchlings were released alive. Necropsies were performed on a total of 56 (50.5%) juvenile–adult turtles.

3.1. Size and sex of turtles

The average size (CCL) of juvenile–adult turtles ($n = 95$) was 52.6 ± 21.0 cm, ranging from 9.8 to 103.0 cm (Table 2). We were able to determine the sex of 58 turtles, 48 (82.8%) of which were females and 10 (17.2%) were males, for a combined female to male ratio of 4.8:1.0.

Table 2. Size classes and sexes of hawksbill turtles encountered during stranding events in Hawai'i between 1984 and 2018. CCL: curved carapace length

Size class	Size class range (cm)	No. of strandings	% of strandings	CCL (mean \pm SD)	Sex		
					Male	Female	Unknown
Post-hatchling juvenile	>8–20	3	2.7	14.3 \pm 3.9	0	0	3
Small juvenile	>20–40	24	21.6	33.0 \pm 4.6	0	13	11
Medium juvenile	>40–60	40	36.0	47.7 \pm 5.6	7	18	15
Large juvenile	>60–75	11	9.9	69.3 \pm 5.0	2	4	5
Adult	>75	18	16.2	87.7 \pm 7.0	1	14	2
Unclear	–	15	13.5	–	0	4	12
Total		111			10	53	48

3.2. Stranding impacts

Interaction with nearshore coastal fishing gear was the most prevalent threat for juvenile–adult turtles, comprising 35 (48.6%) turtles for which impacts were evident (Fig. 2A). Of the 35 records, the majority ($n = 25$; 71.4%) involved hook-and-line gear. The remaining 28.6% were related to gill/trawl net entanglement ($n = 7$; 20.0%) and lobster/crab trap entanglements ($n = 3$; 8.6%) (Fig. 2B). A single turtle may have had multiple threats; therefore, one stranded turtle does not equal one threat. For instance, a turtle may have interacted with fishing gear, been in an emaciated physical state, and had evidence of predation. Of the 72 strandings with associated impacts, 19 (26.4%) had multiple threats. We were unable to assign impact categories to 39 (35.1%) strandings, mainly due to advanced carcass decomposition that precluded determining the cause of stranding or death.

The second and third most important cause of stranding included emaciation ($n = 18$; 25.0%) and predation ($n = 9$; 12.5%). The remaining categories (Table 1) included internal pathology ($n = 8$), geographic entrapment ($n = 5$), physical deformity ($n =$

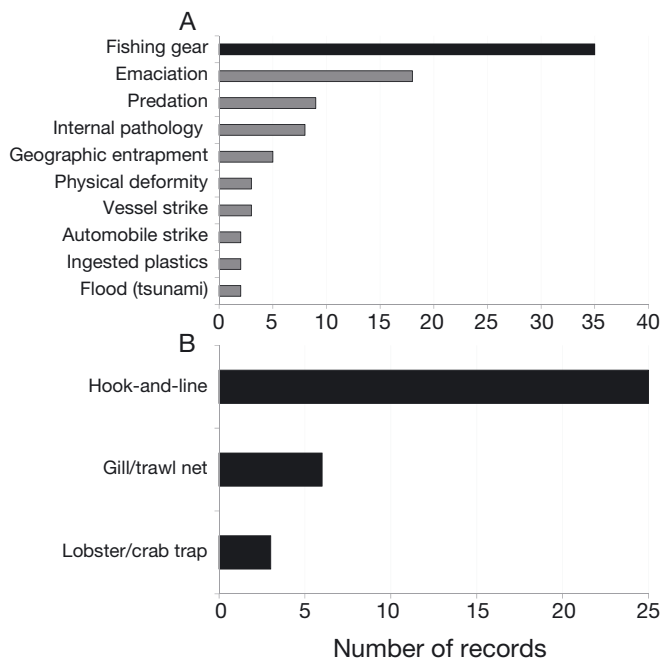


Fig. 2. (A) Impacts associated with strandings of 72 hawksbill turtles in the Hawaiian Islands between 1984 and 2018. A single turtle may exhibit multiple impacts. Of the 72 strandings, 19 (26.4%) were impacted by multiple threats. Figure excludes turtles for which no impacts were evident ($n = 39$). (B) Further classification of recreational fishing gear-type for the 35 hawksbills recorded in the fishing gear impact category

3), vessel strike ($n = 3$), automobile strike ($n = 2$), ingested plastics ($n = 2$), and flood/ tsunami ($n = 2$).

3.3. Spatial and temporal distribution of strandings

Most juvenile–adult strandings were recorded on Oahu ($n = 47$; 42.3%) and Hawai'i ($n = 29$; 26.1%), with occasional records from the remaining MHI and NWHI (Fig. 1).

An average of 3.2 ± 2.5 stranding events occurred annually between 1984 and 2018, with a maximum of 12 events occurring in 2018 (Fig. 3A). Adult stranding events were less common, with an average of $0.5 \pm 0.7 \text{ yr}^{-1}$, while juvenile strandings were more common, with an average $2.2 \pm 2.1 \text{ yr}^{-1}$. Most adults (72.2%) stranded between June and September (Fig. 3B).

4. DISCUSSION

We found the most important causes of hawksbill strandings in Hawai'i to be fishing gear interactions, emaciation, and predation. Interaction with nearshore fishing gear was identified as the primary threat, which highlights the need to focus management and conservation efforts towards mitigation of sea turtle interactions with nearshore fisheries.

The relative proportion of hawksbill stranding events associated with fishing gear was particularly concerning, with nearly half (48.6%) of the stranding events showing obvious signs of gear interaction. The fishing gear identified within the hook-and-line fisheries threat mainly consisted of monofilament or Kevlar™ line of various test strengths and circle or J-hooks typically used by fishermen targeting nearshore coastal marine resources within State-managed waters (Honebrink & Hendricks 2016, Delaney et al. 2017) as opposed to commercial fishing gear used by US federally managed pelagic longline fishing vessels (Watson & Kerstetter 2006, WPRFMC 2018). Several of these stranding events occurred under circumstances where the cause of death was confirmed. This included 6 cases where the turtle was hooked or entangled in fishing line that was ensnared on the substrate, or where the turtles were caught in a lobster/crab trap, thus preventing them from surfacing for air (i.e. resulting in drowning). Additionally, in all 7 cases of the gill/trawl net stranding impact category, the turtles were so entangled it would have been impossible for them to move (to dive, feed, breathe, etc.), eventually leading to mortality.

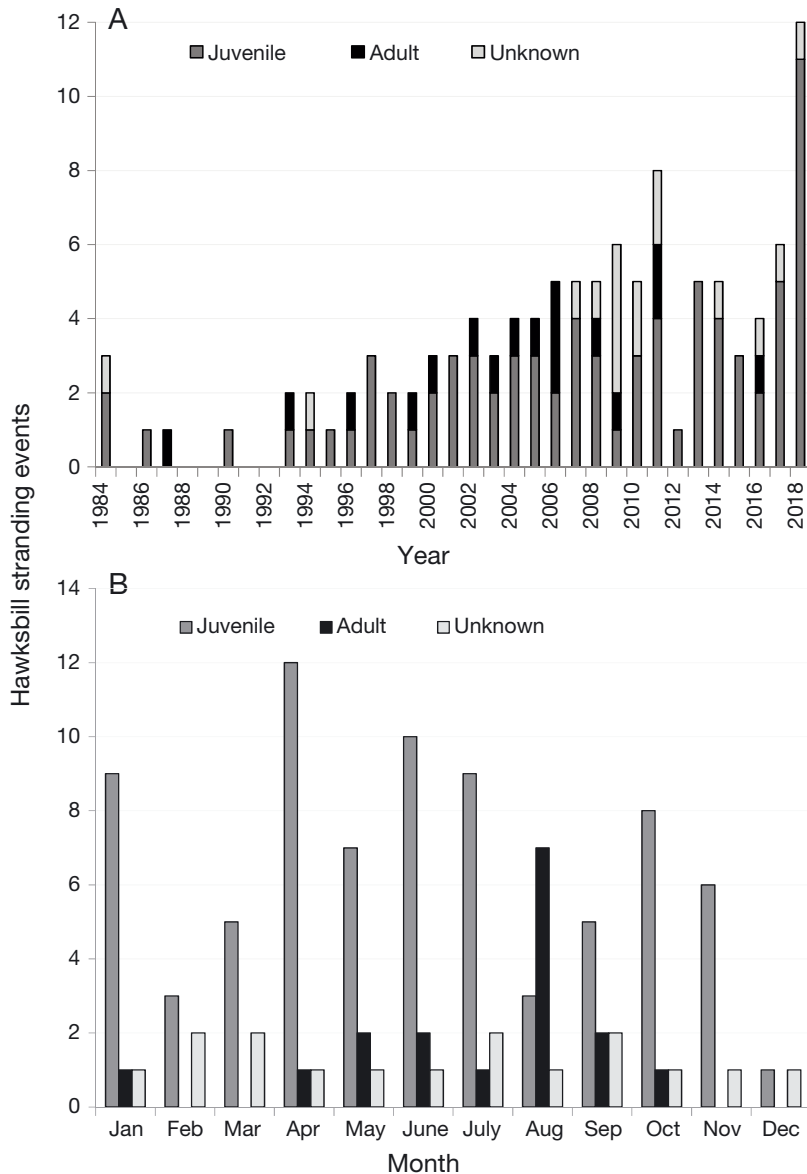


Fig. 3. Number of hawksbill turtle stranding events per (A) year for juvenile, adult, and unknown life stages between 1984 and 2018 and (B) cumulative stranding events by month for juvenile and adult life stages between 1984 and 2018

Hook-and-line (within the nearshore fishing gear impact category) accounted for 71.4% of the fishing gear impact records (Fig. 2B). The gear encountered indicates that nearshore coastal fishers caused nearly all of these interactions, which is not particularly surprising considering that hawksbills also use neritic habitats for foraging (e.g. Parker et al. 2009, Gaos et al. 2012a,b). We found multiple hooks ingested within 3 of the necropsied turtles, including 2 turtles with 2 hooks and one turtle with 3. These 'repeat offenders' may represent turtles that forage in coastal fishing hotspots and thus are more vulnerable

to gear interactions. One way to help reduce the impacts of these interactions is to remove any derelict fishing line and gear found along the beaches and reefs and place them in designated fishing line recycling bins.

We were unable to associate a large proportion of stranding events to any specific impact category, and thus these cases remain unidentified. It should be noted that turtles in several of the other categories (e.g. emaciated, internal pathology, predation) may have also had other threats contributing to the cause of stranding. However, carcass condition, an inability to conduct necropsies, or a lack of any obvious external signs would have prevented us from attributing these strandings to a specific threat.

A subjective assessment of emaciation, or level of body fat reserve, was scored for each turtle, with 25% (18 of 72) of stranded turtles identified as 'emaciated'. Additionally, emaciated turtles were disproportionately (83%) juveniles (15 of 18). Drawing from literature among other species of marine turtles (Monteiro et al. 2016), emaciation can result from poor habitat quality and insufficient forage (Wabnitz et al. 2010), which may also explain our findings in and around the MHI. If so, this idea of limited forage density may be one reason why population levels have remained relatively low in the region. Further research on hawksbill foraging items in the Hawaiian Islands will need to be conducted to explore this possibility.

Of interest was evidence of healed tissue, often around partial amputation of a flipper, suggestive of a predation event, most likely due to sharks (Stacy et al. 2021). These types of bodily injuries were observed in 12.5% (9 individuals) of total strandings and may indicate the vulnerability of hawksbill turtles in this region to multiple threats. Observations were made across size classes, indicating a lack of a specific bias in different life-history stages.

Threats impacting adult hawksbills merit specific recognition considering the high reproductive value of this life stage (Crouse et al. 1987, Crowder et al.

1994, Heppell 1998). Five of the 14 adults recorded in this study showed signs of interacting with fishing gear. Rather unique to this location is the finding that 4 adult hawksbills died in stranding events associated with geographic entrapments (specifically, crevasses in lava fields) and 2 adults died from automobile strikes. The 4 geographic entrapment events occurred when nesting females emerged from the water and became wedged in the rocks within large volcanic fissures in the vicinity of the primary hawksbill nesting beaches on the southern coast of the Island of Hawai'i (Seitz et al. 2012, Kurpita 2016). The other 2 females were struck by vehicles while crossing North Kihei Road on Southern Maui. These 6 strandings occurred during emergence from or returning to the ocean during nesting as opposed to previously described stranded turtles found washed ashore.

One adult and one juvenile hawksbill were encountered after presumably being washed inland by the tsunami resulting from the magnitude 9.0–9.1 undersea earthquake off the coast of Japan on 11 March 2011 (https://www.tsunami.gov/previous.events/?p=03-11-11_Honshu). Both turtles were encountered by researchers and were returned to the sea alive, but each had been trapped in isolated locations whereby they would not have been able to return to sea without human assistance.

One juvenile hawksbill was encountered on Pearl and Hermes Atoll in the NWHI in 2003. The turtle was found washed ashore, entrapped in netting, and was released to the sea alive (Donohue 2003). The fact that this turtle was encountered is quite remarkable considering the isolated and uninhabited nature of this atoll, where staff conducting research on Monk seals *Monachus schauinslandi* serendipitously happened to be present in the area. This phenomenon of increased detectability of strandings near populated areas is reflected in our stranding data but is also a bias in our monitoring efforts.

Our documentation of 111 hawksbill stranding records from the Hawaiian Islands over more than 3 decades is considerably less than the ~9700 green turtle strandings recorded over the same time frame (PIFSC 2018). This difference is likely a reflection of the stark differences in population sizes between these 2 nearshore species and not an indication of a disproportionate number of strandings by species.

The hawksbill population in the Hawaiian Islands was historically and is currently extremely small (Balazs 1978, Van Houtan et al. 2012) and has even been described as the smallest sea turtle population on the planet (Van Houtan et al. 2016). No current estimates exist on the total number of hawksbill turtles (i.e. ju-

veniles and adults) in Hawai'i. However, the number of individuals documented nesting on the MHI is extremely low (Snover et al. 2013), with an annual average of approximately 14 nesting females and a cumulative total of 178 nesting females (and 1280 nests) documented between 1988 and 2018 (Gaos et al. 2021). In comparison, the central North Pacific green turtle population has been estimated to have 3846 nesting females (Seminoff et al. 2015).

An investigation into the temporal or seasonal component of our strandings data demonstrated the majority (72.2%) of adult hawksbill strandings occurred during a 4 mo period between June and September (Fig. 3B), which coincides with the primary hawksbill nesting season in Hawai'i (Seitz et al. 2012). With regards to a spatial component, observed strandings of adults have largely been confined to the southern tip of the Island of Hawai'i, which is in relative proximity to their primary nesting site (NMFS & USFWS 1998), and to a lesser extent near southern Maui, which also hosts a smaller number of nests (King et al. 2007, Seitz et al. 2012, Kurpita 2016, Hawai'i Wildlife Fund 2019). The timing and location of adult strandings suggest an association with breeding, which may be worthy of further analysis, especially given the high reproductive value of adult individuals in a critically endangered population such as hawksbills in Hawai'i.

Sightings of juvenile (<20 cm) marine turtles are often rare, given that during these 'lost years' (Carr 1952) young individuals are commonly believed to leave natal areas and spend a multi-year period entrained in major offshore currents, often circulating entire ocean basins (Bolten 2003, Luschi et al. 2003, Mansfield et al. 2014). However, this paradigm has been challenged for hawksbills in Hawai'i (Van Houtan et al. 2012), and recent research has suggested that post-hatchling hawksbills in the Eastern Pacific may lack or undergo a truncated open-ocean phase (Gaos et al. 2017), a scenario that may also be playing out in Hawai'i. We documented 3 pelagic-stage juvenile hawksbills (i.e. >8–20 cm size class), two of which were encountered in-water approximately 5 km from shore, one caught by a recreational troll-fisher, and the other found adrift, entangled in a net. A third animal in this size class was stranded on land on Kauai, 100s of km from its primary nesting beach on Hawai'i. Investigations to understand the movement patterns of hatchling hawksbills, including particle modeling, acoustic tracking of hatchlings, and satellite telemetry of post-hatchling juveniles, will be important to better understand hatchling dispersal patterns as well as juvenile

movements in Hawaiian waters (Gaspar et al. 2012, Thums et al. 2013, Mansfield et al. 2014).

Understanding population sex ratios is an important component of wildlife management and represents a key parameter for population modeling (Lande 1988, Tarsi & Tuff 2012, Allen et al. 2015). Understanding the mechanics of this phenomenon is particularly true for marine turtles, as they exhibit temperature-dependent sex determination during the egg incubation period. From this study, we identified a nearly 5-fold increase in stranded females compared to males. Assuming relatively similar vulnerabilities to becoming stranded between the sexes, and excluding nesting females, our data suggest the potential for a large female bias in the overall population of hawksbills in Hawaiian waters. Several marine turtle studies have reported highly female-biased hatchling and juvenile sex ratios in marine turtle populations (Jensen et al. 2018, Liles et al. 2019, PIFSC unpubl.). Directed studies to establish baseline sex ratio information for hawksbills in Hawai'i (e.g. using hormone assays; Allen et al. 2015) are needed, particularly in the face of a projected rise in global temperature which has the potential for feminization of turtle populations (Hawkes et al. 2009, Pike 2014), all of which would be important parameters to include in population models that can assist in the conservation and management of this critically endangered species.

Despite the numerous challenges posed by responding to stranding events of marine species across extensive and often remote coastlines, this study illuminates the importance of continued monitoring and recording of biological data from both stranded and nesting hawksbill turtles. Interaction with nearshore coastal fishing gear was identified as the primary threat to population growth, which highlights the need to focus management and conservation efforts towards mitigation of sea turtle interactions with nearshore fisheries. Further research is necessary to examine the role of environmental factors, such as foraging habitat and climate change, which may also be contributing to the threats facing the Hawaiian hawksbill population.

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