



Mapping the past for the future: Spatial and temporal patterns and long-term trends of sea turtle strandings in Hong Kong and wider East Asian waters

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ABSTRACT

Sea turtle strandings provide critical insights into population health and anthropogenic threats, yet long-term data remain scarce for East Asia region, including Hong Kong waters. Here we retrospectively analysed 23 years (2002–2024) of 223 (58 live, 165 deceased) sea turtle stranding records to characterize species composition, demographics, temporal trends, spatial hotspots, and causes of stranding. Standardized Level A data were compiled, complemented since 2019 by virtopsy-integrated necropsy (postmortem CT, 3D surface scanning), and analysed using generalized additive models (GAMs; Poisson family) for temporal trends; kernel density estimation (KDE) and Getis-Ord G_i^* statistics for spatial clustering and hotspot detection. Green turtles (*Chelonia mydas*) dominated (76.7%, $n = 171$), primarily juveniles, with hawksbill (*Eretmochelys imbricata*; 7.2%), loggerhead (*Caretta caretta*; 5.4%), olive ridley (*Lepidochelys olivacea*; 3.6%), leatherback (*Dermochelys coriacea*; 0.8%), and unidentified (6.3%). GAMs revealed a significant nonlinear increasing trend over the study period (adjusted $R^2 = 0.595$, $p < 0.001$), with the fitted smooth visually levelling after 2018, and seasonal peaks in spring (Mar–May) and autumn (Sep–Nov). Spatial hotspots concentrated in eastern and southern waters, including marine protected areas. Cause of stranding was determined conservatively based on pathognomonic lesions identified through virtopsy-integrated necropsy; undetermined cases predominated (78.5%, $n = 175$), followed by anthropogenic causes (17.5%, $n = 39$), other causes (typhoon entrapment, buoyancy disorder) (2.7%, $n = 6$), and natural causes (1.3%, $n = 3$). The most common anthropogenic cause of stranding was fishery interaction including bycatch and fishing gear entanglement ($n = 23/39$), vessel collision ($n = 9/39$), and pollution ($n = 7/39$). Limitation of this study included the majority of cause of strandings were classified as undetermined, underscoring the urgent need for enhancements in stranding investigation methodologies. This first long-term assessment for Hong Kong integrates advanced postmortem imaging with spatial and temporal modelling. Eastern and southern spatial hotspots and spring/autumn seasonal peaks warrant priority fishery bycatch mitigation, vessel speed restrictions, and targeted stranding patrols to enhance East Asian sea turtle conservation.

1. Introduction

Sea turtles function as umbrella species whose protection benefits associated marine communities and habitats: green turtles sustain

seagrass beds through grazing (relevant to Sham Wan seagrass in Hong Kong), hawksbill turtles control macroinvertebrates on coral reefs (relevant to eastern Sai Kung assemblages), and loggerhead/leatherback turtles influence pelagic food webs via jellyfish predation during

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migrations (Gallegos-Fernandez et al., 2023). Exposure to natural and anthropogenic impacts can disrupt the population dynamics of sea turtles, and hinder the ability to fulfil their ecosystem functions efficiently (Gaus et al., 2019). The sea turtle fauna comprises seven migratory species, six of which are classified in the threatened categories or as Data Deficient on the International Union for Conservation of Nature Red List (IUCN, 2025), following the reclassification of the green turtle (*Chelonia mydas*) from Endangered to Least Concern in October 2025. Five out of the seven sea turtle species, including the green turtle, hawksbill turtle (*Eretmochelys imbricata*), loggerhead turtle (*Caretta caretta*), olive ridley turtle (*Lepidochelys olivacea*), and the leatherback turtle (*Derموchelys coriacea*), have been documented in the South China Sea and Hong Kong waters (Chan et al., 2007; Ng, 2015).

The endangered green turtle, Hong Kong's most frequently encountered species and only known nester at Sham Wan (Lamma Island; regular nesting 1998–2012), represents one of Southern China's few remaining nesting sites. (Chan et al., 2007) Despite establishment of restricted area during nesting season between April and October (AFCD, 2025), there has not been official documentation of green turtle nesting in Sham Wan since 2013 (MTSG, 2020). These findings highlighted the urgent need to protect nesting sites and habitats to conserve populations and maintain the ecological health of oceans, benefiting other key species and ecosystems (Gallegos-Fernandez et al., 2023).

Various stressors, including habitat degradation, vessel collision, direct harvest, bycatch, pollution, climate change and diseases may account for the dwindling of sea turtle, marine mammals and seabirds populations both locally and worldwide (Flint et al., 2015; Moore et al., 2009; Oros et al., 2021; Yamin and Wei, 2008). In Hong Kong waters, key sea turtle stressors mirror cetacean threats, such as vessel strikes and fishery bycatch, which create global megafauna stranding hotspots through longline fisheries (Lewison et al., 2014) but remain unquantified (Chung et al., 2022). Although these impacts have been studied in cetaceans, sea turtle fishery interactions lack long-term baseline data, paralleling chronic under-reporting documented in machine learning reassessments (Tava and Huettmann, 2025). While satellite tracking studies have revealed East Asian sea turtle migration patterns, habitat usages and life history (Jang et al., 2018; Song et al., 2025), stranding data is necessary to provide essential health, threat, and spatiotemporal information (Botterell et al., 2020; Casale et al., 2010; Sönmez, 2018; Turkozan et al., 2018) despite intrinsic sampling bias towards coastal cases (Cook et al., 2021). This study fills this critical gap through 23-year stranding analysis.

Stranding response protocols vary globally based on local authorities and carcass condition. Live strandings receive veterinary rescue, clinical assessment, rehabilitation, and tagging (Inconel tags, microchips, satellite transmitters) prior to release. Fresh carcasses undergo necropsy and laboratory analyses to assess health, pathologies, dietary history and genetic diversity (Lam et al., 2006; Li et al., 2021a). Decomposed cases (decomposition code 3–5) are typically recorded for basic information (including spatial, temporal, demographic, and morphometric records, which are relatively straightforward to collect even without training) and buried in situ (Cheng et al., 2019; Ng, 2015). Cause of stranding for these cases will be solely based on direct observation and judgement of the responders (stranding response team, marine police or coast guards) (Sönmez, 2018), based on the assumption that decomposed carcasses yield limited pathological findings due to autolysis and uneconomical retrieval costs (Flint et al., 2015). Nonetheless, the stranding data from decomposed carcasses provide essential 'Level A data' that are useful for population analyses and conservation measures (Dudhat et al., 2022; Lennon et al., 2025; Li et al., 2021b; Magurran et al., 2010; McCleachan et al., 2012; Mustika et al., 2022; NOAA, 2021; Ten Doeschate et al., 2018; White et al., 2017). Building on this foundation, we present the first 23-year spatial and temporal analysis (2002–2024) of 223 Hong Kong sea turtle strandings, integrating virtopsy-enhanced necropsy with GAMs for temporal trends and KDE/Getis-Ord G_i^* for spatial hotspots, with direct implications for evidence-based conservation in Hong Kong

and wider East Asian waters.

2. Materials and methods

2.1. Source of data and sea turtle stranding response in Hong Kong

Since January 2002, sea turtle strandings (both live and deceased individuals) in Hong Kong waters have been handled and documented by the Agriculture, Fisheries and Conservation Department (AFCD) of the Hong Kong Special Administrative Region Government (see Supplementary Material, Fig. S1). Stranding reports were submitted through various channels, including a 24-h interactive hotline 1823, direct field observations, and citizen reports via mobile application eSeaAnimals (see Supplementary Material, Fig. S2) and social media platforms.

The field records consisted of 'Level A data' (NOAA, 2021), including the date and location of discovery, species, status, age class estimation, and other remarks (presence of wounds, markings, injuries, possible cause of stranding, as visually determined by field officers). Records with incomplete or unclear date and location were excluded in this analysis ($n = 5$). Age class estimation was based on curved carapace length (CCL) according to established guideline. For example, life stages of green sea turtles based on CCL were classified into juveniles (from hatchlings up to 67 cm), sub-adults (67–84 cm), and adults (>84 cm) (Ng et al., 2018). Sea turtle in the first few weeks of life with umbilical scar still present were considered as hatchlings. Sex was determined by sexually dimorphic traits including tail length and whenever possible, the gross morphology of the gonads. Live stranded animals were rescued and transported to Ocean Park Hong Kong for initial assessment, intervention and rehabilitation, followed by tag and release when deemed appropriate by in-house veterinarians. For deceased animals, postmortem examinations were performed selectively, with external and internal assessment limited to essential findings, and focusing primarily to the collection of scute, muscle and stomach content for inventory. For deceased animals before 2019, Level A data was collected in all included cases while complete postmortem examination was only performed in fresh or selected cases. In remaining cases, only gross external and internal examination were conducted, and essential findings were recorded, followed by collection of tissue and stomach content samples for archive.

Since August 2019, sea turtle strandings in Hong Kong have been investigated by the Aquatic Animal Virtopsy Laboratory (<https://bit.ly/AAVLab>) at City University of Hong Kong, using a virtopsy-integrated approach adapted from local cetacean protocols (Kot et al., 2018, 2020a,b; Tsui et al., 2020). Live individuals received clinical ultrasonography and/or computer tomography (CT) (Valente et al., 2007a,b) and/or computed tomography with 3D surface scanning (3DSS); deceased individuals underwent postmortem CT (PMCT), 3DSS, and conventional necropsy (Kot et al., 2018, 2020a; Tsui et al., 2020). Results of PMCT were used to detect abnormalities, and estimate age classes based on skeletal development in conjunction with the body length measurement (Abou-Madi et al., 2004; Arencibia et al., 2006, 2021; Kwan et al., 2022; Ricciardi et al., 2019). Results of 3DSS were used to document the external conditions and surface texture of the bodies, which supplement conventional necropsy (Kot et al., 2018, 2020b). A conventional necropsy with systematic assessment of the external and internal organs was conducted with standardized protocol (Flint et al., 2009; Poppi, 2015). Histological, toxicological, and microbiological analyses were performed when deemed appropriate. Findings from PMCT, 3DSS, necropsy, and subsequent laboratory analyses were combined for a comprehensive evaluation of possible cause of strandings (see Supplementary Material, Fig. S3). Causes of stranding were conservatively classified based solely on pathognomonic lesions (e.g., parallel slash marks from nets, propeller cuts, intestinal plication/necrosis from entanglement). Cases lacking definitive diagnostic features, even with suggestive but non-specific findings, were classified as undetermined. All the procedures have been reviewed and approved by

AFCD of the Hong Kong Special Administrative Region Government (AFGR CON 09/68PT.15). Difference in percentage of undetermined cases was quantified and described in the Results section.

2.2. Demographic and temporal analysis

The demographic and temporal data of sea turtle strandings were visualized using R version 4.4 (Team, 2024). The demographic analysis included the visualization based on age, condition, and sex classes. Seasons in Hong Kong were classified into four seasons, including spring (March–May), summer (June–August), autumn (September–November), and winter (December–February) (Leung, 2004). The temporal analysis included the visualization of aggregate number annual and monthly strandings, and the calendar heatmap based on condition of strandings. To analyze the temporal pattern of sea turtle strandings and assess potential seasonal variation across years, a Generalized Additive Model (GAM) was implemented in R using the mgcv (v. 1.9–3) package. A Poisson distribution was selected, in conjunction with model diagnostics to evaluate potential overdispersion. The model incorporated three predictors: a smooth function of year to capture long-term trends, a cyclic smooth of month to reflect seasonal patterns, and a tensor interaction between year and month to assess temporal changes in seasonality. To ensure complete temporal coverage, all year-month combinations were created in the full grid, and any combination without a stranding case was assigned as zero stranding. Smoothing parameters were estimated via REML, and model selection was guided by the Akaike Information Criterion. Model diagnostics were performed using the DHARMA package, including tests for overdispersion, zero-inflation, and temporal autocorrelation. The Poisson model showed no significant overdispersion (dispersion parameter ≈ 1.05), no evidence of zero-inflation, and no residual temporal autocorrelation in autocorrelation function plots. A negative binomial distribution was also tested but did not improve model fit. The results were visualized by plotting the estimated GAM curves with 95% confidence intervals (Lennon et al., 2025; Pikesley et al., 2012; Prado et al., 2016). Seasonal information was displayed to provide additional insight into seasonal trends.

2.3. Spatial analysis and cause of strandings

Spatial map of the Hong Kong Special Administrative Region including the boundaries, and the spatial index of coordinate reference system for grid projection were obtained from Common Spatial Data

Infrastructure (CSDI) (available at: <https://portal.csd.gov.hk>). Grid projection in this study used HK1980 coordinate reference system provided by CSDI. Marine protected areas shapefile including marine park and reserve areas was obtained from AFCD. The map of Hong Kong Special Administrative Region was showed in Fig. 1. Spatial distribution mapping of sea turtle strandings were employed using QGIS version 3.34 (QGIS Association). Spatial analyses were employed using Kernel density estimation (KDE) and Getis-Ord G_i^* (G_i^*) analysis (Liu et al., 2022). KDE analysis was employed using QGIS Density Analysis. The kernel radius was set at 1 km with discrete interpolation. G_i^* analysis was applied to identify spatial clusters of stranding locations in Hong Kong. The grid was created along coastline and islands of Hong Kong, with the grid size of 1×1 km and fixed distance set to 1 km to maintain consistency with the KDE method. We acknowledged that the 1 km kernel radius and matching grid size represented an arbitrary choice in KDE parameters and was smaller compared to other studies (Lennon et al., 2025; Nardi et al., 2025). However, this scale was more appropriate for Hong Kong's compact coastal geography (~ 1100 km shoreline within ~ 1650 km² marine area), providing sufficient smoothing for hotspot detection without excessive blurring across distinct embayments or islands. The analysis used the aggregate number of strandings located in each grid. Based on the G_i^* statistical analysis, the classification of hotspots was determined through z-scores with a certain significance level. Hotspots were defined as areas with significant positive z-scores at 90% ($z \geq 1.645$), 95% ($z \geq 1.960$), and 99% ($z \geq 2.576$) confidence levels. Areas with z-scores less than 1.645 were categorized as not significant (Liu et al., 2022). G_i^* analysis was employed in R (version 4.4) and visualized using QGIS (version 3.34).

The causes of stranding were categorized into several categories, including anthropogenic causes (fishery interaction, vessel collision, pollution), natural causes (predation, disease), other causes, and undetermined. Other causes included cases where causes of stranding were identified but do not fall into anthropogenic or natural causes (e.g. trapped in typhoon shelter, buoyancy disorder). Undetermined cases referred to strandings that no clear evidence of cause can be identified. This situation typically occurred when carcasses were in advanced decomposition condition, exhibited no apparent injuries or signs of disease, and lack indications of anthropogenic or other identifiable causes.

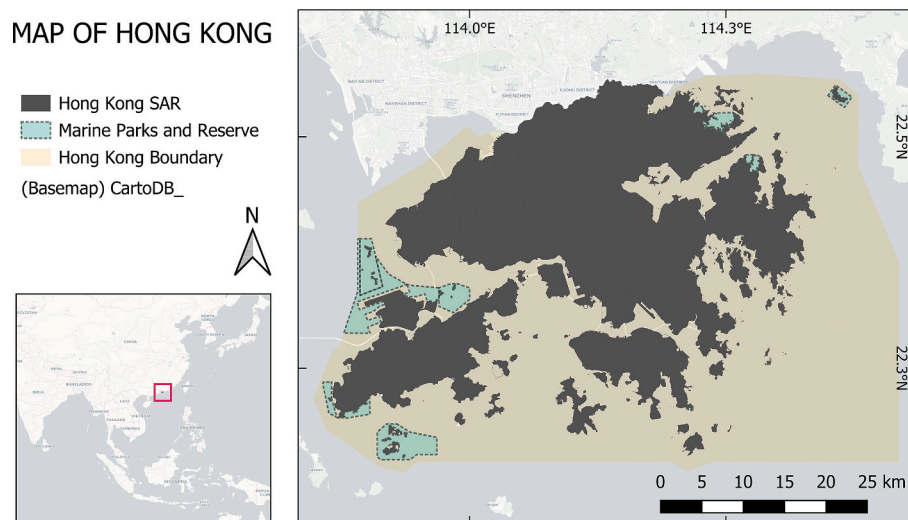


Fig. 1. Map of the Hong Kong Special Administrative Region. Left lower map showing location of Hong Kong (red square) situated within the Indo-Pacific region. Right map showing a close-up map of Hong Kong, including the boundaries indicated by yellow colour and designated Marine Parks and Marine Reserve represented by dotted line and green colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results

From 2002 to 2024, a total of 223 (58 live, 165 deceased) sea turtle strandings were recorded. Green turtle (CM) was the most recorded species, contributing to 76.7% ($n = 171$) of the total stranding cases, while leatherback turtle (DC) was the least recorded species with only 0.8% ($n = 2$) of the total stranding cases. The proportion of recorded stranding cases for each species is shown in Fig. 2A, including hawksbill turtle (EI; $n = 16$, 7.2%), loggerhead turtle (CC; $n = 12$, 5.4%), olive ridley turtle (LO; $n = 8$, 3.6%), and undetermined species (UNK; $n = 14$, 6.3%). Most strandings involved deceased turtles, except hawksbills, which had equal numbers of live and dead cases, as shown in Table 1.

There was an increasing pattern of sea turtle strandings in Hong

Kong from 2002 to 2018, followed by stagnancy from 2018 to 2024, and mostly dominated by green turtle (Fig. 2B). This temporal pattern could reflect a combination of increasing anthropogenic pressures (e.g. fisheries bycatch, marine debris, vessel strikes) and ecological shifts (e.g. changes in prey distribution or environmental conditions) up to 2018, followed by stabilization in these drivers and/or reporting effort. However, the current dataset did not allow these potential mechanisms to be formally tested or confirmed. January, April, and November were the months with highest aggregate number of strandings, with February as the month with the least stranding records (Fig. 2C). The age and sex classes of stranded sea turtles varied among species, as shown in Fig. 3 and Table 1. Overall, annual and monthly distribution of stranding cases mostly dominated by juvenile turtles, followed by adult and sub-adult

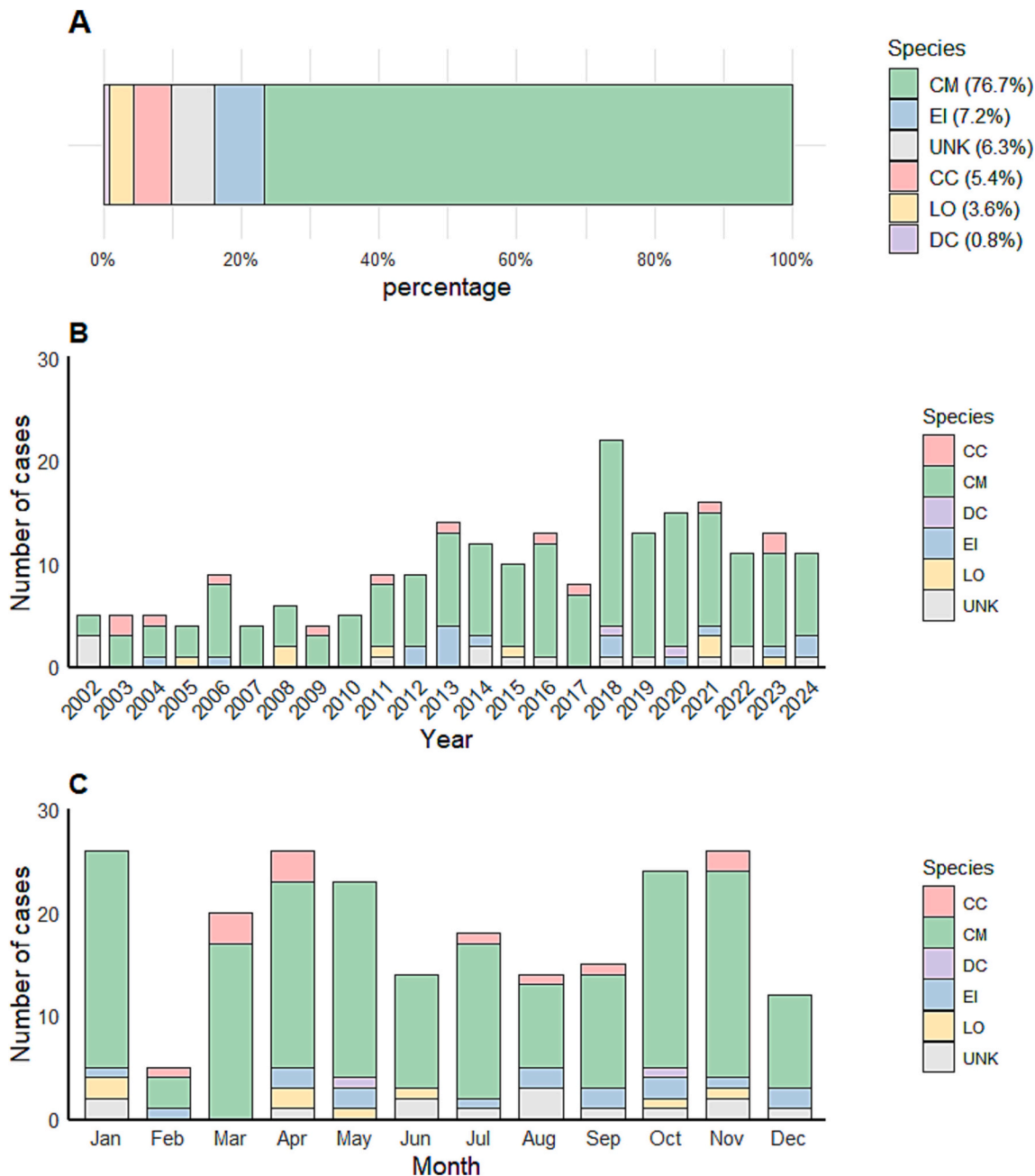


Fig. 2. Sea turtle stranding cases in Hong Kong waters between 2002 and 2024 sorted by (A) species, (B) year, and (C) month. Species included: loggerhead turtle *Caretta caretta* (CC), green turtle *Chelonia mydas* (CM), leatherback turtle *Dermochelys coriacea* (DC), hawksbill turtle *Eretmochelys imbricata* (EI), olive ridley turtle *Lepidochelys olivacea* (LO), and undetermined species (UNK). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Demographic composition of sea turtle strandings in Hong Kong based on species, age class, and sex.

Species	Age class					Sex			Status	
	A	SA	J	H	Unk	M	F	Unk	L	D
Green (<i>Chelonia mydas</i>)	42	14	107	1	7	16	43	112	46	125
Hawksbill (<i>Eretmochelys imbricata</i>)	0	1	14	0	1	2	1	13	8	8
Loggerhead (<i>Carretta carretta</i>)	8	1	2	0	1	1	4	7	0	12
Olive ridley (<i>Lepidochelys olivacea</i>)	4	0	3	0	1	1	4	3	1	7
Leatherback (<i>Dermochelys coriacea</i>)	1	0	1	0	0	0	0	2	0	2
Undetermined species	0	0	4	0	10	0	0	14	3	11
Total	55	16	131	1	20	20	52	151	58	165

*Note: A = Adult, SA = Sub-adult, J = Juvenile, H=Hatchling, M = Male, F=Female, Unk = Undetermined, L = Live, D=Deceased.

turtles. Age classes in green and hawksbill were mostly dominated by juveniles (62.6% and 87.5%, respectively), while loggerhead and olive ridley were mostly dominated by adults (66.7% and 50.0%, respectively). In the condition group, strandings were dominated by deceased turtles. Sex determination was limited by decomposition (68% undetermined, $n = 151/223$). High proportion of undetermined sex (due to advanced decomposition or immaturity) limited reliable sex-ratio inference but did not affect species composition, size-class, or spatio-temporal patterns. Among sexed cases, strandings showed female bias (52F:20M overall), except hawksbill turtles (more male), though not significant. This limited sex ratio interpretation but did not affect inferences on age class trends (CCL-based), temporal patterns, or spatial hotspots, which use sex-independent variables.

Temporal trend analysis of sea turtle strandings using GAMs for both annual and monthly patterns was shown in Fig. 4. The annual GAM model explained a substantial proportion of variation (adjusted $R^2 = 0.595$, deviance explained = 67%), with a significant trend across years ($p < 0.001$). Visualization of the annual model showed an increasing trend from 2002 until peaked in 2018, followed by relatively plateaued phase. The monthly GAM model explained a less variation (adjusted $R^2 = 0.144$, deviance explained = 16.7%), reflecting the greater variability of monthly strandings. In the monthly model, all predictors were statistically significant, including the year effect ($p < 0.001$), monthly effect ($p = 0.019$), and year-month interaction ($p = 0.027$). These results indicated the presence of both annual and monthly patterns in stranding occurrences, as well as seasonal variation across years. Monthly trends visualization showed that the number of stranding cases was higher in months during autumn and spring, and lower in months during winter. The statistically significant year-month interaction suggested that this seasonal pattern was dynamic and might vary from year to year. Model diagnostics for both annual and monthly models indicated no significant overdispersion, zero-inflation, or temporal autocorrelation, suggesting a good model fit. Calendar heatmap showed strandings cases mostly contributed by deceased cases that varied between the year (Fig. 5).

The spatial distribution of sea turtle strandings was shown in Fig. 6. Strandings were distributed along the entire coastline, in conjunction with offshore events (e.g. floating carcasses, live buoyancy rescues) of Hong Kong waters. The strandings were mainly concentrated in the eastern part of Hong Kong within Sai Kung district (88 cases, 39.4% of the total stranding cases). Several strandings also located within the marine parks and marine reserve in Hong Kong (15 cases, 6.7% of the total stranding cases). One stranding case located in Sha Chau and Lung Kwu Chau Marine Park, two cases in Cape D'Aguilar Marine Reserve, two cases in Hoi Ha Wan Marine Park, three cases in Yan Chau Tong Marine Park, and seven cases in Tung Ping Chau Marine Park. Kernel density estimation showed the strandings mostly located in the eastern and southern parts of Hong Kong (Fig. 7). Higher densities of deceased stranding were recorded in eastern and southern parts of Hong Kong, while higher densities of live strandings were documented primarily in eastern part of Hong Kong. Hotspot analysis using G_i^* statistic found the location of sea turtle stranding hotspots mostly situated in the eastern part of Hong Kong, with small distribution occurred in central and

southern regions (Fig. 8).

Causes of stranding were mostly dominated by undetermined causes ($n = 175$, 78.5%), followed by anthropogenic causes ($n = 39$, 17.5%), other causes ($n = 6$, 2.7%), and natural causes ($n = 3$, 1.3%). Anthropogenic factors, including fishery interaction ($n = 23$), vessel collision ($n = 9$), and pollution ($n = 7$), were the most frequent cause of strandings besides the undetermined cause. In contrast, natural factors were the least frequent factors that possibly caused the strandings, including disease ($n = 2$) and predation ($n = 1$) (Fig. 9). The adoption of virtopsy in postmortem investigations since August 2019 has led to a notable reduction in undetermined cases, from 125 of 149 (83.9%) to 49 of 74 (66.2%). This study also recorded several stranding cases with the possibility of mercy or religious release, marked by the presence of tags or labels or paints on the carapace (Fig. 10). Examples of cases with anthropogenic causes of stranding and suspected mercy release were shown in Fig. 10.

4. Discussion

The current study presented the first comprehensive review of sea turtle stranding records in Hong Kong waters utilizing data acquired over 23 years (2002–2024). Although the study covered a long-term period over two decades, the number of recorded cases was smaller compared to other regional studies, considering the Hong Kong region as a relatively small area, which only covered less than 1% of China's total marine area (Ng et al., 2017). In comparison, a study in Taiwan recorded more than one thousand sea turtle stranding cases over 23 years from 1997 until 2019 (Cheng et al., 2019). Despite the different scale and context of Hong Kong, our findings provided significant evidence that sea turtles are vulnerable to a combination of ecological and anthropogenic pressures across the East Asia region.

The green turtle was the most frequently stranded species during the study period. Green turtles are known to be the most abundant sea turtle species in the South China Sea and the only species that nest along the southern coast of China (Chan et al., 2007). Similarly, stranding investigation in nearby Taiwan also revealed green turtle as the most common species contributing 85.4% of all sea turtle strandings (Chou et al., 2023). The year-round occurrence of green turtle stranding and a high incidence of juvenile green turtles in this study reinforced the prior suggestion that, in addition to serving as a part of the migratory route for post-nesting females travelling to foraging sites in East and South China Seas (Chan et al., 2003), Hong Kong waters may also be an important foraging ground utilized year-round by green turtles, especially juveniles (Chan et al., 2007; Ng et al., 2018).

Stranded green and hawksbill turtles were predominantly juveniles, while loggerhead turtles were mostly adults. This was consistent with findings in Taiwan, where stranded green and hawksbill turtles exhibited shorter CCL compared to stranded loggerhead turtles, suggestive of recruitment to coastal Taiwan waters at different life stages (Cheng et al., 2019). While loggerhead turtles are occasionally recorded in Hong Kong waters and the northern South China Sea, the species is considerably more abundant in the East China Sea, with primary nesting

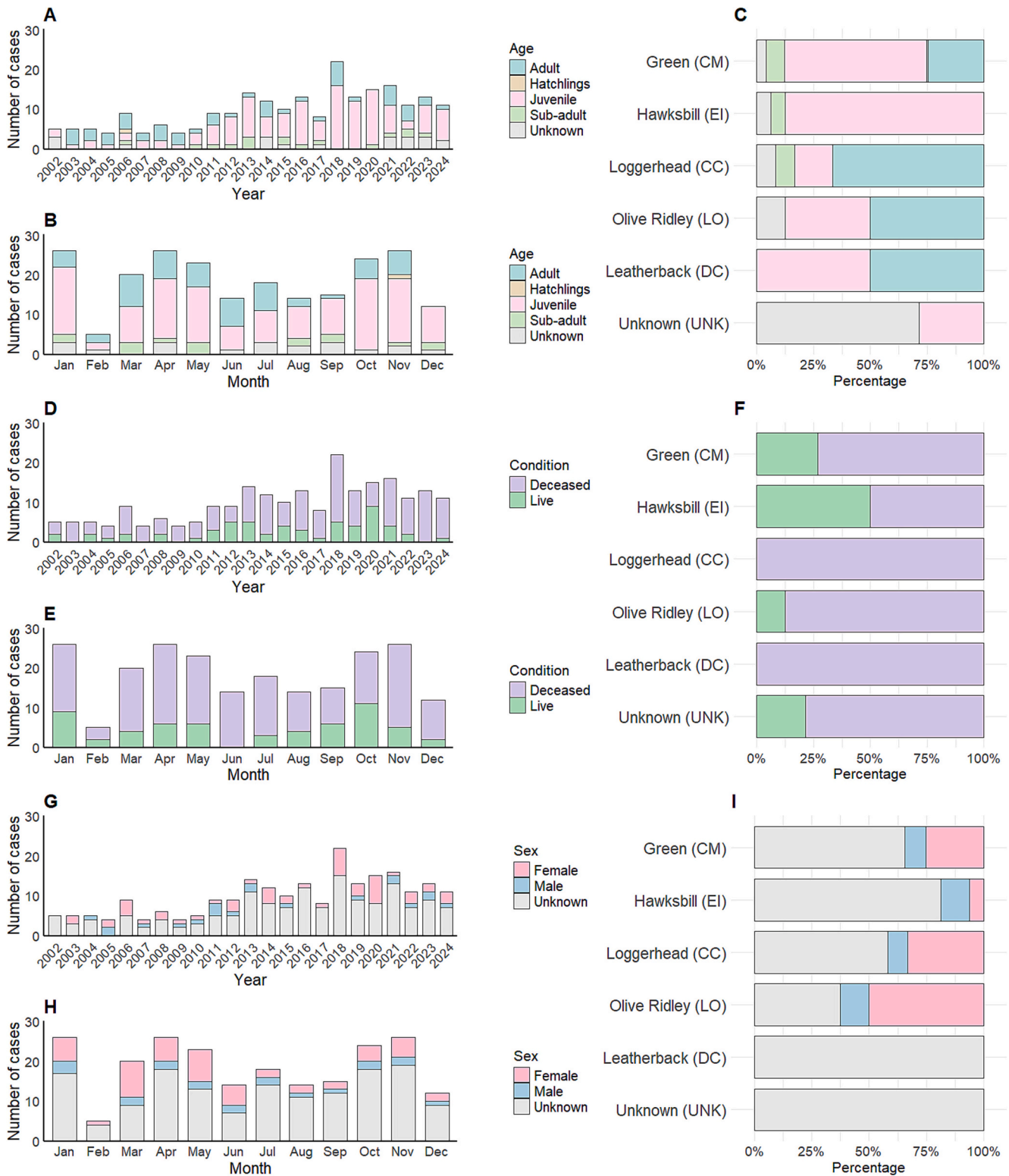


Fig. 3. Sea turtle stranding cases in Hong Kong waters between 2002 and 2024 sorted by (A) age group and year, (B) age group and month, (C) age group and species, (D) stranding condition (live or deceased) by year, (E) stranding condition by month, (F) stranding condition and species, (G) sex and year, (H) sex and month, and (I) sex and species.

beaches in Japan and sporadic nesting along the southern coast of the Republic of Korea (MTSG, 2020; Ng et al., 2024). The predominance of adult individuals among stranded loggerhead turtles in Hong Kong waters may suggest that this species occur in Hong Kong as migratory vagrants or visitors, rather than as residents. This may also be similar for

olive ridley turtles, where adults encompassed 50% of the stranding cases, as while this species can be found throughout East and South China Seas, it is relatively uncommon and not known to nest in China (Caceres-Farias et al., 2022; Chan et al., 2007). The leatherback turtle was the rarest sea turtle species to strand in Hong Kong waters, with only

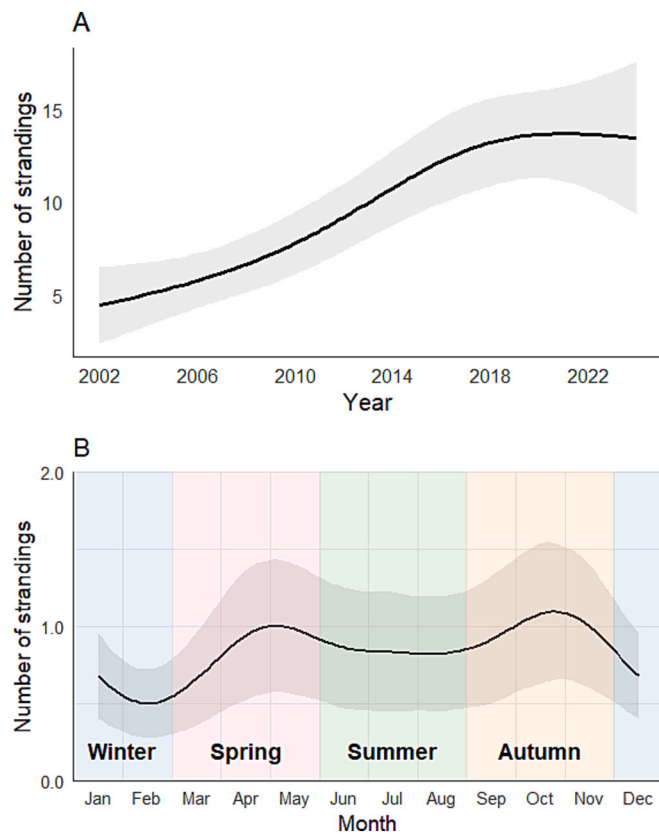


Fig. 4. Generalized additive models (GAMs) showing temporal trends in sea turtle stranding cases in Hong Kong waters between 2002 and 2024, by (A) annual trend of strandings and (B) monthly trend of strandings during the study period. Black lines indicate GAMs curves and grey areas represent 95% confidence intervals.

two documented cases reported over the 23-year study period (2018 and 2020).

The majority of strandings were of undetermined sex, likely due to incomplete carcasses or advanced decomposition hindering sex determination. Given the importance of understanding sex ratio and breeding females in sea turtle population dynamics, improved resolution in sex data in stranded sea turtles is required. Future studies may apply molecular techniques for sex determination using archival and prospective tissue samples to supplement gross morphological and histological assessment of gonads, especially in decomposed carcasses.

Temporal analysis of sea turtle stranding records over the 23-year study period revealed a significant increasing trend up to 2018, followed by a plateau in subsequent years. A similar increase in annual stranding numbers has been observed in Taiwan, where reports of sea turtle strandings sharply rose after 2012. However, whether this was followed by a plateau was not demonstrated (Cheng et al., 2019). Temporal analysis of long-term sea turtle stranding data in other East Asian countries is currently lacking. In the Hawaii Archipelago, a similar pattern with increasing green turtle stranding numbers since 1982, followed by plateau from the late 1990s was documented, which was attributed to a recovering population as the increase in stranding rate was comparable with the degree of population growth, although increased reporting effort and anthropogenic pressure may also be involved (Chaloupka et al., 2008). In Hong Kong, multiple overlapping factors likely have contributed to the observed temporal pattern. The increasing trend of stranding reported between 2002 and 2018 might be attributed to heightened anthropogenic pressures such as coastal fisheries bycatch, marine debris ingestion, and vessel strikes. Besides, maturation of local conservation initiatives, such as introduction of

government hotlines (e.g. Hotline 1823 in Hong Kong handles enquiries, compliments and suggestions for 23 participating departments and receives requests for government service/complaints about any areas of government services) and mobile applications may have promoted public awareness and improved accessibility for reporting stranded marine animals. The post-2018 plateau may reflect stabilizing influences, such as enhanced reporting saturation from increased environmental awareness, regulatory measures like expanded restricted areas at nesting sites (e.g., Sham Wan, Lamma Island) or potential population decline (no nesting reported since 2013). However, the relative contribution of these factors cannot be resolved with the present data. Continuous monitoring of sea turtle stranding records beyond the study period, along with further studies on at-sea abundance in Hong Kong waters, are necessary to clarify these dynamics.

Interannual variability in sea turtle stranding number was evident throughout the study period. This could be attributed to environmental variability leading to changes in sea turtle habitat usage or stranding (e.g. ocean currents, monsoon events), variable human activities (e.g. fishing effort), and true stochasticity in stranding detection. Further studies investigating the effects of environmental and human variables on stranding events is required to delineate their effects on sea turtle stranding in Hong Kong (Chaloupka et al., 2008; Chou et al., 2023).

Sea turtle stranding events in Hong Kong also demonstrated significant seasonal peaks during spring and autumn, and a relative decrease in winter. It has been suggested that the seasonal pattern in sea turtle stranding in Hong Kong may be related to seasonal migration, with the regional green turtle nesting season in April to June followed by post-nesting migration in August to October (Ng, 2015; Ng et al., 2018). The result from this study was also consistent with a study in Taiwan that found higher strandings in spring, which were from March to May (Chou et al., 2023). Another study in the Philippines showed that the highest incidence of sea turtle strandings was observed in March to May and in September (Lucero et al., 2010). Studies that tracked the migration of sea turtles found that green turtles from Jeju Island in the Republic of Korea moving towards the southwest and passing through the Hong Kong adjacent waters around November (Kim et al., 2022, 2024). This suggested that these seasons were likely the seasons in which sea turtles were mostly located around the Hong Kong adjacent waters during their migration period, which might increase the probability of strandings. However, as majority of the sea turtle strandings in this study was juvenile green turtles, whether the seasonal patterns can be solely explained by post-nesting migration, or other factors such as oceanographic or human factors, still need to be studied. Relatively low number of sea turtle stranding events in winter, especially February, may reflect seasonal environmental variation leading to less sea turtle carcasses appearing at shore (Cook et al., 2021; Flint et al., 2017; Hart et al., 2006), or lower reporting rate as there are less public recreational activities in the coastal areas during winter months.

Significant year-month interactions also indicated seasonal patterns varied year by year during the study period, which may reflect a complex interaction between environmental and anthropogenic factors. The impact of climate change that can alter migration patterns also needed to be considered. Rising ocean temperatures can shift migration patterns and change the visiting periods of sea turtles to certain waters, which can affect the seasonal stranding pattern between years (Fukuoka and Fukuda, 2024; Goudarzi et al., 2024). Studies of loggerhead turtles in the North Pacific Ocean show a shift in habitat range as ocean waters warm (Briscoe et al., 2025). Overall, further research is needed to examine these assumptions related to temporal trends of sea turtle strandings in Hong Kong.

Spatial analysis of sea turtle stranding events in Hong Kong waters revealed stranding hotspots in the eastern and southern coastal waters, which might not represent true mortality locations due to carcass drift driven by prevailing currents, detectability differences along coastlines, and variable public reporting. However, several lines of evidence support habitat association. Stranding hotspots (Fig. 8) were not located in

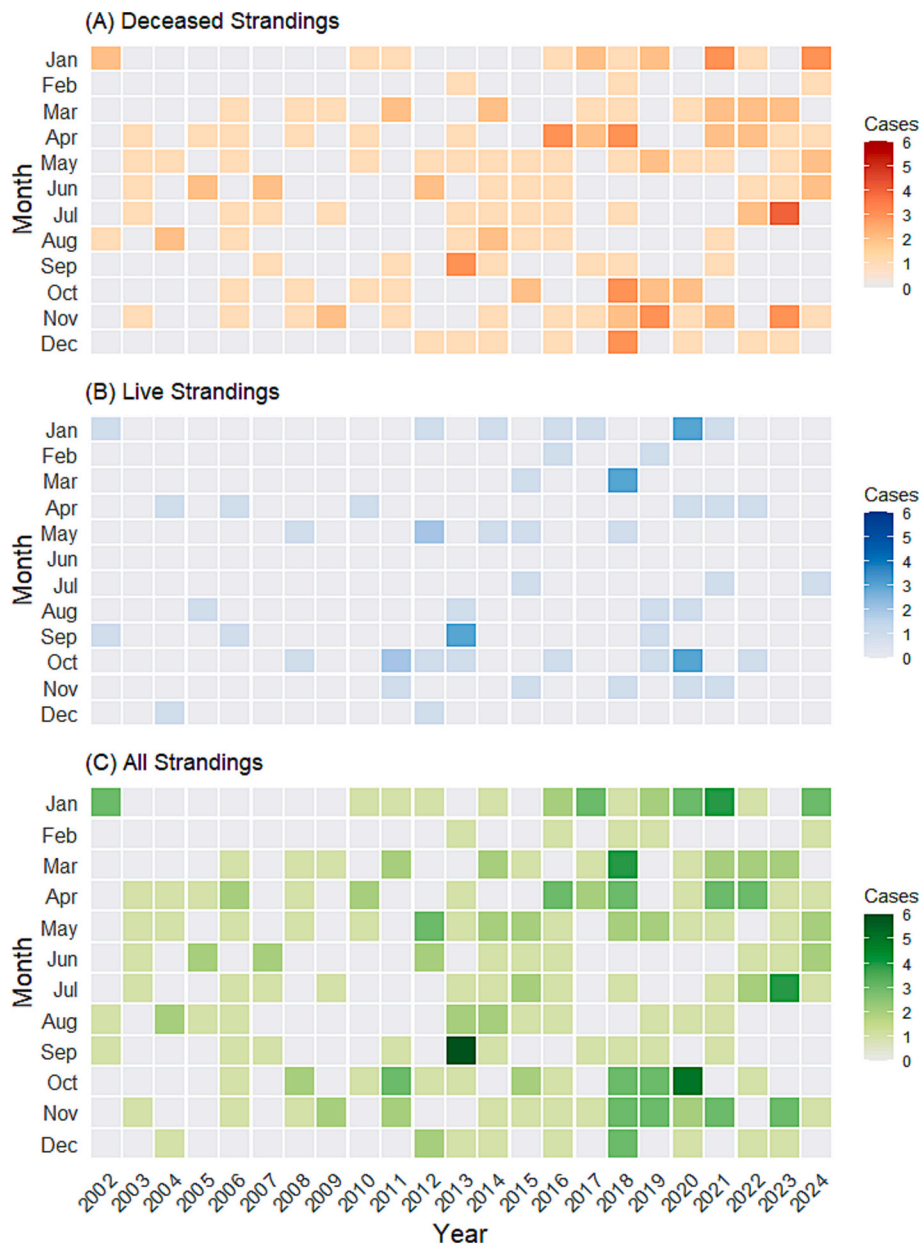


Fig. 5. Calendar heatmaps of sea turtle stranding cases in Hong Kong waters between 2002 and 2024, showing number of (A) deceased stranding cases, (B) live stranding cases, and (C) all stranding cases, in each month during the study period.

highly accessible urban areas (Victoria Harbour/Kowloon). The hotspots were associated with more favourable oceanic habitat in the eastern and southern waters with more corals and macroalgae, in contrast to the western waters that receive estuarine effluence from the Pearl River Estuary (Ng, 2015). Recent surveys also indicated that macroalgae is more abundant in eastern waters compared to western waters (Cheung-Wong et al., 2022), as well as a higher abundance of corals in eastern and southern Hong Kong waters with particularly higher coral coverage and diversity in eastern waters (Loke et al., 2024). Notably, various stranding hotspots identified in the current study, for example Port Shelter, Tung Ping Chau, Tai Long Wan and Long Ke Wan in eastern waters, and Cheung Chau in southern waters, also show proximity with identified coral assemblages in Hong Kong waters (Goodkin et al., 2011; Loke et al., 2024), suggesting these areas are potential key foraging habitats for sea turtles in Hong Kong waters.

Spatial distributions of sea turtle stranding records have also been correlated to anthropogenic stressors such as fishery activities and vessel

traffic to identify areas where sea turtle and human activities coincide to aid conservation management (Chou et al., 2023; Monteiro et al., 2016; Nicolau et al., 2016; Santos et al., 2018a; Tagliolatto et al., 2020). Fishery activities are also abundant in the eastern and southern waters in Hong Kong (AFCD, 2022). However, further studies quantitatively comparing the spatial distributions of sea turtle stranding and human activities are required to draw meaningful conclusions to inform effective conservation strategies. Multiple cases of sea turtle stranding were also reported within designated marine parks and marine reserves in Hong Kong. These cases may not necessarily indicate these marine protected areas failed to provide protection to local fauna, and instead may demonstrate that these areas are key habitats utilized by sea turtles. In addition, in cases of deceased strandings, ocean currents may also play a role to where the sea turtle carcasses end up, as demonstrated by various drift model studies (Cook et al., 2021; Hart et al., 2006; Koch et al., 2013; Santos et al., 2018a, 2018b). Thus, the relationship between seasonal oceanographic variables and spatial distribution of sea turtle

DISTRIBUTION OF SEA TURTLE STRANDINGS IN HONG KONG

ALL STRANDINGS (A)

- Live
- Deceased

SPECIES (B – G)

- Loggerhead
- Green
- Leatherback
- Hawksbill
- Olive ridley
- Unknown

■ Hong Kong SAR

■ Marine Parks and Reserve

(Basemap) CartoDB_

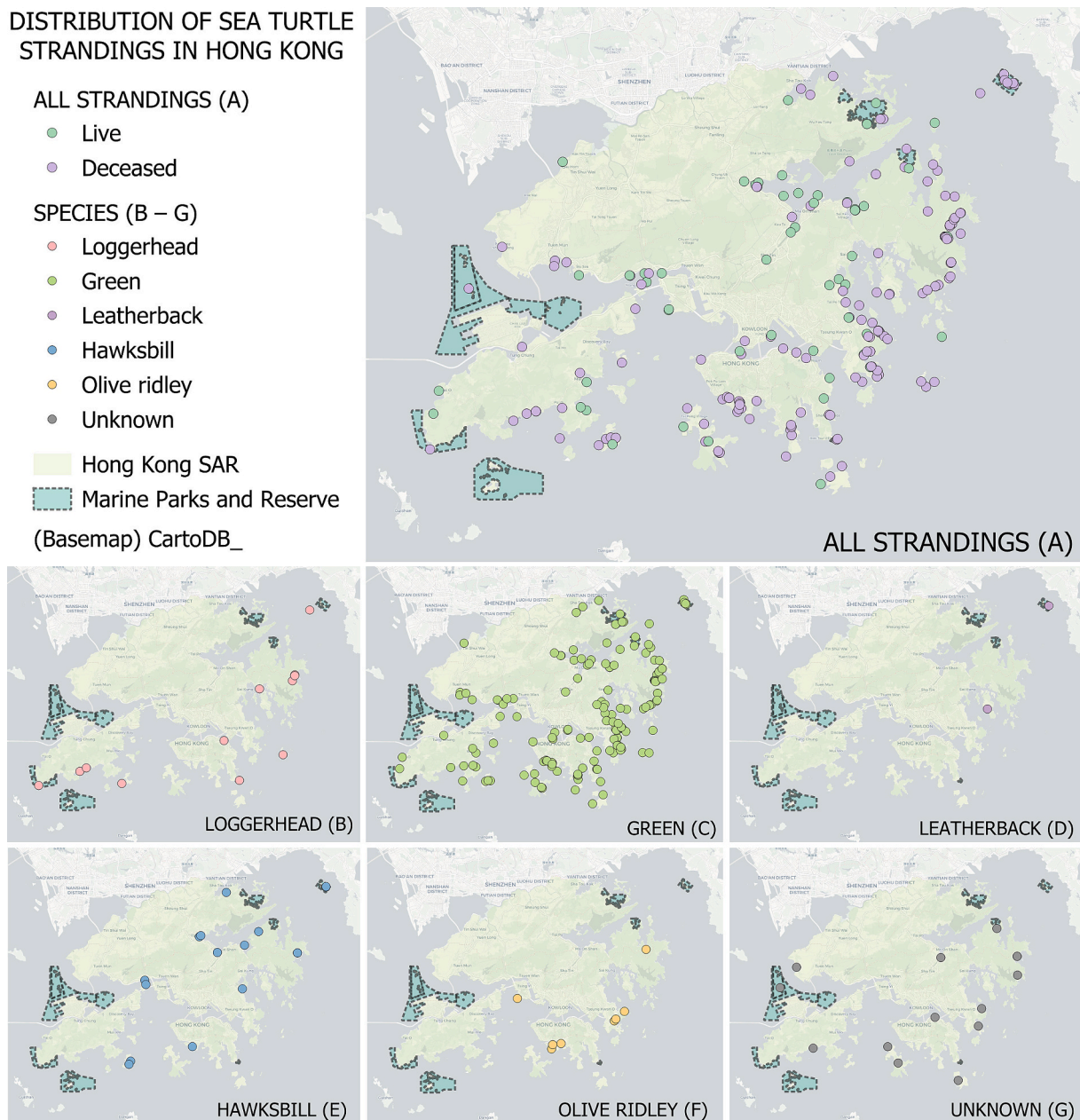


Fig. 6. Location of sea turtle stranding cases in Hong Kong waters between 2002 and 2024, including (A) all species sorted by live cases (green) and deceased cases (purple), and by individual species: (B) loggerhead turtle *Caretta caretta*, (C) green turtle *Chelonia mydas*, (D) leatherback turtle *Dermochelys coriacea*, (E) hawksbill turtle *Eretmochelys imbricata*, (F) olive ridley turtle *Lepidochelys olivacea*, and (G) undetermined species. Each dot represents the location of a single stranding case. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

stranding in Hong Kong needs to be investigated. Nonetheless, targeted effort to protect potential key habitats utilized by sea turtles will be important for the conservation of sea turtles in Hong Kong. Improved routine surveillance of stranding hotspots identified by the current study may also provide more opportunities to obtain biological data to better understand sea turtles in Hong Kong and the wider East and South China Seas.

A thorough analysis of the pattern of turtle strandings in Hong Kong waters over decades provided a complex picture of the possible causes of stranding. Determining the cause of stranding is often hampered by the highly decomposed state of carcasses, leaving many cases unidentified (Tsui et al., 2020). Although causes of stranding are sometimes difficult to determine as they could be influenced by many factors and varied across carcass conditions, identifying common patterns is critical for formulating more focused and effective conservation strategies. To

address this challenge, the virtopsy approach (utilizes advanced post-mortem imaging techniques) has been applied to complement and enhance conventional necropsy by guiding the identification of possible anthropogenic factors including trauma, or natural factors related to the diseases (Granados-Zapata et al., 2022; Chung et al., 2022; Kot et al., 2022a,b; Tsui et al., 2020). The implementation of routine postmortem examination and virtopsy have reduced sea turtle stranding investigation in Hong Kong from 83.89% to 66.21%. Accurate determination of the causes of stranding will allow prioritization of mitigation efforts, thereby reducing negative impacts on sea turtle populations and increasing the success of conservation programs in the region.

Anthropogenic factors were the most commonly identified causes of stranding, with significant contributions from fishery interactions, vessel collisions, and pollution. Vessel strikes, marine debris pollution, and fishery interactions including ghost net entanglement, hooks and

DISTRIBUTION OF SEA TURTLE STRANDINGS

Kernel density estimation

ALL STRANDINGS (A)

- <= 1
- 1 - 3
- 3 - 5
- 5 - 7
- 7 - 10
- > 10

DECEASED (B)

- <= 1
- 1 - 3
- 3 - 5
- 5 - 7
- 7 - 10
- > 10

LIVE (C)

- <= 1
- 1 - 3
- 3 - 5
- 5 - 7
- 7 - 10
- > 10

Hong Kong SAR

Marine Parks and Reserve

(Basemap) CartoDB_

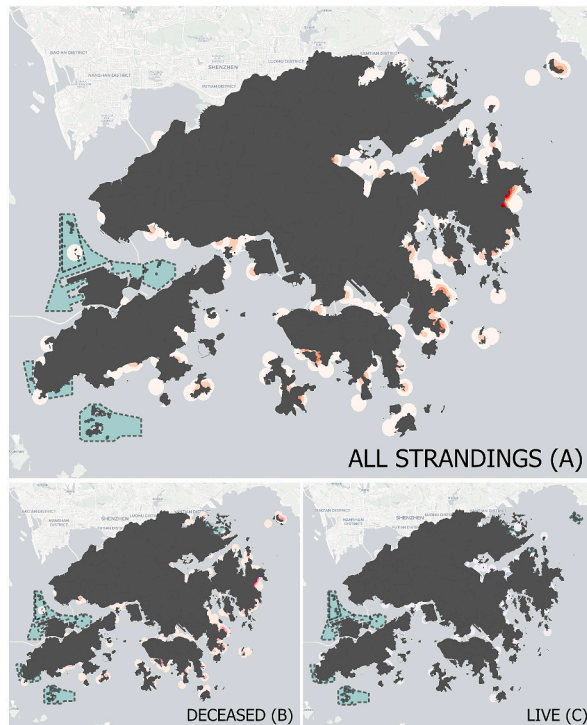


Fig. 7. Spatial distribution of sea turtle stranding cases in Hong Kong waters between 2002 and 2024 presented using kernel density estimation with a 1-km radius, including (A) all stranding cases, (B) deceased stranding cases, and (C) live stranding cases. Darker colours represent a higher density of stranding cases in the area.

HOTSPOTS OF SEA TURTLE STRANDINGS

Getis-Ord-Gi*

All strandings (A)

- Hotspot - 99% significant
- Hotspot - 95% significant
- Hotspot - 90% significant
- Non-significant

Deceased (B)

- Hotspot - 99% significant
- Hotspot - 95% significant
- Hotspot - 90% significant
- Non-significant

Live (C)

- Hotspot - 99% significant
- Hotspot - 95% significant
- Hotspot - 90% significant
- Non-significant

Hong Kong SAR

Marine Parks and Reserve

(Basemap) CartoDB_

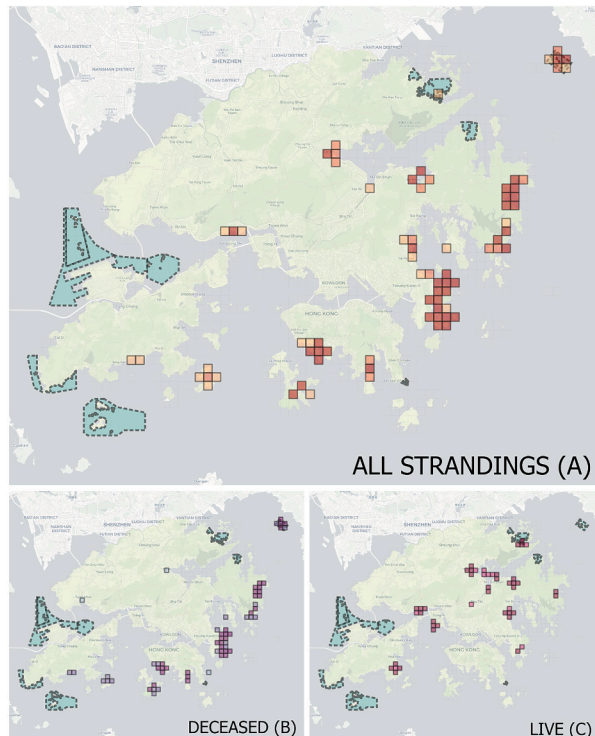


Fig. 8. Spatial hotspots of sea turtle stranding cases in Hong Kong waters between 2002 and 2024 obtained using Getis-Ord Gi* in 1 km × 1 km grids, including (A) all stranding cases, (B) deceased stranding cases, and (C) live stranding cases. Different colours represent varying significance levels (90%, 95%, 99%) of the hotspots.

lines, and bycatch are also some of the main threats that impacting sea turtles worldwide (Donlan et al., 2010; Duncan et al., 2017; Finkbeiner et al., 2011; Foley et al., 2019; Schuyler et al., 2014, 2016; Wallace et al., 2013). Studies in Taiwan as one of the adjacent waters to Hong Kong also found pollution including heavy metals, and fishing disturbance as

one of the main causes of sea turtle strandings (Cheng et al., 2019; Chou et al., 2023). In addition, natural factors made relatively small contributions in this study, with only three cases related to diseases and predation. However, the causes of stranding in this study were predominantly classified as undetermined, suggesting underestimation

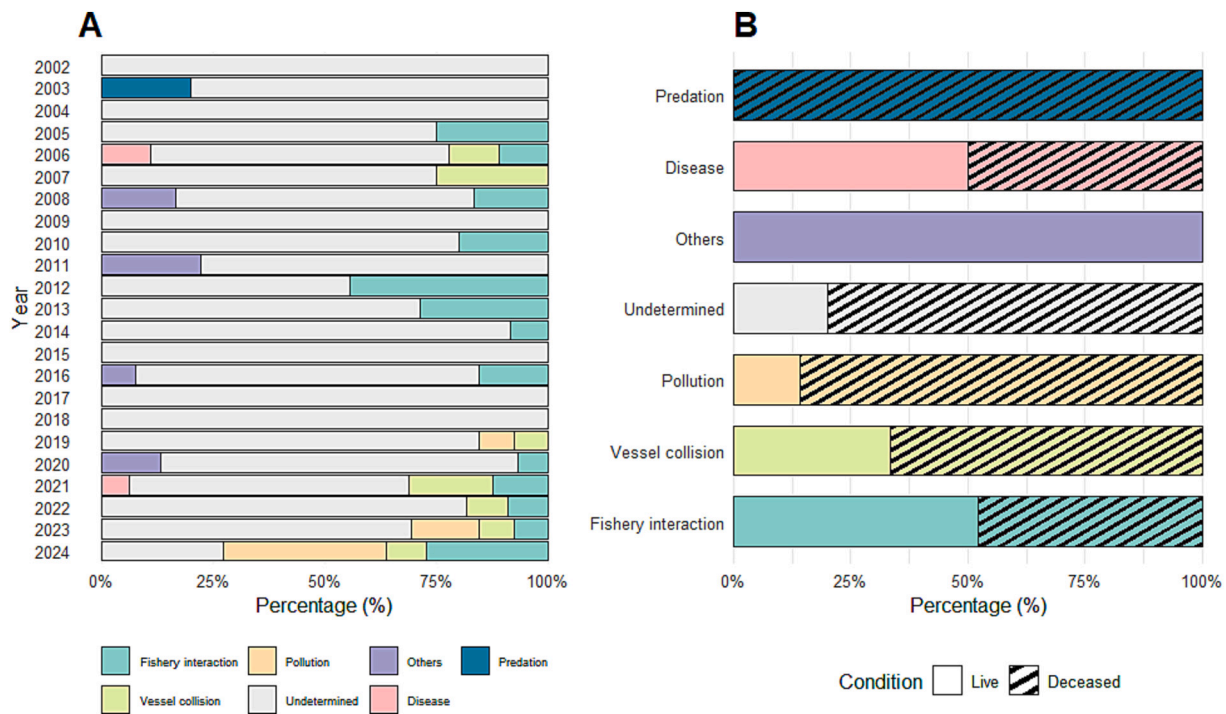


Fig. 9. Causes of stranding in sea turtle stranding cases in Hong Kong waters between 2002 and 2024 sorted by (A) year and (B) stranding condition (live or deceased).

of anthropogenic impacts (the dominant diagnosed cause) since only high-confidence diagnoses were classified. This was partly attributed to a high proportion of carcasses in advanced decomposition condition, which limits detailed postmortem examinations and poses a significant challenge for local cetacean stranding investigations in Hong Kong (Tsui et al., 2020). Uncertainty could be reduced in future by routine virtopsy for all fresh cases, more timely retrieval of stranded carcass, and establishment of a tissue bank to re-examine undetermined stranding cases through detailed histopathological analysis. Additionally, the fact that full postmortem examinations were not consistently performed in sea turtle stranding cases prior to 2019 may have further contributed to the high number of undetermined causes during the study period. Virtopsy and standardized necropsy implementation since 2019 reduced undetermined diagnosis from 83.9% to 66.2%, demonstrating feasibility.

This study also documented evidence of the practice of mercy release of sea turtles, which is common in various communities in East Asia, with captive-bred, bycatch, or live-stranded sea turtles acquired by institutions then released for religious purpose (Kuo et al., 2017; Lin et al., 2021, 2023; Severinghaus and Chi, 1999; Shiu and Stokes, 2008). A previous interview-based study in Hong Kong also showed that while most fishermen will release bycaught sea turtles immediately on site, a minority may sell the sea turtle to religious institutions for mercy release practice (Ng, 2015). Several stranding cases during the study period demonstrated evidence of mercy release, including colour paint on the carapace, prayer labels, or tags that were intentionally attached before release. These findings suggested that improper release practices may contribute to sea turtle stranding and mortality, particularly if the individuals were bycatch or stranded and not properly rehabilitated and evaluated before release. While underscoring a unique regional challenge, its impact relative to dominant threats like bycatch and vessel collision requires further study through enhanced post-release tracking. Future conservation efforts including public education on the impact of mercy release, governmental regulations, as well as encourage potential collaboration between religious institutions and licensed rehabilitation organizations to balance between traditional practice and conservation

efforts.

While this study provided a comprehensive overview of the sea turtle strandings in Hong Kong waters over the past two decades, several limitations needed to be addressed, particularly in terms of response and data recording. The availability of data from public reports and field observations still relied heavily on detection and reporting by the public or local authorities, which was unlikely to capture all actual strandings. This might introduce spatial and temporal bias, especially in areas with limited access or low reporting rates. In addition, there were limitations in past identification and documentation, such as the actual location coordinates, species identification, biological data records, and limitations in determining the exact cause of strandings. Therefore, rapid response to reports of sea turtle strandings and the development of a more integrated monitoring and recording system are needed to support more accurate records and strengthen the scientific basis for future conservation strategies.

The increasing number of strandings indicated significant variability that needed to be addressed through more focused and responsive conservation strategies. These findings highlighted the importance of intensive monitoring and implementation of data-driven conservation policies, especially in identified hotspots, and helped to mitigate risks to vulnerable sea turtle populations. There is also concrete government effort through the Green Turtle (*Chelonia mydas*) Species Action Plan 2023–2027 by the AFCD (AFCD, 2023). This action plan included strengthening the species and habitat protection, research and collaboration, and public awareness campaigns.

Community involvement in the reporting of stranded sea turtles plays a critical role in enhancing the effectiveness of stranding response efforts. The citizen science approach can improve the early detection of stranded sea turtles and expand the scope of data collection. Public involvement as active observers can make stranding reports collected more quickly and widely (Nascimento et al., 2024; Rousso et al., 2024). To support the stranding response, the development of conventional and innovative reporting tools is essential, such as government hotlines (e.g. Hotline 1823 in Hong Kong) and mobile applications to educate and facilitate the public to report sea turtle and cetacean strandings. As an

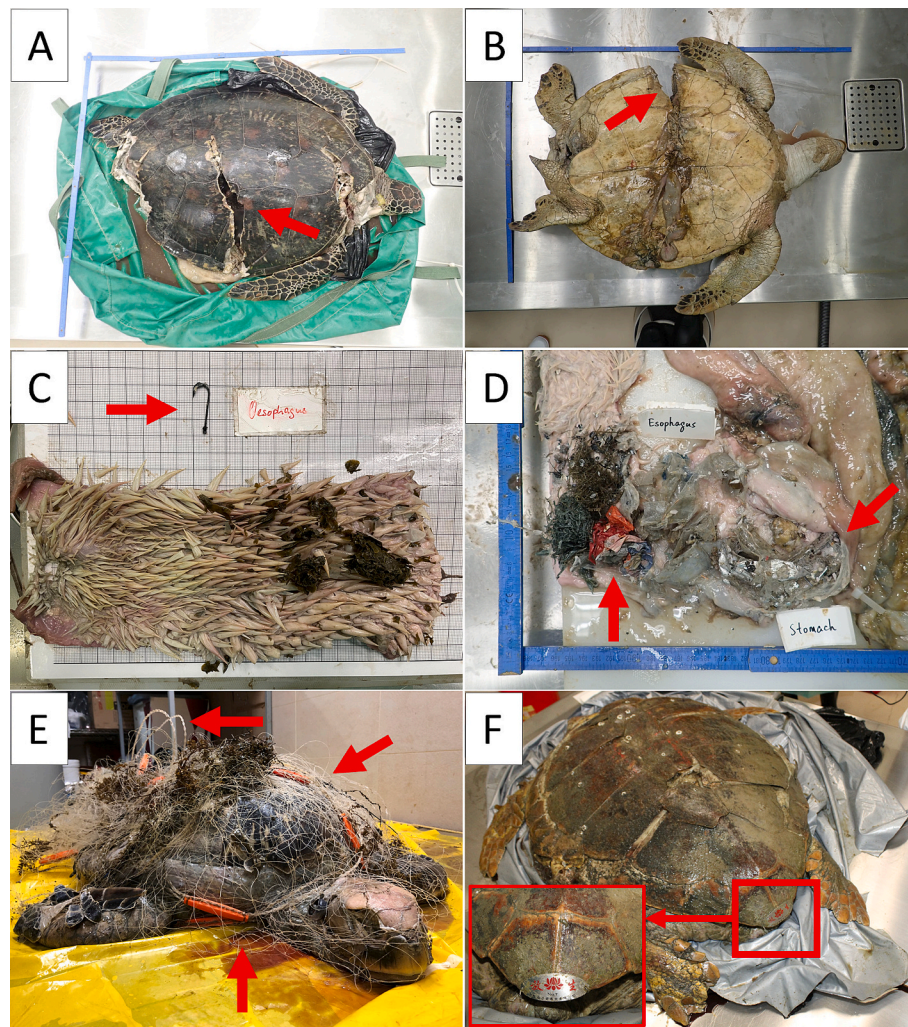


Fig. 10. Necropsy findings of selected sea turtle stranding cases associated with anthropogenic causes in Hong Kong waters. (A and B) Cases with injuries consistent with vessel collision, including fractured carapace or plastron characterized by parallel linear or curvilinear wounds likely made by propellers. (C) A case with fishing hook found in the esophagus and possibly associated with fishery interaction. (D) A case with substantial quantity of marine debris recovered from the stomach, associated with potential gastric impaction and stranding due to pollution. (E) A case was found extensively entangled in a gillnet and associated with fishery interaction. (F) A case associated with mercy release, suggested by a metallic tag attached on the caudal central scute of the carapace engraved with the word 'mercy release' in Chinese (放生) and the name of a religious institution.

innovative advancement in stranding investigation method, a virtopsy-based approach was implemented and subsequently integrated into a dedicated citizen science mobile application (eSeaAnimals, see Supplementary Material, Fig. S2) on both iOS and Android system, in conjunction with an integrated web-accessed database, developed by the Aquatic Animal Virtopsy Laboratory, City University of Hong Kong. This approach allows real-time recording of stranding data, mapping of incident points, and automatic notification sending to the rapid response team, thereby accelerating the process of diagnosing the cause of stranding and mitigation actions in the field.

The sea turtle population in Hong Kong waters is part of the wider South China Sea population. Therefore, anthropogenic pressures or other activities in South China Sea may affect the same sea turtle population. This condition emphasizes the importance of regional collaboration in stranding monitoring and postmortem investigation that can facilitate the open exchange of information, data, and case management protocols between countries. Standardization in reporting stranded turtle data in the South China Sea region is needed to facilitate the exchange of stranding and postmortem information between cities and countries (Chan et al., 2017). By collecting and sharing data collaboratively, investigations into the causes of stranding can be carried out

more comprehensively. Holistic data analysis is expected to be an important reference for conservation networks in the regional area. Overall, these findings emphasized the need for a multidisciplinary approach and collaboration in conservation efforts to identify key factors influencing sea turtle strandings and formulate effective mitigation strategies.

5. Conclusion

This study highlights an increasing trend in sea turtle strandings in Hong Kong, predominantly involving green turtles, alongside consistent spatial and temporal patterns. Strandings peak in autumn and spring, and locations are concentrated in eastern and southern waters. These findings underscore Hong Kong's strategic position within the South China Sea sea turtle habitat network. Among diagnosed cases, anthropogenic factors dominated despite 78.5% undetermined causes (suggesting underestimation of fishery interactions and vessel strikes, the leading global and regional threats), highlighting limitations in reporting and diagnostics that necessitate standardized protocols including timely carcass retrieval, routine virtopsy and conventional necropsy. Conservation implications should be prioritized, including habitat

protection, regulation of fishery interactions, mitigation of vessel collisions, and enhancement of reporting systems. These efforts demand international cooperation and multidisciplinary collaboration, as Hong Kong's eastern hotspots represent shared foraging habitat across the South China Sea essential for sustaining migratory sea turtle populations throughout this connected ecosystem.

CRediT authorship contribution statement

Brian Chin Wing Kot: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Tabris Yik To Chung:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Virgilius Martin Kelake Kedang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Data curation, Conceptualization. **Henry Chun Lok Tsui:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Chun Keat Ooi:** Writing – review & editing. **Heysen Hei Nam Ho:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecoinf.2026.103735>.

Data availability

The raw stranding data supporting the findings of this study belong to the Agriculture, Fisheries and Conservation Department (AFCD) of the Hong Kong Special Administrative Region Government and cannot be publicly shared due to restrictions under data-use agreements and government regulations. Requests for access should be directed to the AFCD for consideration on a case-by-case basis via their official procedures (contact: enquiry@afcd.gov.hk or <https://www.afcd.gov.hk>). All analytical methods and model specifications are fully described in the Materials and Methods section to ensure reproducibility using standard open-source software.

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