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Marine debris impacts on Hawaiian green sea turtles (*Chelonia mydas*): High prevalence of hook-and-line fishing gear in strandings

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ABSTRACT

Stranding data are critical for monitoring threats to sea turtles. By analyzing four decades of green turtle (*Chelonia mydas*) strandings from the Main Hawaiian Islands, we elucidate temporal and spatial trends. In Hawai'i, fibropapillomatosis (FP) has been the dominant threat for stranded turtles since records began in 1982. In the last decade (2010–2019), FP constituted on average 25 % of stressors in stranded turtles, followed by fishing lines (22 %), hooks (8 %), shark predation (5 %), boat strikes (5 %), and net entanglements (3 %). As of 2016, fishing line injuries constitute the most common primary threat. Turtles injured by lines and hooks were often found and released alive (hooks: 86 % alive, lines: 64 % alive), underscoring the importance of timely reporting and response. O'ahu was found to be the main hotspot for hook-and-line strandings, while there was more variation across islands for the other stressors. Spatial predictions highlighted areas without prior stranding observations, suggesting that some strandings may go undetected. As the main hotspot for fishing line strandings, we modelled the presence of derelict line around O'ahu using data from in-water debris cleanup efforts; we found that (1) derelict fishing line was positively associated with shore access points and boat harbors and (2) negatively associated with human population density. The increase in strandings with fishing line could be a result of the recovering turtle population and their overlap with year-round coastal fishing activities. Our findings emphasize the need for sustained cleanup efforts and measures to reduce fishing gear losses and interactions with non-target species.

1. Introduction

In tropical marine ecosystems, green sea turtles (*Chelonia mydas*) are keystone megaherbivores that provide essential ecosystem services through maintaining seagrass beds (Cardona et al., 2020) and preventing overgrowth of macroalgae on coral reefs (Duarte et al., 2013; Lefcheck et al., 2019). The species is considered an indicator of ecosystem health due to its ecological importance and life history traits, in combination with known vulnerabilities to human perturbations on the environment (Aguirre and Lutz, 2004; Domiciano et al., 2017). Anthropogenic activities such as habitat degradation, overharvesting of eggs and adults, fisheries interactions and bycatch, as well as climate change, contribute to its status as a globally endangered species (Seminoff, 2023). Through directed conservation efforts and legal protection (e.g., US Endangered Species Act), individual populations, such as the Hawaiian green turtle, known locally as *honu*, have increased appreciably after years of overexploitation (Balazs and Chaloupka, 2004). However, many threats to sea turtles still exist (Fuentes et al., 2023), and as such, there is a continued need for reliable monitoring of population dynamics (Piacenza et al., 2017), and contemporary anthropogenic and environmental threats (Hamann et al., 2010).

In Hawai'i, plastic pollution in the marine environment and its effects on local fauna like the green turtle is a concern for researchers (Clukey et al., 2017), conservationists and non-governmental

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organizations (NGOs), as well as the public and the press (Barney and Van Dyke, 2020). The massive marine debris problem in Hawai'i comes from diverse sources and consists of myriad types, each with different impacts to the region (Brignac et al., 2019; Royer et al., 2023). Abandoned, Lost or Discarded Fishing Gear (ALDFG) constitutes one type, which includes all fishing gear in the environment no longer actively managed, whether it is lost accidentally or intentionally. ALDFG is estimated to make up 80 % of marine plastic pollution in Hawai'i (Lynch, unpublished data), and the vast majority is not from local sources. Instead, it is mostly floating trawl netting tangled into conglomerates with ropes from distant fisheries that has accumulated in the North Pacific Garbage Patch (Royer et al., 2023). This floating ALDFG washes into Hawai'i (Maximenko et al., 2018; Royer et al., 2023) where it poses a long-term threat to marine life, through entanglement and entrapment of invertebrates, fish, mammals, reptiles and seabirds, as well as the destruction of coral reefs (de Carvalho-Souza et al., 2018; Donohue et al., 2001; Suka et al., 2020) and the release of microplastic (Wright et al., 2021).

A smaller proportion (mass or volume) of ALDFG stems from local hook-and-line fishing, where the monofilament lines readily sink as they are made with dense nylon (Brignac et al., 2019; Work et al., 2015). The coasts of the Hawaiian Islands have a year-round presence of line fishing (Delaney et al., 2017) and this fishing style can involve high loss rates on reefs (Williamson et al., 2014). The lines tend to accumulate on benthic structures such as corals (Pinheiro et al., 2023), causing damage and death of coral colonies (Asoh et al., 2004). A recent study investigating seafloor debris in three sites across Hawai'i revealed monofilament fishing lines as prominent among the detected items, while also underscoring the scarcity of data from this marine habitat (Brignac et al., 2019).

Even though fishing lines makes up a smaller share of the ALDFG debris in Hawai'i, it poses disproportionate lethal hazards to sea turtles. Monofilament lines are thin, typically transparent and thus difficult to spot in the water, making them a more cryptic threat for the turtles and for humans to remediate. Sea turtles incidentally caught or injured by fishing line or associated hooks are considered stranded – defined here as any marine turtle found on land or in the water that is dead, injured, or exhibits any indication of ill health or abnormal behavior. Hazards associated with derelict or active fishing lines and hooks include: tight constrictions around flippers which can lead to tissue death and flipper amputation (Work et al., 2015), or restricting the turtles' ability to reach the water's surface to breathe, leading to mortality; line constricting the neck and mouth, impeding their ability to feed; ingestion of hooks and line, causing internal blockages within the digestive system and buoyancy issues that can impede movement, predator avoidance, and feeding; external injuries from hooks that may cause bleeding and infection and impede movement.

In a previous assessment of stranding records from the Hawaiian green turtle population, Chaloupka et al. (2008) found fishing line and hook injuries to be responsible for 7 % of the stranding events from 1982 to 2003. In the two decades since that assessment, the Hawaiian green turtle population has increased by 5.4 % annually (Balazs et al., 2015) while fishing line has presumably accumulated in the nearshore environment (Pinheiro et al., 2023). Therefore, an updated assessment of hook-and-line fishing gear as a stranding cause is warranted.

In this paper, our goal is to understand the prevalence of nearshore hook-and-line fishing gear, a type of ALDFG and marine plastic pollution, as a stranding threat for green turtles in the Main Hawaiian Islands (Hawai'i, O'ahu, Maui, Kaua'i, Moloka'i, and Lāna'i, excluding Kaho'olawe and Ni'ihau). We analyze four decades of stranding records (1982–2024) to elucidate temporal trends and examine the rates of mortality associated with each threat. The main stranding threats include fishing line, hook, net, boat impact, shark predation and fibropapillomatosis (FP), and we examine the prevalence of all in order to provide the context needed to interpret our findings about hook-and-line fishing gear. We further utilize the recorded locations of turtle strandings in combination with anthropogenic and environmental variables to map stressor-specific stranding occurrences across the Main Hawaiian Islands. Additionally, to advance our understanding of accumulation of fishing line, we employ a spatial modelling approach using benthic marine debris data collected by a clean-up organization to predict accumulation of derelict lines in nearshore O'ahu. By analyzing this and the long-term stranding data, we aim to identify temporal and spatial trends that can inform natural resource managers and policy makers.

2. Methods

2.1. Stranding events in the Main Hawaiian Islands

2.1.1. Sea turtle stranding database

Sea turtle stranding data within the Main Hawaiian Islands are collected by the state-wide stranding response network which is managed by NOAA Fisheries and includes the State of Hawai'i and other authorized response partners (e.g., local NGOs). NOAA Fisheries' Marine Turtle Biology and Assessment Program is the data steward, and also conducts investigations into the cause of strandings. From NOAA Fisheries' state-wide marine wildlife stranding hotline, response partners receive public reports of turtles that are stranded and/or appear in ill health or dead. Information on time, location and other circumstances, as well as an initial assessment of the turtle's health is recorded, while more detailed descriptions and data are collected during subsequent necropsy. Each stranded turtle is evaluated for the presence of individual stressors – defined as environmental, biological, or anthropogenic factors that negatively impact a sea turtle's health, behavior, or survival, potentially leading to stranding (i.e., evidence of multiple stressors may be present for a single turtle), and a primary threat of stranding, defined as the stressor that most likely caused the stranding given the evidence examined (i.e., this is not always a definitive cause of death as determined by a veterinary pathologist). The primary threat is determined as the most likely cause of stranding based on the most significant and severe gross lesion (Chaloupka et al., 2008).

Although records of five turtle species exist in the Hawaiian archipelago, the overwhelming majority (97 %) of turtles stranding are green turtles (Chaloupka et al., 2008). To investigate temporal trends in both stressors and primary threats of stranding (2.1.2), we utilize the full dataset (1982–2024) for green turtles, but for spatial analysis, we focus on a subset (2003–2018) to reflect recent dynamics and match the available environmental predictor data (2.1.3).

2.1.2. Temporal trends: prevalence of stressors and primary threats of stranding

The prevalence of stressors and primary stranding threats for turtles documented from 1982 through 2024 were investigated by quantifying the proportion of stressors and primary threats recorded for all green turtles stranded per year, estimating a linear regression of each stressor over time, and summarizing annual proportions using decadal means. We use proportions for this analysis due to the interannual variation in overall stranding numbers. This also accounts for the fact that observation effort, and hence total stranding numbers, has likely increased over time due to public awareness of reporting mechanisms, advancements in communication technology, and population growth (of both humans and turtles in Hawai'i). By analyzing the proportions within each year, we assume that any changes in overall reporting effort are distributed evenly across different stressors and primary threats.

For this study, we included the presence of any stressor on an individual turtle, i.e., a turtle could be subject to more than one stressor at the time of stranding. The main stressors considered are injuries from fishing line (entanglements and ingestions), fishing hooks (attached or ingested), fishing net entanglements (both local gillnets and distant trawl and gill ghost nets), boat strike impacts, shark predation and the presence of tumors, which indicates FP. For a turtle to be placed into a fishing gear stressor category, the fishing gear must have been present at the time of stranding (i.e., scarring indicating possible previous entanglement have not been counted). In addition to the main stressors, we grouped less frequently observed stressors as *miscellaneous*, which encompasses cases of human take (e.g., speargun injury), entrapment in fishing traps, turtles requiring an intervention to reach the sea (e.g., stuck between rocks on shore), or if foreign matter, such as plastic, was present in the gut of the turtle. Turtles with detected fishing line and/or hooks ingested were also counted as having foreign matter in the gut. If an individual did not have any of the main or miscellaneous stressors assigned, either due to lack of discernable threat upon inspection or if the turtle was unassessed, it was considered *undetermined*.

The primary threats categories mirrored the stressor categories, but also included cases of internal pathology (as determined from necropsies) which are added to the *miscellaneous* threats group. In the stranding database, 3784, or about 37 % of all stranded turtles were necropsied, which in some cases, provided additional information about stressors and further informed the assessment of the primary threat of stranding. We analyzed the full dataset for primary threats (i.e., cases with and without necropsy results) as the biologists and veterinarians assessing the turtles can confidently determine the primary threat of stranding (or assign it as undetermined) from external assessment without need for necropsy (see Fig. S1 for examples). We also considered "survival status" to shed light on the mortality linked to the different threats. We assess the final status (alive or dead) of all stranded turtles, i.e., both found alive as well as deceased, in addition to that of turtles exclusively found alive.

2.1.3. Spatial patterns: distribution of stranding probabilities by stressor

The compiled stranding observations offer a comprehensive overview of turtle strandings in the Main Hawaiian Islands, however, the data predominantly rely on public reports. We therefore expect underreporting in less frequented areas due to less human activity. To address this limitation and enhance the understanding of stranding patterns, we employ Maximum Entropy modelling (Maxent) (Phillips et al., 2017). Maxent is a probabilistic framework widely used in ecological studies to predict the distribution of species or phenomena based solely on observed presence data and a set of predictors (Elith et al., 2011). This method is particularly valuable when dealing with incomplete datasets, which is often the case with wildlife strandings. In addition, the modelling approach can provide insight into environmental factors that help explain the observed stranding data. It also investigates the degree to which the spatial patterns vary according to each stressor, which may not be readily apparent through the stranding records alone. We utilized Maxent to generate predictive models for each anthropogenic stressor contributing to turtle strandings, i.e., fishing lines, fishing hooks, fishing nets, boat strikes and FP; we did not investigate shark predation as it is a natural occurrence.

We selected nine fixed spatial predictors that represent critical environmental conditions assumed to affect both turtle presence as well as reported turtle strandings. As a proxy for primary productivity levels and to gauge the availability of habitat and feeding grounds, we considered chlorophyll-a long-term averages (2002–2013) (Kappel et al., 2017i), mean carbon phytoplankton biomass (Assis et al., 2018; Tyberghein et al., 2012), and percent coverage of macroalgae as well as corals, estimated from a polygonised habitat classification (BAE, 2007). As physical drivers of stranding, we included the average annual maximum wave power anomaly (2000–2013) (Kappel et al., 2017k), the average depth of the seafloor (Assis et al., 2018; Tyberghein et al., 2012), and an estimated cumulative shoreward velocity based on combining eastward and northward sea water velocity for the period 2003–2014 from the COPERNICUS Global Ocean Physics Reanalysis (CMEMS, 2024). We further incorporated a nearshore new development impact (2005–2010/2011) (Kappel et al., 2017c), reflecting anthropogenic activities and disturbance at Hawai'i's shoreline, and sediment export to nearshore water (Kappel et al., 2017i), indicative of reduced light penetration, both triggering reduced abilities to detect and avoid threats to individual turtles. Additionally, specific layers corresponding to each considered anthropogenic stressor were included, i.e., estimated catch data from both commercial and non-commercial line fishing (2004–2013) (McCoy et al., 2018) for fishing line and hook interactions (Kappel et al., 2017a,d,e), similar catch data for fishing net entanglements (Kappel et al., 2017b,f,h), compiled data from all non-commercial boat fishing activities for boat strikes (Kappel et al., 2017d), and total effluent from onsite sewage disposal systems for the presence of FP (Kappel et al., 2017l). Green turtle stranding data from 2003 to 2018 were used to ensure a temporal match with the environmental predictors. After removing duplicate points (keeping only one per cell) and points where predictors were not available, we ended up with 539 unique points for line entanglements, 206 for hooks, 135 with nets, 143 boat impacts, and 514 with FP.

All spatial layers were resampled to a cell size of approximately 525 m at the equator. Given that stranding locations were reported as point localities, the environmental data for these points were generalized by averaging over a 3×3 cell moving window, i.e., approximately 1.5 km, to better capture the wider conditions around the reported location. Missing data were imputed using the mean values from neighboring cells until all gaps were filled. The spatial analysis covered stranding incidents from 2003 to 2018 to align with the temporal availability of the predictor data while maintaining the largest share of the stranding data.

The strength of Maxent lies in its ability to use features and their transformations to estimate the likelihood of occurrence at sites that have not been sampled (Elith et al., 2011). Maxent thereby relies on background points (default: $n = 10{,}000$) to gauge the environmental background conditions (Elith et al., 2011). It assumes an unbiased collection of presence data and estimates response curves by contrasting these environmental background conditions to conditions at observed locations. However, the presence of reported strandings is presumably biased by the detectability of stranded individuals, post-mortem movement of turtles in the water, the presence of potential reporters, and their willingness to report incidents. To account for this preferential sampling, we employed a target-group background sampling which has proven to be an effective measure against spatially biased occurrence data although prone to overcompensating this bias (Barber et al., 2022). As proxy for the relative magnitude in anthropogenic activities, we selected data on direct human impacts on marine ecosystems (Halpern et al., 2015), to emulate sampling effort at Hawai'i's shoreline, and, hence, adjusting the fit for the increased likelihood of stranding detection in more frequently sampled areas.

In addition, Maxent employs regularization multipliers to prevent overfitting, with higher regularization multipliers yielding more generalized models (Merow et al., 2013). To optimize the models, we iterated through all possible combinations of predictor variables ($n = 10$, yielding 1013 combinations), feature transformations, i.e., linear, quadratic, hinge, product, and threshold ($n = 31$ combinations), and a selection of regularization multipliers (i.e., 1, 2, 4, 8, 10). In total, we fitted 157,015 models for each anthropogenic stressor using the R package ENMeval (Muscarella et al., 2014) in R (Version 4.3.1) (Team, 2013). We assessed the performance of each model using 4-fold cross-validation. To further counteract the spatially biased records, folds were assigned using spatial blocks (Roberts et al., 2017), i.e., the latitude and longitude lines that split the stranding localities into four equally sized bins.

The best performing models were selected based on equal weighting of three metrics (Hirzel et al., 2006; Lobo et al., 2008; Peterson et al., 2008; Radosavljevic and Anderson, 2014), the Area Under the Curve (AUC) of the Receiver Operating Characteristic, the Continuous Boyce Index (CBI), and the 10-percentile omission rate (Table S3). The AUC measures the ability of the model to distinguish between locations where strandings have occurred and where they have not. An AUC value of 1 indicates a perfect model, while a value of 0.5 suggests a model performance equivalent to random guessing. The CBI ranges from −1 to 1 and assesses the model's ability to assign higher probabilities of occurrence at actual stranding sites as opposed to random background locations. The 10-percentile omission rate refers to the proportion of known stranding localities that the model fails to predict at a given threshold.

2.2. Fishing line debris in coastal waters of O'ahu

2.2.1. Marine debris database

Hawai'i Marine Animal Response (HMAR) is a nonprofit marine species conservation and animal response organization, located in Kailua, O'ahu (https://h-mar.org/). In addition to animal response operations, HMAR conducts targeted marine debris clean-up operations in coastal waters around O'ahu. Since 2019, HMAR has measured and logged marine debris collected during clean-up dives. The dives were performed by HMAR staff and volunteers using SCUBA gear ($n = 35$) or snorkeling ($n = 102$), throughout the year. Diving sites included near-shore reef, rock and sand habitats at mostly photic depths (mean: 13 m, range: 5–50 m). Some locations were visited more frequently than others (Table S4), often due to ease of access and/or upon finding high levels of debris, in order to increase the debris removal yield. Thus, the initial choice of and return to locations are largely non-random and some stretches of the coastline are never visited (Fig. 1).

The total length of collected fishing lines is estimated by HMAR from the weight. A section of the collected lines is measured and weighed in order to extrapolate to overall length. The dives varied in terms of how many people were involved, the time spent in the water, time of the year, and the total area searched during the dive. This information can be interpreted as the *effort* which is applied to normalize the quantities of fishing line (m) collected per dive. Owing to the varying number of clean-up activities over the years and the potential for a learning effect increasing clean-up efficiency, the datapoints were pooled for use in the model described below (2.2.2). We excluded entries where clean-up was not the only objective of the dive (e.g., the staff was surveying a new location, conducting training of staff, special missions, etc.) or where key data were missing, in order to achieve a standardized dataset with similar effort placed per dive.

The final dataset includes 137 datapoints from five years of debris clean-up missions, where the majority of data were collected in 2021 and 2022 (Fig. S11). Locations included 23 areas around the shores of O'ahu with several different entry points identifiable by logged coordinates for each dive.

2.2.2. Spatial patterns: modelled distribution of fishing line debris

The accumulation of monofilament fishing line along the coast of O'ahu was estimated using a marked log-Gaussian cox process (LGCP) (Illian et al., 2008; Møller et al., 1998) obtained within a Bayesian framework. A LGCP is a doubly stochastic point process model with two layers of stochasticity: a Poisson process where the sampled points are independent given a spatially varying Gaussian effect used to account for unmeasured covariates and potential spatial autocorrelation. This joint-likelihood framework was selected to account for the biases due to preferential sampling of monofilament present in the data. By using a marked LGCP, we can separate the observation process from the mark process, thereby allowing us to construct more accurate predictions of monofilament across the region. We therefore modelled the intensity of the point pattern of the sampling locations as:

$$\Lambda(s) = exp(\alpha_{01} + \zeta(s)),$$

where: s denotes the coordinate vector of the sampling locations, $\alpha01$ represents the intercept of the model and $\zeta(s)$ is a zero-mean Gaussian process with a Mátern correlation structure. The Gaussian process was

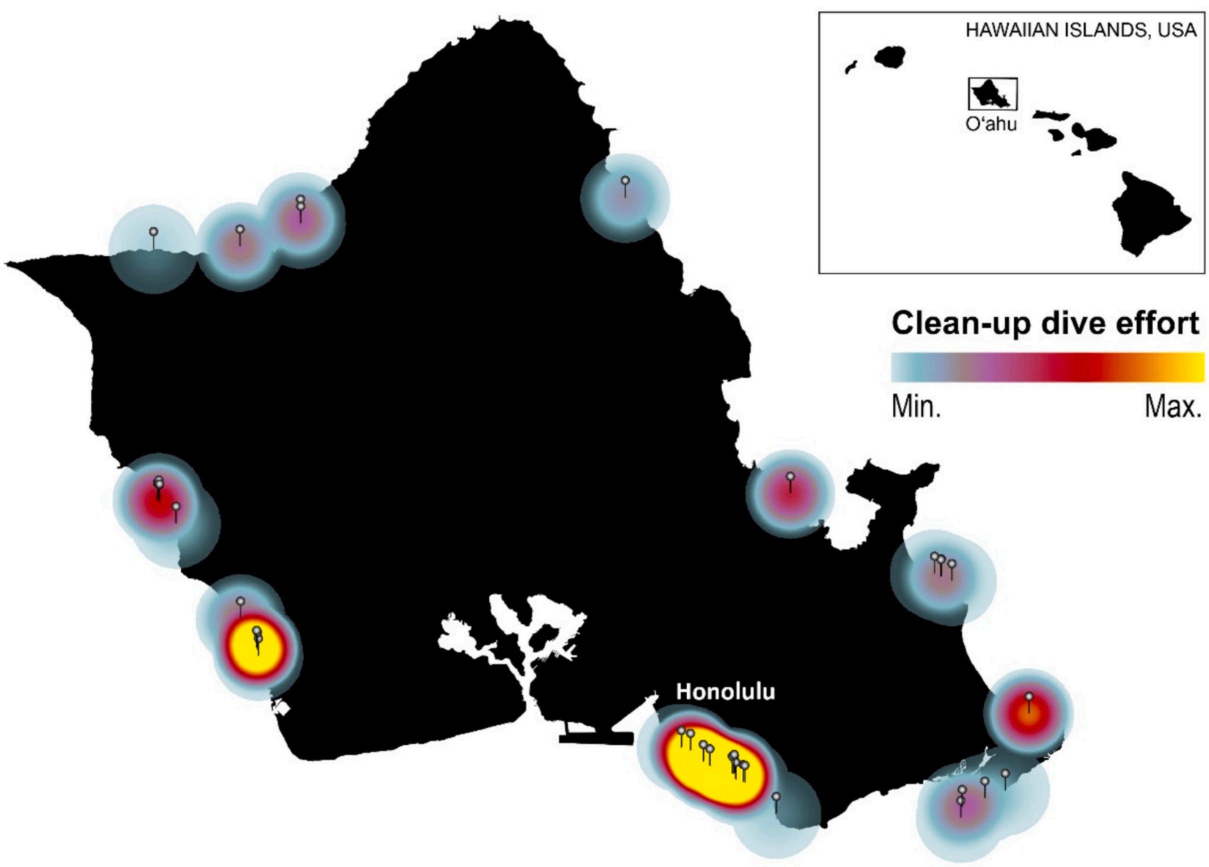

Fig. 1. Locations (pins) of clean-up dives on O'ahu from 2019 to June 2023, with effort (time, people, area) shown as a heatmap from minimum (blue) to maximum (yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

approximated using the stochastic partial differential equation (SPDE) approach by Lindgren et al. (2011), which allowed us to fit these computationally demanding spatial models within an appropriate time frame. Each sampling location contained information on monofilament line density, which we modelled alongside the points-model using a joint-likelihood formulation. The monofilament line density was assumed to be log-Gaussian distributed, and dependent on the distribution of the sampling location:

$$\eta(s) = exp\left(\alpha_{02} + \sum_{i=1}^{p} \beta_i(s)X_i(s) + \gamma\zeta(s) + \omega(s)\right),$$

where: α_{02} is the intercept of the model and $Xi(s)$ are spatially varying covariates with associated parameters $\beta i(s)$. The point-process spatial effect is included in the model using the term γ, which is a scaling variable used to connect and determine the strength and relationship for the interaction between the monofilament line estimates and the sampling locations. The term $\omega(s)$ is a zero-mean Gaussian random effect specific to the monofilament lines, conditionally independent to the points model of the sampling locations, used to account for terms unexplained by the intercept and the covariates. We selected covariates relevant in explaining levels of monofilament line, which were: the benthic structure (BAE, 2007), focal population (US Census Bureau, 2021), density of shore access points (NOAA Fisheries, 2014) and distance from boat harbors (DLNR/DOBOR, 2014). The benthic layer was used as a binary variable separating coral and hardbottom from sand and sediment. All covariate layers were rasterized and standardized before any inference was completed. In addition, we included an offset in the model calculated as the number of people hours and extent of area covered (Table S4) to account for uneven sampling effort across the cleanup dive locations. We fit multiple models with different covariate combinations (Table S5), which were compared against one another using their WAIC scores, which is a generalization of popular deviance measures, such as AIC and DIC.

The model was estimated using the *R* package *inlabru* (Bachl et al., 2019), which is a wrapper around the *R-INLA R* package (Rue et al., 2009), and is designed to assist the user fit spatial processes using the integrated nested Laplace approximation methodology in an accessible manner. We assumed default R-INLA priors for the fixed effects, which is a Gaussian prior with mean 0 and precision 0 for the intercept terms, and Gaussian priors with mean 0 and precision 0.001 for the spatial covariates. The prior for the scaling parameter included to connect the spatial field between the two likelihoods was assumed to be Gaussian with 0 mean and precision 10. We furthermore assumed penalizing complexity (PC) priors for the spatial random effects, which are weakly informative priors designed to pull the model towards its simplest realization (Simpson et al., 2017). With these priors, we specified that the true range of the spatial field being smaller than 2 km was 1 %, and that the true standard deviation of the spatial field being greater than 0.1 was 1 %. For the mark field, we assumed that the probability of the range of the spatial field being smaller than 1 km was 1 %, and that the true standard deviation of the spatial field being greater than 0.5 was 1 %. Further details on the model selection process, and the estimates obtained for the selected model can be found in the Supporting information (S.I 2.2).

3. Results & discussion

3.1. Temporal prevalence of stressors and primary threats in stranded turtles

From 1982 to 2024, a total of 10,347 green turtle stranding events have been recorded across the Main Hawaiian Islands. Since the beginning of the time series, the majority of strandings have been registered on O'ahu, the most densely human populated island, followed by Maui and Hawai'i Island (Fig. 2).

The number of strandings initially increased until it fluctuated between 200 and 300 events annually from 1993 to 2017. The rise may be linked to positive human and turtle population trends, heightened public awareness, ease of reporting procedures, and potential increases in anthropogenic stressors (Chaloupka et al., 2008). While the distribution of stranding events among the islands remained relatively stable

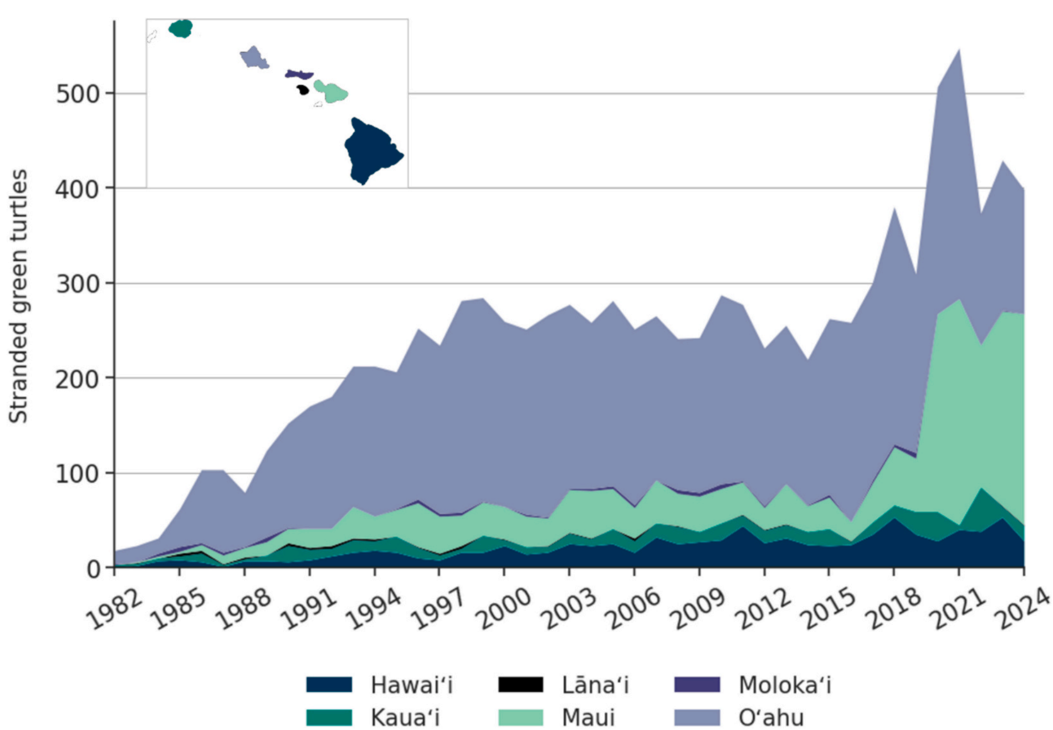

Fig. 2. All Hawaiian green turtle (*Chelonia mydas*) strandings ($n = 10{,}347$) per island per year from 1982 to 2024. O'ahu ($n = 6711$), Maui ($n = 2109$), Hawai'i ($n = 901$), Kaua'i ($n = 506$), Moloka'i ($n = 78$), and Lāna'i ($n = 42$). The sharp increase observed for Maui in 2020 is addressed in the main text.

during this period, a surge in records from Maui occurred in 2020 (Fig. 2), attributable to active in-water responses commenced by the local wildlife response organization Maui Ocean Center Marine Institute. In 2022, in-water responses comprised over 60 % of the events from Maui (Cutt et al., 2023). Despite introducing inconsistency to the time series, the spike serves to highlight that the number of turtles afflicted with stressors increases with survey effort (Monteiro et al., 2016) as only a fraction of sick, injured (e.g., turtles with a hook embedded in their body which may eventually come out), or deceased turtles will strand and be documented (Cook et al., 2021).

The different causes of hazard or mortality to the turtles range from naturally occurring events such as shark predation or weather-related phenomena, to anthropogenic activities like boat strikes or entanglement in ALDFG. Within the broader category of ALDFG, the sources differ from hooks, lines and gillnets deployed in local near-shore waters, to the larger trawl nets and rope conglomerates drifting in from distant sources. While the relative prevalence of most stressors has remained stable or decreased, the share of stranding events involving hook-and-line has increased since the year 2000 (Fig. 3). Fishing line related strandings constituted on average 22 % of stressors from 2010 to 2019 and were found to be the most prevalent individual stressor since 2016 (Table S1). The presence of hooks was less frequent (8 %), but follows a similar pattern as fishing line, as they often appear jointly. In contrast, net entanglements, which include both local gillnet and distant trawl net/rope conglomerates, appear to follow a downward trend (Fig. 3), going from 7 % on average in 1982–1989, to 3 % in 2010–2019 (Table S1).

The observation of FP in stranded green turtles peaked in the mid-1990s, after which it constitutes a dwindling share of all stressors (Fig. 3) yet amounting to 25 % on average in the period 2010–2019 (Table S1). While the tumor-forming disease is linked to a known herpesvirus (*Scutavirus chelonidalpha5*) (Work et al., 2020), the influence of environmental cofactors on the prevalence of FP in sea turtle populations are not clear (Herbst and Klein, 1995), and the causal reasons for the decline in Hawai'i are unknown (Chaloupka et al., 2009). Although absolute numbers fluctuate, the proportion of total strandings with evidence of shark predation remains stable over time, which we might expect for naturally occurring events like predation if the predator-prey dynamics are relatively stable. The miscellaneous category, which encompasses different stressors, does not increase with time, while the undetermined category follows a downward trend. Lastly, the prevalence of boat strikes remains relatively stable (Fig. 3).

Determining a single primary threat believed to cause the stranding for each turtle is not always possible due to lack of evidence of any stressor, several stressors appearing jointly, or decomposition of the turtle. However, efforts have been placed to determine and assign a primary threat to each turtle stranding from the external observations and necropsy records. This offers additional insights into the relevancy of the stressors as *threats* to turtles' health. While FP has historically been the most prevalent primary stranding threat for green turtles in Hawai'i (Chaloupka et al., 2008), fishing line injuries constitute the most documented single primary threat since 2016 (Fig. 4).

Notably, hook-and-line injuries were the primary threats assigned to 42 % of the turtles in the most recent years (2020–2024) (Table S2). However, the rates from these years are confounded by active in-water searches on top of regular stranding data, which contributed to the increase in sightings of injured turtles.

Across the time series, 48 % (n = 4941) of the turtles were found alive, while 51 % (n = 5303) were found dead and ~1 % lacked a known status. Most registered cases of shark predation and boat strikes have resulted in mortality, while hooked turtles appear to have the best outcome among all primary threats (Fig. 4). Turtles stranding with FP were found dead or later died in 80 % of the cases, while fishing line injuries were fatal in 35 % of the cases. This remains consistent with the previous review of stranding records, where a higher mortality rate was found for turtles stranding with FP compared to hook-and-line injuries (Chaloupka et al., 2008). Upon consideration of only turtles that were initially found alive, 90 % or more of turtles stranding due to fishing gear (hooks, lines and nets) were released alive (Fig. S4). Moreover, the last years (2020–2024) have seen all time high stranding numbers (Fig. 2), while the absolute number of dead turtles is lower than the preceding period (Fig. S5).

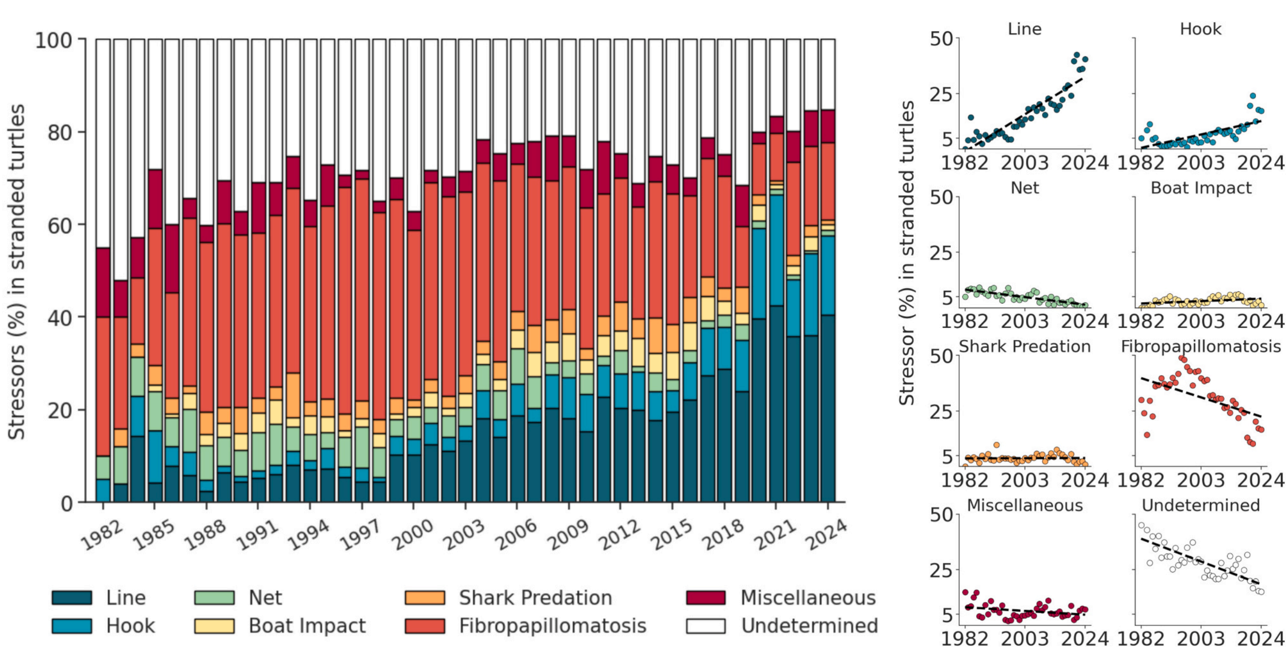

Fig. 3. Temporal trends (1982–2024) in main stressors (colored according to legend) in stranded green turtles (*Chelonia mydas*) across the Main Hawaiian Islands. *Miscellaneous* is a grouping of several less prevalent stressors (see method Section 3.2), while *undetermined* refers to cases where none of the main stressors were observed or the turtle was unassessed. Note that an individual turtle stranding event can have multiple stressors (n = 12,248 stressors including undetermined, n = 10,347 strandings). Left: Stacked shares of present stressors in turtles per year. Right: Individual plots with regression lines for each stressor (see Fig. S4 for additional details). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

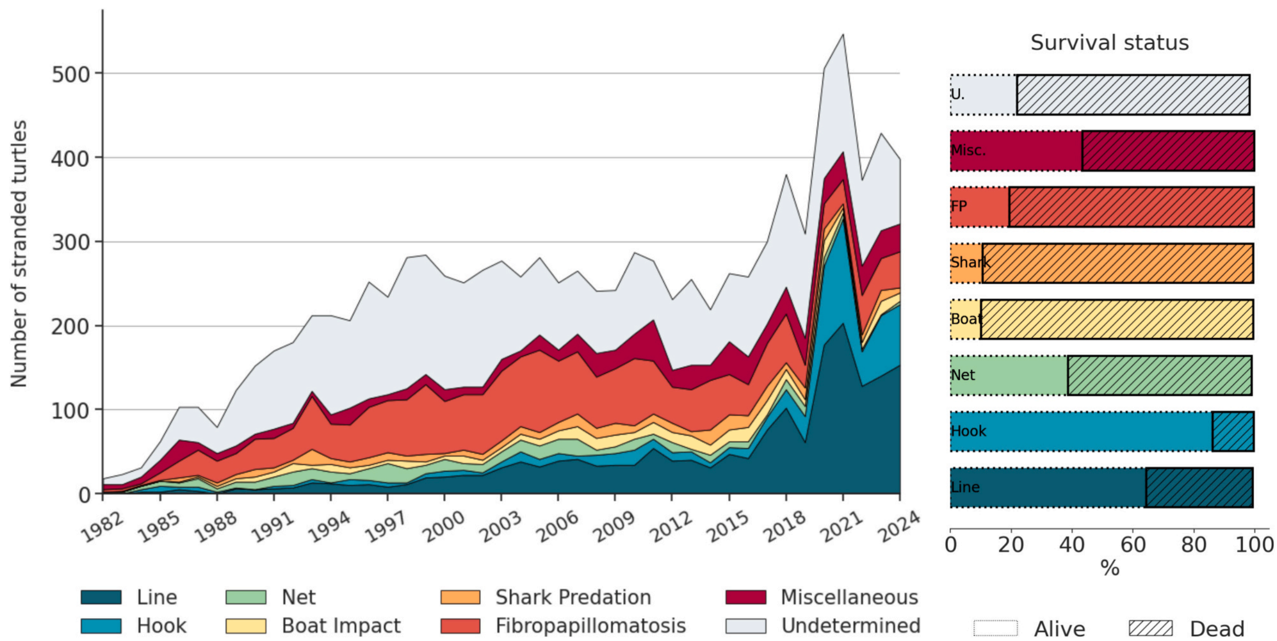

Fig. 4. Green turtle (*Chelonia mydas*) strandings across the Main Hawaiian Islands (n = 10,347) separated by the primary threat of stranding (colored according to legend). Undetermined (U.) applies to all cases where a primary threat was unidentified or unassessed. Right panel bar chart shows the final survival status ratio, alive ($n = 3558$) or dead ($n = 6694$) per primary threat, with $n = 95$ undetermined cases. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Spatial patterns by stressor in stranded turtles

Combining the point localities from the stranding database with environmental and anthropogenic variables, we derived stressor-specific relative occurrences of stranding events across each island. The model predicts O'ahu to be a clear hotspot for turtles stranding with fishing line (Fig. 5), and the relative occurrence was found to increase with estimates of line fishing catch (Fig. S6).

The higher likelihood of stranding events with hook-and-line occurring on O'ahu is likely linked to this being the most populated MHI and hosting the greatest number of nearshore fishers (Chaloupka et al., 2009; Chaloupka et al., 2008). Aside from a few notable "cold" spots (SI 1.2) practically all shores of the island are characterized by a high relative occurrence of fishing line interactions. As the second most densely populated island, Maui has one main hotspot on the south shore. This stretch has multiple beaches and is subject to high levels of on-reef

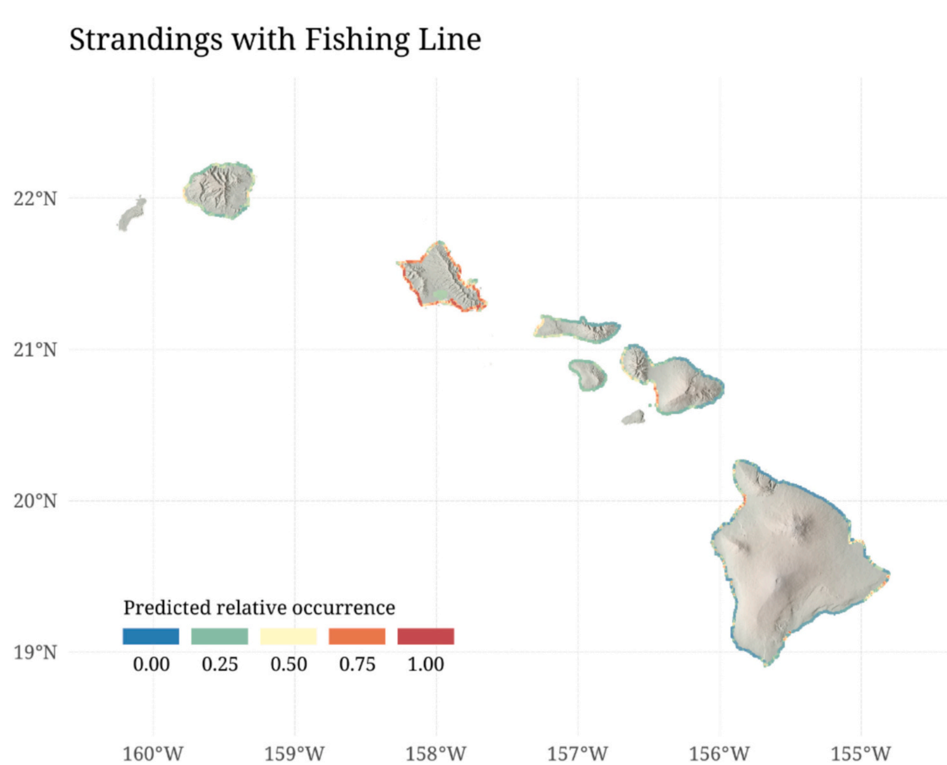

Fig. 5. Predicted stranding pattern for green turtles (*Chelonia mydas*) with presence of fishing line found across the Main Hawaiian Islands 2003–2018.

tourism (Lin et al., 2023), and thus more public observers to report entangled or stranded turtles. On Hawai'i Island, high occurrence points are more isolated yet situated in areas estimated to have substantial hook-and-line fishing catch (Kappel et al., 2017a,g). On Kaua'i, Moloka'i and Lāna'i, the occurrence of strandings with fishing line are comparatively low with few scattered areas of medium occurrence levels. It should be noted that stranding reports from Moloka'i and Lāna'i are in general rare and inconsistent (Fig. 1). However, as the model utilizes the characteristics of sites with stressor-specific strandings from the other islands, areas with potential for high stranding occurrence were still predicted on Moloka'i and Lāna'i (Fig. S8). Turtles stranding with fishing hooks largely followed the same spatial distribution as lines (Fig. 6), although differences in the variable responses were found (Fig. S7).

Higher spatial variation within and among islands was observed for the other stressor-specific models. The occurrence of strandings with net entanglements was high on O'ahu and the south shore of Maui, while remarkably infrequent on Hawai'i Island compared to all other islands (Fig. S9). For turtles impacted by boat strikes, areas with higher densities of boat traffic such as harbors stand out as hotspots across the islands (Fig. S10). The relative chance of turtles stranding with FP was found to be highest around most of O'ahu, west/central/south Maui as well as east/central Moloka'i (Fig. S8). Notably, hotspots of occurrence on Maui and Moloka'i appeared more pronounced on the leeward sides of the islands across all the stressor-specific models.

As green turtles are known to have relatively small core home ranges (Brill et al., 1995; Pillans et al., 2021), the stranding datapoints and the subsequent predictions may in fact represent where the interactions with stressors actually occur, though it is possible for turtles to drift, sink, and float back to the surface or onto the shore before being discovered. Given the often more acute nature and the higher mortality rate associated with boat strikes and shark predation (Fig. 4), it is likely that spatial patterns of strandings reflect the areas where impacts originate because the turtles are more likely to immediately strand adjacent to where the impact occurred. In contrast, the locations of sea turtle strandings associated with fishing gear can vary depending on the severity of fishing gear injury and its impact on the turtles' ability to move to other sites before stranding (e.g., if their mobility is not immediately hampered). However, the variables that explain the spatial variations in the stressor-specific models are largely associated with the given stressor, indicating a link between our areas of relative occurrence and areas with stressors. For example, hook-and-line fishing catch estimates accounted for over 60 % of the variation in both the line and hook stranding models (Figs. S6, S7), while the distribution of net entanglements was best explained by carbon phytoplankton biomass and estimates of fisheries catch by net (Fig. S9). Notably, the majority of nets entangling Hawaiian green turtles appear to be local gillnets rather than the distant-source trawl netting that washes ashore in Hawai'i (Murakawa, personal observation). Lower wave power and higher nearshore development were linked to higher occurrences of boat strikes (Fig. S10), possibly due to boats traveling at higher speeds in calmer waters, while factors such as effluent explained higher occurrences of strandings with FP disease (Fig. S8).

3.3. Derelict fishing lines on O'ahu

Utilizing the site-specific data collected from clean-up dives around O'ahu as the response variable in a model with anthropogenic and environmental covariates as predictors, the best-fitting model predicted the accumulation of fishing line to be high in patches across the island (Fig. 7), including spots not yet targeted by clean-up missions (Fig. 1).

As the amount of derelict fishing line was modelled on a log scale, we refer to relatively high and low levels of fishing line intensity. According to the model, fishing line intensity increases with the availability of access points to shore (mean: 0.11; standard error: 0.13) and decreases with greater distances to boat harbors (mean: −0.51; standard error: 0.29). This is in line with previous studies which found a correlation between higher amounts of fishing line and coastline accessibility (Bauer-Civiello et al., 2018) as well as boat densities (Bauer et al., 2008). On the other hand, the intensity also decreased with greater human

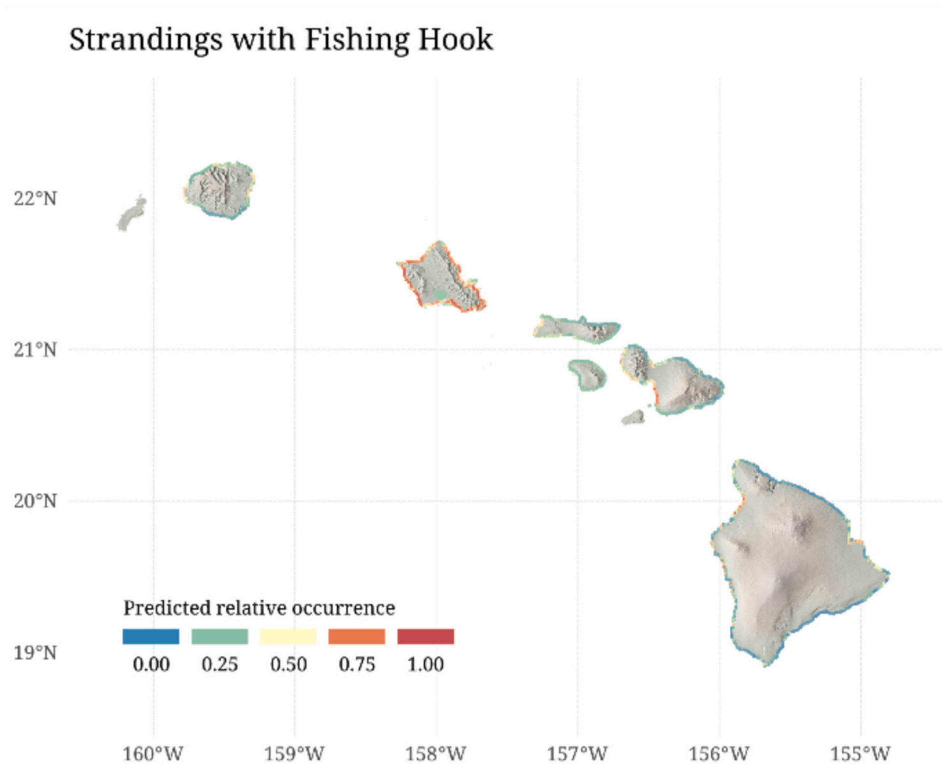

Fig. 6. Predicted stranding pattern for green turtles (*Chelonia mydas*) with presence of hooks found throughout the Main Hawaiian Islands 2003–2018.

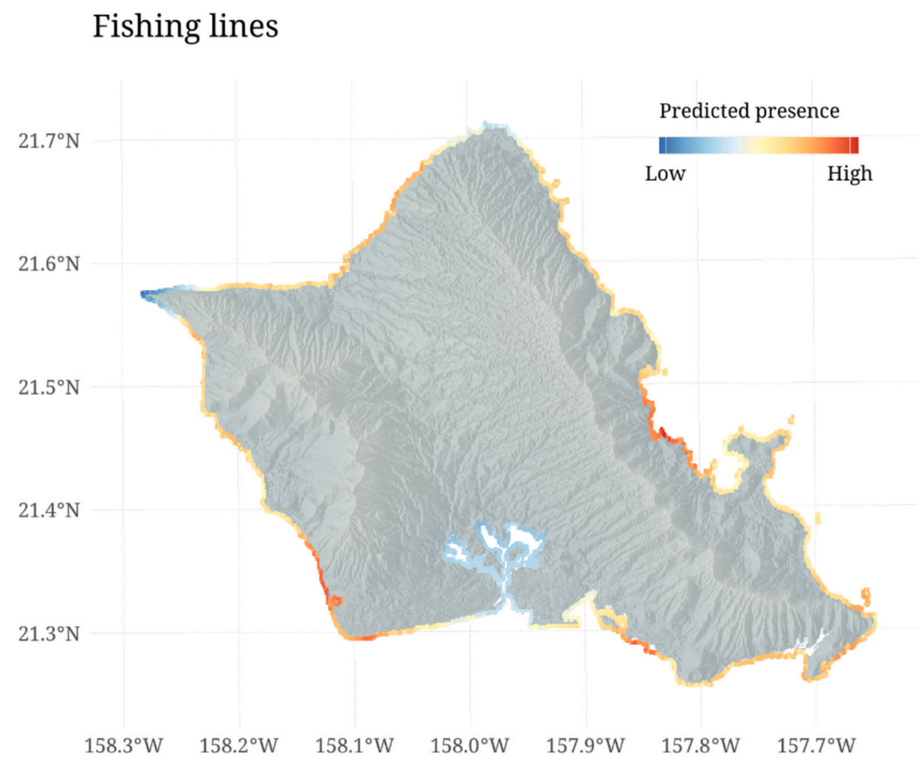

Fig. 7. Predicted monofilament fishing line debris distribution from low (light) to high (dark) in the nearshore waters around O'ahu. The estimated presence is the mean of the log-intensity for the marked point process model.

population density (mean: −0.35; standard error: 0.14), contrary to other regional findings for levels of debris on reefs (Bauer-Civiello et al., 2018). Delaney et al. (2017) found that annual fish catch was low in urban and tourist-dominated areas on O'ahu, while a study from the Hawaiian archipelago found a negative association between human population density and the biomass of targeted reef fish (Friedlander et al., 2017), indicating that fish stocks close to more densely populated areas could be depleted (Williams et al., 2008). Notably, on a global scale, fishing debris on coral reefs is largely independent of coastal population sizes (Pinheiro et al., 2023). While the reasons for the negative association between fishing line and population density in the O'ahu specific model are not clear, it is plausible that fishing activities on densely populated islands with abundant shoreline access and short distances between locations, are more spread out. Generally, amounts of fishing debris correlate with fishing effort globally (Richardson et al., 2022) and popular fishing and recreation locations regionally (Edgar and Stuart-Smith, 2014). Thus, on an island-wide scale, we expect O'ahu to have higher levels of accumulated fishing line compared to the other islands, as the number of fishing trips conducted annually on O'ahu is estimated to be much higher (Delaney et al., 2017). This is driven by the high human population density, where sport fishing also via tourism could exacerbate line accumulation on reefs (Asoh et al., 2004). The specific gear which entangles the turtles should be assessed in a future study to determine which hook-and-line fishing techniques are most common (Honebrink, 2016). These are likely to include slide baiting, trolling, bottom fishing, and jigging techniques (Lynch, personal observation).

On smaller scales, the model may not successfully capture all potential hotspots where clean-ups have not been conducted, as different styles of fishing target sites with varying properties such as accessibility. For example, fishing effort was previously estimated to be high in Pearl Harbor (Delaney et al., 2017) while a spatial model predicted little to no fish catch in the largely restricted shore area (Kappel et al., 2017j). Our model also suggests the lowest levels of fishing line intensity, but there are currently no clean-up dive datapoints from Pearl Harbor. This is also the case for more pristine areas such as Ka'ena Point, which constitutes a known spot for anglers, but can be hard to access for divers due to strong currents, high wave activity and rocky cliffs.

Fishing line is routinely the most encountered debris type on reefs (Bauer-Civiello et al., 2018; Chiappone et al., 2005) typically associated with rocky substrate compared to cobble or sand (Watters et al., 2010), as it may easily snag onto hard and rugged surfaces. We therefore expected fishing line to accumulate in areas with reef and rock compared to sediment and sandy bottom. Our model supports this, with a positive significant covariate for the hard benthic substrate (mean: 2.71; standard error: 0.67).

Previous studies have found highly weathered, floating marine debris to accumulate in higher concentrations on the windward or east side of islands in the Hawaiian archipelago, linked to the proximity to the North Pacific Garbage Patch (Brignac et al., 2019; Royer et al., 2023) and the prevailing wind-driven surface currents. However, monofilament line debris specifically can be generated locally on all sides of the island where recreational fishing activities occur. Brignac et al. (2019) suggested that the sources of debris on the leeward sides of the Main Hawaiian Islands are likely more local, from activities such as fishing and boating. Indeed, coastal areas and reefs tend to act as both source and sink for debris generated through recreational fishing activities (Watson et al., 2022).

Given that the processes determining the spatial structure of the clean-up locations are not necessarily independent of the processes governing fishing line intensity, the model included the term γ to connect the spatial field of the points model to the marks model. The estimate for the scaling parameter connecting the shared spatial fields between the two likelihoods was 0.9 (standard error = 0.24), suggesting that fishing line density is greater in locations of high sampling density. This might indicate that areas accumulating debris are more targeted by clean-up efforts (Haarr et al., 2022). We note that clean-up efforts are repeated at several of the locations within a year, indicating that either not all the debris can be collected at once, or there is a constant influx. Lastly, we cannot rule out that the amounts of debris collected at various sites can be influenced also by other local organizations or individuals conducting clean-up dives on O'ahu (Sciutteri et al., 2024).

4. Conclusions

Assessing stranding data can elucidate temporal and spatial patterns in the contemporary threats faced by recovering wildlife populations. In the Main Hawaiian Islands, the proportion of green turtles stranding with fishing line has increased steadily since the late 1990s, emerging as the most common stressor and primary threat as of 2016. The relatively high prevalence of hook-and-line injuries in Hawaiian green sea turtles establishes this as the leading stranding threat of concern. Additionally, the prevalence in stranded turtles could be higher than reported considering that turtles that swallow fishing line may not show any obvious external signs (Work et al., 2015). The observed increase is likely a result of the Hawaiian green turtle population recovering, thus being more abundant in nearshore waters, in combination with their year-round overlap with hook-and-line fishing activities, which may also have expanded the past four decades (Asoh et al., 2004). Notably, turtles with hook or line injuries exhibited the highest survival rates (hooks: 86 % alive, lines: 64 % alive) compared to the other threats, which highlights the importance of timely conservation efforts, including: (1) help from fishers when turtles are hooked or entangled in active gear (i.e., removing as much line as possible), (2) public calls to the stranding hotline to report injured or stranded turtles, (3) field assessments and treatment by authorized stranding response partners, (4) treatment and rehabilitation of injured turtles at authorized facilities, and (5) marine debris clean-ups in the nearshore reef environment.

In this paper, we publish the first spatial distribution of stranding occurrences on a sub-island scale for all the Main Hawaiian Islands. The stressors-specific spatial analysis highlighted O'ahu as the main hotspot for both hook and line strandings, while there was more inter-island variation for the other stressors. Estimated fishing catch explained the majority of the variation in the models for turtles stranding with line, illustrating the overlap in fishing activities and turtles' presence. On O'ahu, data gathered from marine debris dive clean-up operations further suggests that fishing line debris quantities are high in patches across the island, which was associated with accessibility of sites and small boat harbors in areas of lower population density. Despite efforts to account for observation and sampling bias in the analysis, the unknown influence of varying reporting efforts on temporal and spatial trends remains a source of uncertainty, which can influence the spatial patterns of both the stranding and fishing line models.

Considering the increase in turtles with hooks and/or line entanglements revealed by the in-water surveys in the most recent years, sustaining clean-up efforts could reduce nearshore hazards for the turtles, and spatial models such as the one used here could help to direct efforts where fishing line may accumulate. Measures to reduce fishing gear losses are warranted, also in light of a recent assessment of the endangered Hawaiian hawksbill sea turtle (*Eretmochelys imbricata*), where the majority of strandings occurring in Hawai'i were attributed to hook-and-line injuries on O'ahu (Brunson et al., 2022).

This study focused on identifying threats to individual sea turtles' health, which can provide a basis for conservation strategies for sea turtle populations (Work et al., 2015). However, in order to elucidate potential population-level impacts of the prevalence of threats documented in this paper, future work should consider the age and sex composition of the stranded turtles combined with the status and trend of the nesting population in the Northwestern Hawaiian Islands. In addition, further investigation of the stranding data could allow for determination of the specific hook, line, and net types that constitute the fishing gear injuries to further refine the management nexus. As indicators of ecosystem health, understanding the contemporary threats to green sea turtle populations is instrumental, not only for the conservation of the species, but also for the broader context of sustainable ecosystem management.

CRediT authorship contribution statement

Marthe A. Høiberg: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Jan Borgelt:** Writing – review & editing, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Philip Mostert:** Writing – review & editing, Visualization, Software, Methodology. **Shawn K. Murakawa:** Writing – review & editing, Data curation. **Summer L. Martin:** Writing – review & editing, Data curation. **Jon Gelman:** Writing – review & editing, Data curation. **Jennifer M. Lynch:** Writing – review & editing, Conceptualization. **Francesca Verones:** Writing – review & editing, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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DAR - State of Hawai'i, Division of Aquatic Resources; DLNR - State of Hawai'i, Department of Land and Natural Resources; DOCARE - State of Hawai'i, Division of Conservation and Resources Enforcement; DOD - US Department of Defense; DOT - State of Hawaii, Department of Transportation; HFD - City and County of Honolulu, Honolulu Fire Department; HIHP - Hawai'i Island Hawksbill Project; HIHWNMS - US Hawaiian Islands Humpback Whale National Marine Sanctuary; HMAR - Hawai'i Marine Animal Response; HPA - Hawai'i Preparatory Academy; HPD - City and County of Honolulu, Honolulu Police Department; HPU - Hawai'i Pacific University; HWF - Hawai'i Wildlife Fund; JCNWR - US Fish and Wildlife Service, James Campbell National Wildlife Refuge; MNH - Mālama i Nā Honu; MOC - Maui Ocean Center; MOCMI - Maui Ocean Center Marine Institute; MTBAP - US NOAA PIFSC, Marine Turtle Biology and Assessment Program; NIST - US National Institute of Standards and Technology; NOAA OLE - US National Oceanic and Atmospheric Administration, Office of Law Enforcement; NOAA PIFSC - US National Oceanic and Atmospheric Administration, Pacific Islands Fisheries Science Center; NPS - US National Park Service; OS - City and County of Honolulu, Ocean Safety; PIRO - US National Oceanic and Atmospheric Administration, Pacific Islands Regional Office; PL - Pūlama Lāna'I; PMRF - US Navy, Pacific Missile Range Facility; SLP - Sea Life Park Hawai'I; TNC - The Nature Conservancy; UHH MOP - University of Hawa'ii at Hilo, Marine Option Program; UH-HCC MOP - University of Hawai'i, Hawai'i Community College, Marine Option Program; UH-MCC MOP - University of Hawai'i, Maui Community College, Marine Option Program; UHM MOP - University of Hawai'i at Mānoa, Marine Option Program; USFWS - US Fish and Wildlife Service; USGS NWHC HFS - US Geological Survey, National Wildlife Health Center, Hawai'i Field Station.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.117869.

Data availability

Data will be made available on request.

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