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Review

Interactions between marine megafauna and plastic pollution in Southeast Asia

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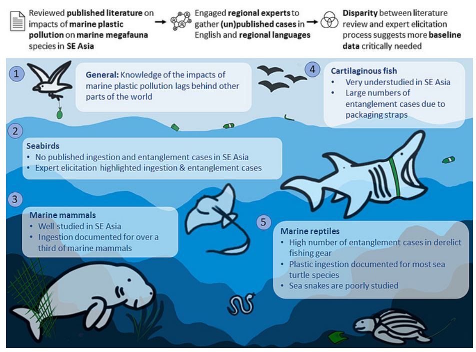
HIGHLIGHTS

- Marine plastic-wildlife interactions identified as a research priority in SE Asia
- Combined a structured literature review with a regional expert elicitation
- Knowledge of marine pollution impacts on marine megafauna in SE Asia lags behind.
- Many entanglement/ingestion cases remain in the grey literature in the region.
- Additional baseline data critically needed to inform policy/solutions in SE Asia

GRAPHICAL ABSTRACT



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ABSTRACT

Southeast (SE) Asia is a highly biodiverse region, yet it is also estimated to cumulatively contribute a third of the total global marine plastic pollution. This threat is known to have adverse impacts on marine megafauna, however, understanding of its impacts has recently been highlighted as a priority for research in the region. To address this knowledge gap, a structured literature review was conducted for species of cartilaginous fishes, marine mammals, marine reptiles, and seabirds present in SE Asia, collating cases on a global scale to allow for comparison, coupled with a regional expert elicitation to gather additional published and grey literature cases which would have been omitted during the structured literature review. Of the 380 marine megafauna species present in SE Asia, but also studied elsewhere, we found that 9.1 % and 4.5 % of all publications documenting plastic entanglement ($n = 55$) and ingestion ($n = 291$) were conducted in SE Asian countries. At the species level, published cases of entanglement from SE Asian countries were available for 10 % or less of species within each taxonomic group. Additionally, published ingestion cases were available primarily for marine mammals and were lacking entirely for seabirds in the region. The regional expert elicitation led to entanglement and ingestion cases from SE Asian countries being documented in 10 and 15 additional species respectively, highlighting the utility of a broader approach to data synthesis. While the scale of the plastic pollution in SE Asia is of particular concern for marine ecosystems, knowledge of its interactions and impacts on marine megafauna lags behind other areas of the world, even after the inclusion of a regional expert elicitation. Additional funding to help collate baseline data are critically needed to inform policy and solutions towards limiting the interactions of marine megafauna and plastic pollution in SE Asia.

Contents

1. Introduction

Southeast Asia (hereafter SE Asia) is a known biodiversity-rich region, with exceptionally high levels of species endemism and richness (Jefferson and Costello, 2020), linked to its complex biogeographical history (Metcalfe, 2011). The region hosts two of the 18 marine biodiversity hotspots, namely Indonesia and the Philippines (Roberts et al., 2002), harbouring some of the highest mean diversity across marine taxa (Miller et al., 2018; Tittensor et al., 2010). Alongside its extensive biodiversity, several countries in the region of SE Asia are predicted to be major contributors of plastic waste entering the marine environment (Jambeck et al., 2015; Lebreton et al., 2017; Meijer et al., 2021). Specifically, in 2015, Indonesia, Malaysia, the Philippines, Thailand, and Vietnam were estimated to cumulatively contribute almost a third of marine plastic pollution to the world's oceans (Jambeck et al., 2015). This includes 29 rivers in SE Asian countries that are among the predicted global top 50 plastic-emitting rivers (Meijer et al., 2021). The scale of the marine plastic pollution in SE Asia is of particular concern as plastic pollution is known to have potential wide-ranging adverse ecological, social, and economic effects, having consequential impacts on multiple ecosystem services (Abalansa et al., 2020; Beaumont et al., 2019; Thushari and Senevirathna, 2020). The latter are defined by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services as 'nature's contribution to people', which is essential to human existence and quality of life (Brauman et al., 2019).

At the ecological level, plastic ingestion is being documented across an increasing number of marine species (Kühn and van Franeker, 2020) and across food webs (Carbery et al., 2018). The ingestion of plastic items can lead to numerous sub-lethal impacts, including physical blockage or perforation of the gastrointestinal tract and altered growth, and potential mortality (Puskic et al., 2020). The presence of plastic pollution in the marine environment can also lead to wildlife becoming entangled, potentially resulting in body deformities if the entanglement is chronic in juveniles or death if individuals cannot feed or breathe (e.g. Duncan et al., 2017; Jepsen and de Bruyn, 2019; Parton et al., 2019; Ryan, 2018).

Outside of SE Asia, several marine vertebrates are being used as bioindicator species for plastic pollution, including the loggerhead turtle (*Caretta caretta*) (Fossi et al., 2018) and the northern fulmar (*Fulmarus glacialis*) (Avery-Gomm et al., 2012), due to their high abundance and broad distributions (Bonanno and Orlando-Bonaca, 2018). However, the impacts of plastic pollution are often spatially variable, as well as population and species specific, requiring research to be conducted at various spatial scales (Wilcox et al., 2015). For example, modelling suggests that entanglement rates are expected to be higher in oceanic gyres and along coastlines, which are known plastic debris hotspots (Høiberg et al., 2022). Likewise, plastic ingestion appears to differ among taxonomic groups and species (Kühn and van Franeker, 2020; Provencher et al., 2017). For example, based on home range and life history traits, cartilaginous fishes, ray-finned fishes, mammals, and reptiles are predicted to be at higher risk of plastic ingestion in the Mediterranean sea than cephalopds or crustaceans (Compa et al., 2019).

Plastic pollution is a known threat to marine vertebrate species in SE Asia (Todd et al., 2010). However, several recent reviews have highlighted knowledge gaps in our understanding of its impacts on the region (Curren et al., 2021; Lyons et al., 2020, 2019; Omeyer et al., 2022). A review of the published literature relating to plastic pollution from SE Asian countries and including China, Japan, and the Republic of Korea pointed out the need for further research on plastic-wildlife interactions in the marine environment (Lyons et al., 2020). This was similarly reiterated by Omeyer et al. (2022), in which they identified this need as a key research priority for the region. Here, we aimed to address this research priority (1) by reviewing the literature (in English) of the impact of marine plastic pollution on marine megafauna species present in SE Asia, in addition to cases on these species elsewhere on a global scale to allow for comparison, and (2) by engaging with regional experts to gather published and grey literature in English and other regional languages, going beyond the English publication bias to add more to knowledge gaps. While the total vertebrate species richness in SE Asia is mostly driven by bony fish species (Tittensor et al., 2010), we did not consider this super class due to the scarcity of published literature with respect to plastic pollution (Kühn and van Franeker, 2020). Instead, we focused research efforts on the seabirds, marine mammals, and marine reptiles, as these are more widely studied globally (Kühn and van Franeker, 2020) and often used as bioindicator species (Bonanno and Orlando-Bonaca, 2018). Cartilaginous fishes, such as sharks, rays, and skates, were included because of their importance for the ecosystem functional diversity (Pimiento et al., 2020). Additionally, numerous species from all four of these taxonomic groups are usually present at the top of food chains, where the impacts of plastic pollution may be biomagnified due to trophic transfer (Anbumani and Kakkar, 2018; Carbery et al., 2018) and any adverse impacts of plastic-wildlife interactions will have knock-on effects on ecosystem functioning (Benkwitt et al., 2022; Hammerschlag et al., 2019; Pimiento et al., 2020; Tavares et al., 2019). In general, many of these species are also of broader conservation concern (IUCN SSC Shark Specialist Group, 2007; UNEP/CMS Secretariat, 2015, 2014).

2. Methods

2.1. Structured literature review

A structured literature review was conducted in English to identify peer-reviewed articles and grey literature reporting the impacts of marine plastic pollution, specifically plastic entanglement and ingestion for marine vertebrate species present in SE Asia. The latter species list was determined using the IUCN (International Union for Conservation of Nature) Red List of Threatened Species (IUCN, 2021). This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement, which aims to improve the transparency of systematic literature review and meta-analysis reporting (Page et al., 2021).

2.2. Species list

Three filters of the advanced search function of the IUCN Red List of Threatened Species website (https://www.iucnredlist.org) were used to establish the species list for this literature review. Firstly, the land region filter was used to select SE Asian countries, namely Brunei Darussalam, Cambodia, Indonesia, Laos (the only landlocked country in the region), Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste, and Vietnam. Secondly, the habitat filter was used to narrow down to species present in the marine environment, selecting the following categories: 'marine neritic', 'marine oceanic', 'marine deep benthic', 'marine intertidal', and 'marine coastal/spratidal'. Finally, the taxonomy filter was used to determine species of cartilaginous fishes, marine mammals, non-avian marine reptiles, hereafter referred to as marine reptiles (as defined in Motani, 2009), and avian marine reptiles, hereafter referred to as seabirds (as defined in Schreiber and Burger, 2001).

Alongside this, the IUCN threat status of each species was recorded, and a list of Boolean species search terms was established from the species common names (Table 1, ‘species search terms’). A second list of Boolean search terms was established to capture the various terminologies used to describe or report marine plastic ingestion and entanglement (Table 1, ‘interaction search terms’). One search term from each search list (interaction search term list and species search term list) were combined using an AND operator (e.g. entangle* AND dolphin*), and all combinations were searched. Speech marks (“”) were used to ensure the full search term phrase was present in the text (e.g. “cartilaginous fish” instead of cartilaginous and/or fish) and the asterisk (*) to ensure that multiple combinations of search terms were present in the text (e.g. entangle* returned records for entangle, entangled, entangles, and entanglement).

2.3. Literature search

The Publish or Perish software (Harzing, 2007) was then used to extract records from Google Scholar and Web of Science using an exhaustive combination of interaction and species search terms (Table 1). An upper limit of 100 records was placed on Google Scholar, as upon inspection, no relevant records tended to be found after the first 10 pages. Web of Science was chosen as the most relevant dataset of peer-reviewed journal articles, while Google Scholar was chosen as a broader dataset that would also include grey literature such as government and NGO reports that might be relevant. As such, both datasets complemented each other, with a degree of overlap.

Records up to 12th August 2021 were screened by authors (LCMO and EMD). This returned a total of 50,696 records, of which about half (51.7 %, n = 26,221) were duplicate records of the same search result (Fig. 1). The titles and abstracts of the remaining 24,475 records were screened to determine whether they reported plastic ingestion and/or entanglement for species of interest present in SE Asia, as detailed in Table S1. If in doubt on the species or plastic interaction, records were investigated further if the text was available in full. This screening process resulted in 24,042 records being excluded, and a total of 433 publications that met the criteria or that were of interest but some of the information was unclear (e.g. whether entanglement was in operational or non-operational fishing gear), of which 19 articles (4.4 %) were not accessible (Fig. 1). A total of 414 publications, representing 1.7 % of non-duplicate records, were retrieved in full and screened to determine if they included metrics of plastic ingestion and/or entanglement for species present in SE Asia (see Section 2.4 for a list of metrics extracted). Due to the difficulty of differentiating between bycatch (entanglement in operational fishing gear) and entanglement in Abandoned, Lost, or otherwise Discarded Fishing Gear (ALDFG; also referred to as derelict or ghost gear), only records that specifically mentioned that species were entangled in non-operational fishing gear were included. Records

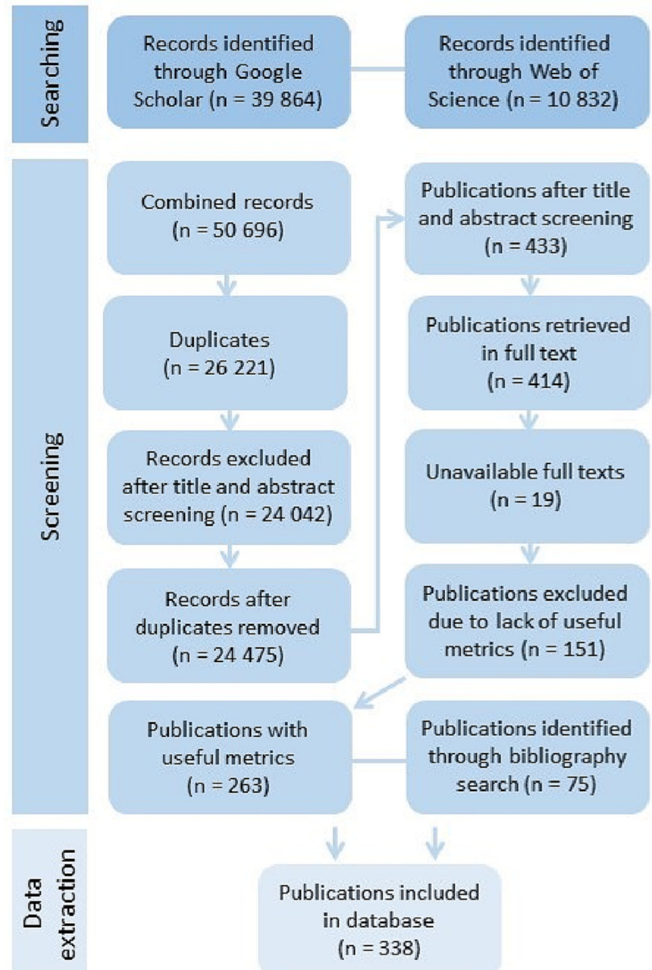


Fig. 1. PRISMA flowchart of the structured literature review process, from the initial searching through to data extraction.

Table 1
List of Boolean search terms used in this structured literature review. Speech marks (“”) and the asterisk (*) were used to ensure the full search term phrase and that multiple combinations of search term were present in the text, respectively.

Interaction search terms		Species search terms			
Entanglement	Ingestion	Cartilaginous fishes	Marine mammals	Marine reptiles	Seabirds
ALDFG	Debris	“Cartilaginous fish*”	Dolphin*	“Marine reptile*”	Albatross*
Derelict	Litter	Chimaera*	Dugong*	“Marine turtle*”	Boob*
Discard*	Microplastic*	Dogfish*	“Marine mammal*”	“Sea snake*”	Cormorant*
Entangle*	“Plastic debris”	Elasmobranch*	Porpoise*	“Sea turtle*”	Frigatebird*
“Ghost gear”	“Plastic ingestion”	Guitarfish*	Whale*	Snake*	Gull*
“Ghost net*”	Plastic* NOT Plasticity	Numbfish*		Turtle*	Jaeger*
		Ray*			Nodd*
		“Sand tiger*”			Pelican*
		Sawfish*			Petrel*
		Shark*			Prion*
		Skate*			Seabird*
		Smoothhound*			“Sea bird*”
		Smooth-hound*			Shearwater*
		Spurdog*			Skua*
		Stingaree*			Stormpetrel*
		Wedgefish*			“Storm petrel*”
		Wobbegong*			Tern*
					Tropicbird*

were not included if the entanglement material was ambiguous to the authors conducting the literature search. A total of 263 publications, representing 1.1 % of non-duplicate records, included useful metrics of plastic ingestion and/or entanglement (Table S1). During this process, if a record included useful metrics, its bibliography was screened for keywords to identify additional records, yielding a further 75 publications with useful metrics which were not returned by the Publish or Perish software, resulting in a total of 338 publications from which data were extracted (Fig. 1).

2.4. Data extraction

Lead author name, article/report title, publication year, country of study (SE Asia or elsewhere), species group (cartilaginous fish, marine mammal, marine reptile, or seabird), species common name, species scientific name, and sample size (total number of individuals) were recorded for all 338 publications containing useful metrics of plastic ingestion and/or entanglement for marine vertebrate species present in SE Asia. For publications on ingestion, plastic size (macro: >5 mm or micro: ≤5 mm), frequency of occurrence (%; number of individuals which had ingested plastic as a function of the total number of individuals included in the study), observation method (necropsy and/or live sampling), and individual impacts (e.g. gut obstruction, impaction) were recorded. For publications on entanglement, entangling material (e.g. packaging, derelict fishing gear) and individual impacts (e.g. abrasions, body deformities) were recorded.

2.5. Data analysis

From these 338 publications, 130 cases of entanglement and 657 cases of ingestion were extracted. Each case was coded to represent an entry for an individual species and publication, with publications covering multiple species yielding multiple cases and with many cases comprising multiple individuals of the same species. For publications investigating entanglement and ingestion in multiple locations, these cases were pooled according to countries inside and/or outside of SE Asia.

Data were analysed and plotted using the statistical programme R version 4.1.2 (R Core Team, 2021) and the packages *cowplot* (Wilke, 2020), *dispmod* (Scrucca, 2018), *ggplot2* (Wickham, 2016), *grid* (Murrel, 2020), *jpeg* (Urbanek, 2021), *MASS* (Venables and Ripley, 2002), *mgcv* (Wood, 2011), *MuMIn* (Barton, 2015), *nlme* (Pinheiro et al., 2022), *patchwork* (Pedersen, 2020), *performance* (Lüdecke et al., 2020), *png* (Urbanek, 2013), and *rstatix* (Kassambara, 2021).

Negative binomial generalised linear models were used to account for overdispersion to explore the relationship between sample size and taxonomic groups for entanglement and ingestion cases. Binomial generalised linear models were used to explore the relationship between plastic ingestion frequency of occurrence and taxonomic groups, accounting for overdispersion. All analyses were replicated, removing single individual cases to explore the impact of these cases on sample size and ingestion frequency of occurrence. Due to the smaller subset of results for SE Asia specifically (see Results), we did not consider differences in sample size or frequency of occurrence between cases for SE Asia and those collected elsewhere. In all instances, the maximal and null models were examined and ranked by Akaike's Information Criteria (AIC). Top-ranked models were defined as models with <2 AIC units of the best-supported model.

2.6. Regional expert elicitation

Although English was adopted as the working language when the Association of Southeast Asian Nations (ASEAN) was established, more than a thousand languages are spoken across the region. As such, to account for how linguistically diverse SE Asia is, regional experts in the field of marine plastic pollution and marine vertebrates were approached to expand the scope of the literature search, which was done solely in English.

Regional experts were identified as (1) those who contributed to publications on the topic in the region during the literature search (typically the corresponding author, but more authors if email addresses were available), and (2) those listed in Lyons et al. (2020) as main players in marine plastic research in SE Asia. When approached, experts were asked if they would like to be involved and, if so, to check that the literature review was as comprehensive as it could be, helping bring enhanced regional perspectives by identifying published and/or unpublished data from publications/reports/news articles from the region in English and any other regional languages that were not obtained through the structured literature search. This expert elicitation process was done to fill in the gaps within the understanding of the impacts of plastic pollution on marine vertebrates in the region, going beyond the English publication bias. Simultaneously, experts were asked to suggest (1) other contacts to ensure that as many regional voices were included and (2) other members of their teams who had contributed to their work to allow good coverage of seniority and gender.

3. Results

3.1. Taxonomic groups

A total of 380 marine vertebrate species present in SE Asia were identified during the filtering of the IUCN Red List of Threatened Species website (Tables S1 and S2), the majority of which were cartilaginous fishes (n = 228, 60.0 %), followed by seabirds (n = 72, 18.9 %), marine reptiles (n = 49, 12.9 %), and marine mammals (n = 31, 8.2 %; Tables S1 and S2). Of these species, over a third were listed as Least Concern (n = 146, 38.4 %), followed by Vulnerable (n = 71, 18.7 %), Endangered (n = 51, 13.4 %), Near Threatened (n = 46, 12.1 %), and Critically Endangered (n = 23, 6.1 %; Fig. S1). The remaining 11.3 % of species were listed as Data Deficient (n = 43), of which over half were cartilaginous fish species (n = 25, 58.1 %), followed by marine reptile (n = 13, 30.2 %) and marine mammal species (n = 5, 11.6 %; Fig. S1). No seabird species present in SE Asia were listed under the Data Deficient category (Fig. S1).

3.2. Publications

The 338 publications identified during the structured literature review process were published from 1968 to 12th August 2021 (Fig. 2), the date at which the Publish or Perish search was conducted. The annual number of publications reporting plastic ingestion and entanglement increased over time (Fig. 2). Approximately two-thirds (n = 37, 69.1 %) and over half (n = 169, 58.1 %) of publications reporting plastic entanglement and ingestion, respectively, were published in the last 10 years (2012–2021; Fig. 2).

3.3. Plastic entanglement

3.3.1. Global perspective

Publications on plastic entanglement for species present in SE Asia were sparse (n = 55; Fig. 2), of which eight publications also covered plastic ingestion. Over two thirds of publications focused on marine reptiles (n = 24, 43.6 %), and in particular sea turtles with only two cases for sea snakes, followed by cartilaginous fishes (n = 12, 21.8 %), marine mammals (n = 7, 12.7 %), and seabirds (n = 4, 7.3 %), while eight publications (14.5 %) covered multiple species groups. Entanglement cases were available for only two of the 23 species (8.7 %) listed as Critically Endangered – the hawksbill turtle (*Eretmochelys imbricata*) and the oceanic whitetip shark (*Carcharhinus longimanus*) – while entanglement cases were lacking entirely for species listed as Data Deficient (n = 43; Fig. S2).

Of the 130 cases of plastic entanglement for species present in SE Asia, over half reported entanglement in derelict fishing gear (n = 76, 58.5 %), followed by packaging items (e.g. packaging straps; n = 21, 16.2 %; Fig. 3a). The majority of marine mammal (n = 8, 80.0 %; Fig. 3c) and marine reptile (n = 46, 82.1 %; Fig. 3d) cases documented plastic entanglement in derelict fishing gear. For cartilaginous fish species, the majority of entanglement cases were either due to derelict fishing gear (n = 18,

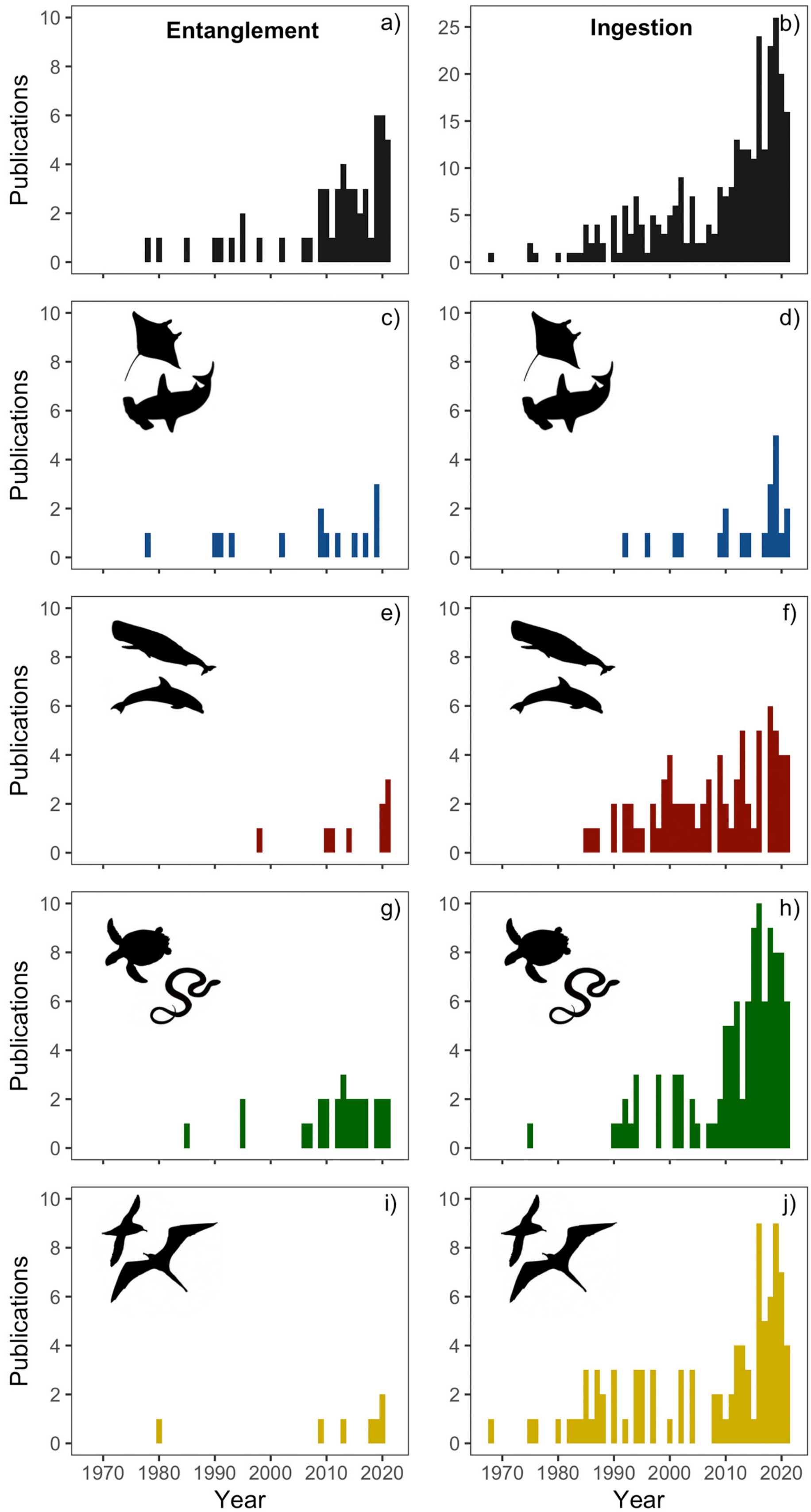


Fig. 2. Annual number of publications reporting plastic entanglement (panels: a, c, e, g, i) and ingestion (panels: b, d, f, h, j) for all species groups combined (black; panels: a-b), for cartilaginous fishes (blue; panels: c-d), marine mammals (red; panels: e-f), marine reptiles (green; panels: g-h), and seabirds (yellow; panels: i-j) present in SE Asia over time. As some publications covered multiple taxa and/or reported entanglement and ingestion, they are included multiple times across panels.

41.9 %) or packaging items, specifically packaging straps (n = 16, 37.2 %; Fig. 3b). Cases for seabird species were spread relatively evenly across derelict fishing gear, packaging, and other land-based categories (Fig. 3e). The impacts of plastic entanglement ranged widely from restricted movement to amputation and body deformities.

Entanglement cases were available for all, or the majority of, taxonomic families of marine reptiles (n = 3, 100 %) and seabirds (n = 10, 80.0 %) present in SE Asia (Table S2, Fig. 4a). Entanglement cases were, however, available for less than half of families of marine mammals (n = 3, 42.9 %) and only 9 of the 46 families of cartilaginous fishes investigated (19.6 %, Table S2, Fig. 4a). At the species level, entanglement cases were unavailable for the majority of species present in SE Asia (n = 334, 87.9 %; Table S1; Fig. 5a). Seabirds had the highest proportion of species with cases (n = 13, 18.1 %,; Fig. 5i), followed by marine reptiles (14.3 %, n = 7; Fig. 5g), marine mammals (n = 4, 12.9 %; Fig. 5e), and cartilaginous fishes (n = 22, 9.6 %; Fig. 5c; Table S1).

Sample sizes for entanglement cases ranged between 1 and 945 individuals (n = 114), with 43.9 % of these cases reporting entanglement for single individuals (n = 50). The number of individuals per case differed among taxonomic groups, when including or excluding single-individual cases (Table S3). On average, cases for marine reptiles (mean [95 % CI]; all cases: 43.0 [34.4–52.2], n = 55; >1 ind. per case: 68.9 [55.8–85.1], n = 34) included more individuals per case than cases for the other groups (Fig. S4a).

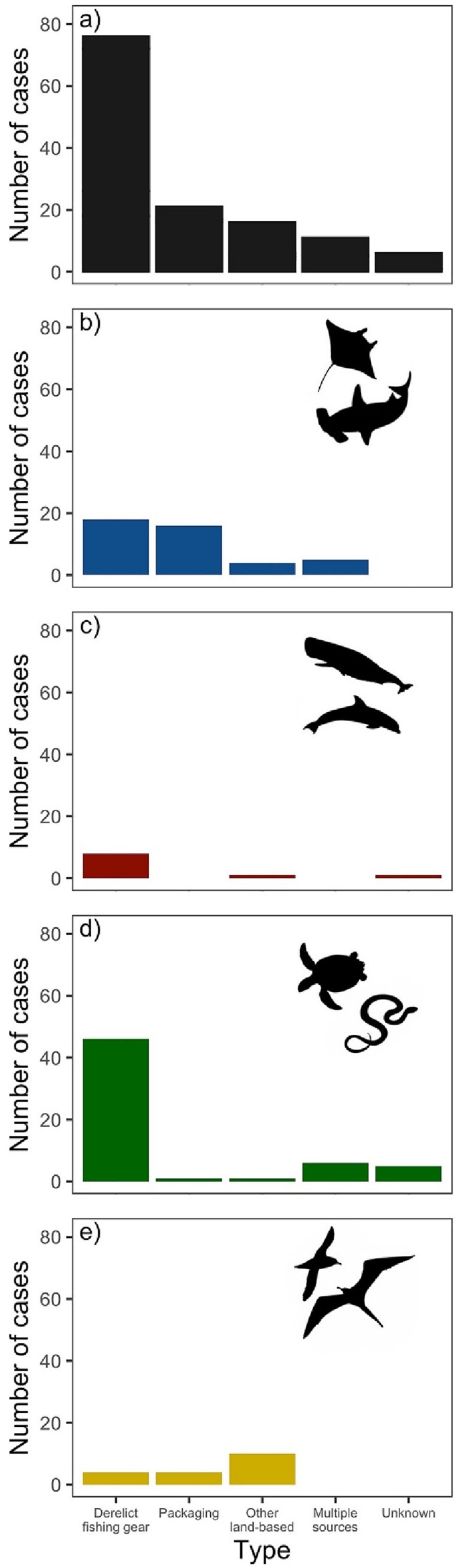


Fig. 3. Number of entanglement cases for all species combined (black; panel a), for cartilaginous fishes (blue; panel b), marine mammals (red; panel c), marine reptiles (green; panel d), and seabirds (yellow; panel e) present in SE Asia identified during the filtering of the IUCN Red List of Threatened Species, as a function of the type of entanglement material. The 'Unknown' category represents those cases for which entanglement in non-operational fishing gear or other plastic material was mentioned, but the specific type of entanglement material was not reported.

3.3.2. SE Asian perspective – literature search

Of the 55 publications on plastic entanglement for species present in SE Asia, only 9.1 % were conducted in SE Asian countries (n = 5; Fig. 6a), more specifically in Malaysia (n = 2) and the Philippines (n = 2; Fig. 7a), or covered countries on a global scale (n = 1; Fig. 7a). Publications reporting plastic entanglement in SE Asia were divided between marine mammals (n = 2; Figs. 4a, 6e), marine reptiles (n = 2; Figs. 4a, 6g), and cartilaginous fishes (n = 1; Figs. 4a, 6c).

At the species level, plastic entanglement cases from SE Asian countries were available for 10 % or less of species within each species group (marine reptiles [n = 5, 10.2 %], marine mammals [n = 2, 6.5 %], cartilaginous fishes [n = 2, 0.9 %], seabirds [n = 0, 0.0 %]; Fig. 5). Specifically, cases from SE Asian countries were available for dugongs (*Dugong dugon*), Irrawaddy dolphins (*Orcaella brevirostris*), all five sea turtle species present in SE Asia (green [*Chelonia mydas*], hawksbill, leatherback [*Dermochelys coriacea*], loggerhead, and olive ridley [*Lepidochelys olivacea*] turtles), pelagic thresher sharks (*Alopias pelagicus*), and whale sharks (*Rhincodon typus*; Fig. 4a). No publication documented plastic entanglement in SE Asian countries for seabird species (Figs. 4a, 6i).

3.3.3. SE Asian perspective – expert elicitation

Regional expert elicitation resulted in an additional 28 plastic entanglement cases from SE Asian countries, over a third of which were from Thailand (n = 11, 39.3 %; Fig. 7c). This process led to plastic entanglement being documented in seven additional taxonomic families (four for cartilaginous fishes, two for seabirds, and one for marine mammals) and ten additional species for which no published cases were found during the literature search for the region (Fig. 4b). Specifically, entanglement cases were available for an additional five cartilaginous fishes, three marine mammal, and two seabird species (blacktip reef shark [*Carcharhinus melanopterus*], blue-spotted fantail ray [*Taeniura lymna*], giant manta ray [*Mobula birostris*], grey carpetshark [*Chiloscyllium punctatum*], spotted eagle ray [*Aetobatus ocellatus*], Bryde's whale [*Balaenoptera edeni*], Indo-Pacific humpback

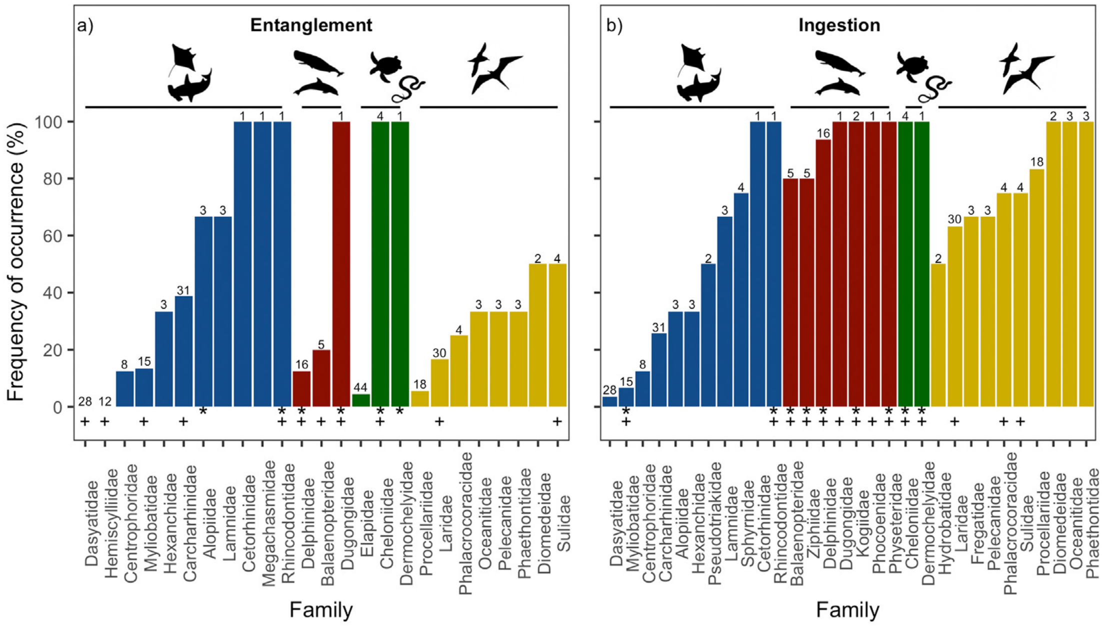


Fig. 4. Frequency of occurrence per taxonomic group for plastic entanglement (panel a) and ingestion (panel b) for cartilaginous fishes (blue), marine mammals (red), marine reptiles (green), and seabirds present in SE Asia identified during the filtering of the IUCN Red List of Threatened Species. Taxonomic families for which no cases were found for the families of interest are not included in this figure. The complete list of species investigated in this study can be found in supplementary material Table S2. The sample size for each family is shown above each bar. The asterisk symbol (*) shows families for which published cases of plastic entanglement and ingestion were recorded in SE Asia. The plus symbol (+) shows families for which cases of plastic entanglement and ingestion were obtained through expert elicitation. – Please see online version of article for colour. Double column fitting image.

dolphin [*Sousa chinensis*], long-beaked common dolphin [*Delphinus capensis*], black noddy [*Anous minutus*], brown booby [*Sula leucogaster*]; Fig. 4a).

3.4. Plastic ingestion

3.4.1. Global perspective

The majority of identified publications covered plastic ingestion (n = 291, 86.1 %; Fig. 2). A third of these ingestion studies for species present in SE Asia focused on marine reptiles, specifically sea turtles (n = 99, 34.0 %), another third on seabirds (n = 92, 31.6 %), while the remaining third were on marine mammals (n = 72, 24.7 %), cartilaginous fishes (n = 19, 6.5 %), or multiple taxonomic groups (n = 9, 3.1 %). No ingestion cases were available for sea snakes in the region (Table S2). In terms of IUCN status, ingestion cases were primarily available for species listed as Least Concern (n = 63, 43.2 %), while only 5 of the 43 species listed as Data Deficient were documented as having ingested plastic (11.6 %, Fig. S3).

Necropsies were the most used method to assess plastic ingestion across all publications (n = 268, 92.1 %), while 5.2 % of publications used live sampling (n = 15) or combined both methods (n = 8, 2.7 %). Macroplastics were the most common size class of plastics investigated (n = 267, 91.8 %), while only 2.7 % of publications looked at microplastics (n = 8) or both size classes (n = 15, 5.2 %). The size range of ingested items was not available for one publication.

Ingestion cases were available for all, or the majority of, taxonomic families of marine mammals (n = 7, 100 %), marine reptiles (n = 2, 66.7 %), and seabirds (n = 10, 100 %) present in SE Asia (Table S2, Fig. 4b). Ingestion cases were, however, available for less than a quarter of taxonomic families of cartilaginous fishes investigated (n = 11, 23.9 %). At the species level, cases of plastic ingestion were available for just over a quarter of those present in SE Asia (n = 107, 28.2 %; Fig. 4b), primarily marine mammal species (n = 28, 90.3 %; Fig. 5f), followed by seabirds (n = 53, 73.6 %; Fig. 5j), marine reptiles, specifically sea turtles (n = 5, 10.2 %; Fig. 5h), and cartilaginous fishes (n = 21, 9.2 %; Fig. 5d; Tables S1 and S2).

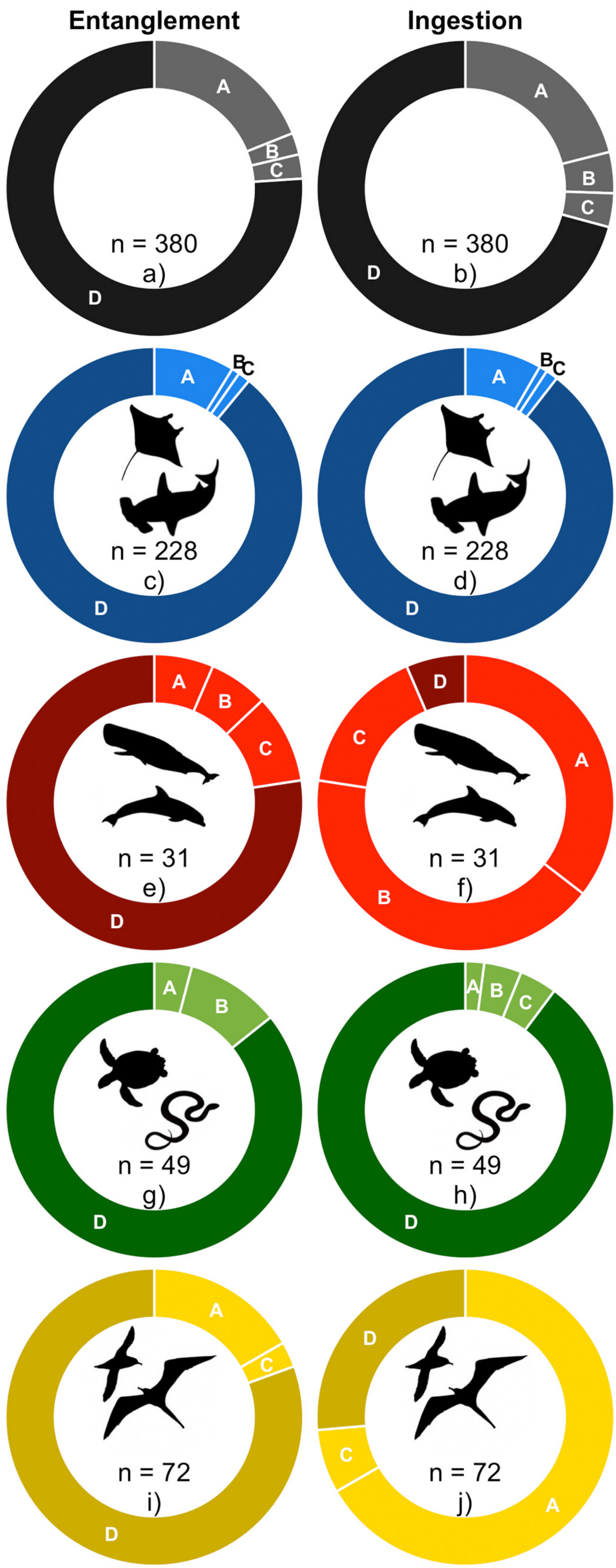
Sample sizes for ingestion cases ranged between 1 and 8584 individuals (n = 634), with almost a quarter (n = 147, 23.2 %) of these cases reporting ingestion for single individuals. The number of individuals per case differed among taxonomic groups, when including or excluding single-individual cases (Table S3). On average, cases for cartilaginous fishes (mean [95 % CI]; all cases: 715.7 [557.0–919.5], n = 37; >1 ind. per case: 854.0 [666.8–1093.7], n = 31) included more individuals per case than for the other groups (Fig. S4b).

Plastic ingestion frequency of occurrence ranged from 0 to 100 % for all taxonomic groups when considering all cases. However, when removing single individual cases, this was reduced to up to 50 % for cartilaginous fishes, while ranging from 0 to 100 % for the remaining taxonomic groups. On average, plastic ingestion frequency of occurrence was lower for cartilaginous fishes (mean [95 % CI]; all cases: 13.1 [9.4–17.9], n = 37; >1 ind. per case: 3.9 [2.21–7.2], n = 31) than for the other groups when including and excluding single individual cases (Table S3, Fig. S5).

3.4.2. SE Asian perspective – literature search

Of the 291 publications on plastic ingestion for species present in SE Asia, only 4.5 % were conducted in SE Asian countries (n = 13; Fig. 6b; Table S1), with half of these publications conducted in the Philippines (n = 7; Fig. 7b). Publications reporting plastic ingestion in SE Asia were divided between marine mammals (n = 7; Fig. 6f), marine reptiles (n = 5; Fig. 6h), and cartilaginous fishes (n = 3; Fig. 6d), while no publication was found for seabird species (Fig. 6j).

At the species level, plastic ingestion cases from SE Asian countries were available for 41.9 % of marine mammal species (n = 13) and for <5 % of marine reptiles (n = 2, 4.1 %), cartilaginous fishes (n = 2, 0.9 %), and seabirds (n = 0; Fig. 5). compared to cases available outside of SE Asia (seabirds [n = 53, 73.6 %], marine mammals [n = 27, 87.1 %], marine reptiles [n = 5, 10.2 %], cartilaginous fishes [n = 20, 8.8 %]; Fig. 5). Specifically, ingestion cases from SE Asian countries were available for 13 marine mammal, two cartilaginous fishes, and two sea turtle species present in SE Asia (Blainville's beaked whale [*Mesoplodon densirostris*], Bryde's whale [*Balaenoptera edeni*], Cuvier's beaked whale [*Ziphius cavirostris*], Deraniyagala's beaked whale [*Mesoplodon hotaula*], dwarf sperm whale [*Kogia sima*], Fraser's dolphin [*Lagenodelphis hosei*], melon-headed whale [*Peponocephala electra*], pantropical spotted dolphin [*Stenella attenuata*], pygmy sperm whale [*Kogia breviceps*], Risso's dolphin [*Grampus griseus*], rough-toothed dolphin [*Steno bredanensis*], short-finned pilot whale [*Globicephala macrorhynchus*], sperm whale [*Physeter macrocephalus*], reef manta ray [*Mobula alfredi*], whale shark, green turtle, leatherback turtle; Tables S1 and S2, Fig. 4b).



3.4.3. SE Asian perspective – expert elicitation

Regional expert elicitation resulted in an additional 43 plastic ingestion cases from SE Asian countries, with a third of which were from the Philippines (n = 15, 34.9 %; Fig. 7d). This process led to plastic ingestion being documented in five additional taxonomic families (two for marine mammals and three for seabirds) and 15 additional species for which no cases were found during the literature search for the region (Fig. 4b). Specifically, ingestion cases were available for an additional five seabird, five marine mammal, three cartilaginous fishes, and two marine reptile species (black noddy, brown booby, brown noddy [*Anous stolidus*], little black cormorant [*Phalacrocorax sulcirostris*], red footed booby [*Sula sula*], dugong, Indo-Pacific beaked whale [*Indopacetus pacificus*], Indo-Pacific finless porpoise [*Neophocaena phocaenoides*], Irrawaddy dolphin [*Orcaella brevirostris*], pygmy sperm whale [*Kogia breviceps*], bentfin devil ray [*Mobula thurstoni*], sickled devil ray [*Mobula tarapacana*], spinetail devilray [*Mobula mobular*], hawksbill turtle, olive ridley turtle; Fig. 4b).

4. Discussion

Several countries within SE Asia are estimated to be major contributors of marine plastic pollution to the world's oceans (Jambeck et al., 2015; Lebreton et al., 2017; Meijer et al., 2021), yet there remains significant gaps in our understanding of the impacts of marine plastic pollution to marine megafauna taxa in the region when compared to other parts of the world, even after the inclusion of regional expert elicitation. This knowledge gap is of particular concern for a region that harbours high levels of biodiversity and endemic vertebrate species (Marchese, 2015; Myers et al., 2000), as well as provides critical habitats for migratory species (e.g. Hill et al., 2020; Miranda et al., 2021).

4.1. Publications

Broadly, research on the impacts of plastics on marine megafauna has seen an upward trend, with numerous scientific reviews published in recent years focusing on entanglement and/or ingestion in several taxonomic groups (e.g. Duncan et al., 2017; Jepsen and de Bruyn, 2019; Kühn and van Franeker, 2020; Nelms et al., 2016; Parton et al., 2019; Provencher et al., 2017; Ryan, 2018; Stelfox et al., 2016). Therefore, it is unsurprising that the majority of papers for species present in SE Asia identified in this literature review were published in the last 10 years, despite these species having been documented interacting with marine plastics for several decades on a global scale (e.g. Laist, 1997). Plastic ingestion, primarily as macroplastics, remains the focus of most studies identified in this literature

Fig. 5. Proportion of species present in SE Asia for which cases of plastic entanglement (panels: a, c, e, g, h) and ingestion (panels: b, d, f, h, j) were reported (lighter colour) for all species combined (black; panels: a-b), and for cartilaginous fishes (blue; panels: c-d), marine mammals (red; panels: e-f), marine reptiles (green; panels: g-h), and seabirds (yellow; panels: i-j), where A shows the proportion of species for which published cases exist globally outside of SE Asia exclusively; B the proportion of species for which published cases exist for SE Asian countries and globally elsewhere; and C the proportion of species for which cases from SE Asian countries were obtained through expert elicitation. This category includes unpublished cases, news articles, cases published after the literature search date, and publications/reports which were not identified during the structured literature search. Category D (darker colour) for each group shows the proportion of species for which cases were not available at a global scale after the literature search and expert elicitation. The number of species present in SE Asia identified during the filtering of the IUCN Red List of Threatened Species is shown inside each donut plot.

review, while those reporting wildlife entanglement were scarce globally for species present in the region. This is potentially the result of multiple factors, including (1) the need to clearly distinguish entanglement in ALDFG versus operational fishing gear, (2) the relative ease in identifying macroplastics within the gut content of dead animals alongside dietary or pathological studies, and (3) entanglement remains underreported and challenging to ascertain on a global scale (Richardson et al., 2019). Although it is likely we omitted true entanglement cases as we did not include studies in which the entanglement material was ambiguous, we echo the call for more-widespread reporting, standardisation, and publishing of entanglement events in ALDFG and other land-based items, such as packaging, in order to better understand the severity of the problem (Duncan et al., 2017; Nelms et al., 2016; Richardson et al., 2019; Ryan, 2018; Stelfox et al., 2016). Shared open-access repositories, harnessing the power of citizen scientists, such as the Global Ghost Gear Initiative, will be essential in addressing this research need in order to meet the United Nations Sustainable Development Goal (SDG) 14.1. The latter goal aims to prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris, by 2025 (United Nations Sustainable Development Goals, 2018).

Despite the global increase in publications on the impacts of marine plastics, there is not equal distribution of research spatially — data gaps relating to plastic pollution and biota have been highlighted for the Caribbean region (Kanhai et al., 2022) as well as large parts of Africa and Central America (UNEP, 2021). Indeed it does not translate on a regional scale for SE Asia, with <5 % and 10 % of identified publications reporting plastic ingestion and entanglement, respectively, for species present in the region being conducted in SE Asian countries. This mirrors observations made by Lyons et al. (2020), in which they highlighted that marine plastics research in the region is still in the nascent stages compared to other parts of the world. However, the lower proportion of publications from SE Asian countries can partly be explained by the fact that the literature search was only conducted in English, in a region that harbours more than a thousand regional languages. In addition, the colonial history of SE Asian countries differs, with some countries being former British colonies and others being previously Francophone nations, such as Cambodia, Laos, and Vietnam, resulting in English proficiency varying across SE Asia (Kirkpatrick, 2017). As former British colonies and with English as one of their official languages, the Philippines and Malaysia were the two countries with the most publications on marine plastic-wildlife interactions, matching their position in the top three leaders of plastic-focused publications in SE Asia (Lyons et al., 2020). In contrast, the lack of publications in English from a country such as Indonesia can partly be explained because local researchers tend to publish in Bahasa Indonesian in local journals, particularly when sample sizes are small. Although English is often considered the international language for science and the working language of ASEAN, the results of the expert elicitation showed that cases of plastic ingestion and entanglement were available for far more countries and species than observed during the literature search. This issue highlights the importance of including local researchers, whose knowledge greatly enhanced our understanding of the impacts of marine plastic pollution on marine vertebrates in SE Asia, going beyond the English publication bias (e.g. Peter et al., 2022), providing novel records of plastic ingestion and entanglement for five (15 species) and seven (10 species) additional taxonomic families, respectively.

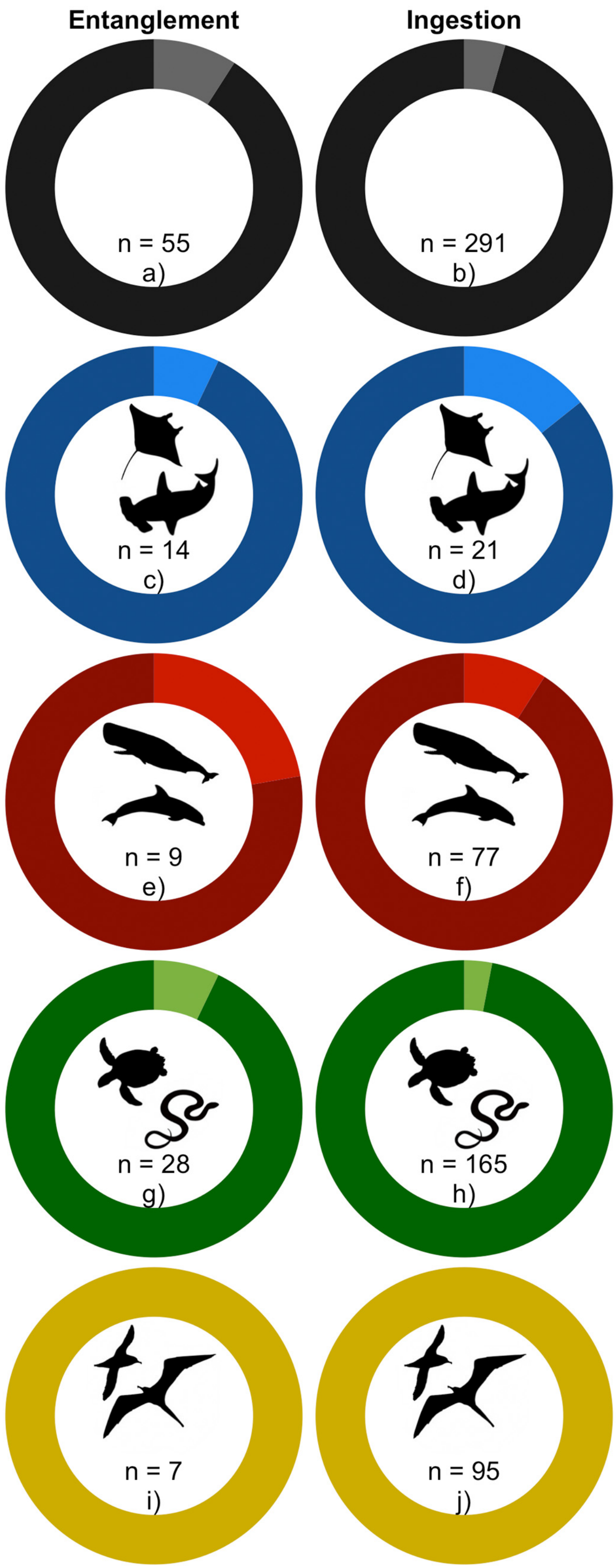


Fig. 6. Proportion of publications reporting plastic entanglement (panels: a, c, e, g, i) and ingestion (panels: b, d, f, h, j) for all species groups present in SE Asia identified during the filtering of the IUCN Red List of Threatened Species combined (black; panels: a-b), and for cartilaginous fishes (blue; panels: c-d), marine mammals (red; panels: e-f), marine reptiles (green; panels: g-h), and seabirds (yellow; panels: i-j) between 1968 and 2021. The lighter colour indicates the proportion of publications for which the research was conducted in SE Asian countries, while the darker colour shows the proportion conducted outside of SE Asian countries. There were no publications from SE Asian countries documenting seabird entanglement (panel i) and ingestion (panel j). The number of publications is shown inside each donut plot. As some publications covered multiple species groups, they are included multiple times across panels c-j.

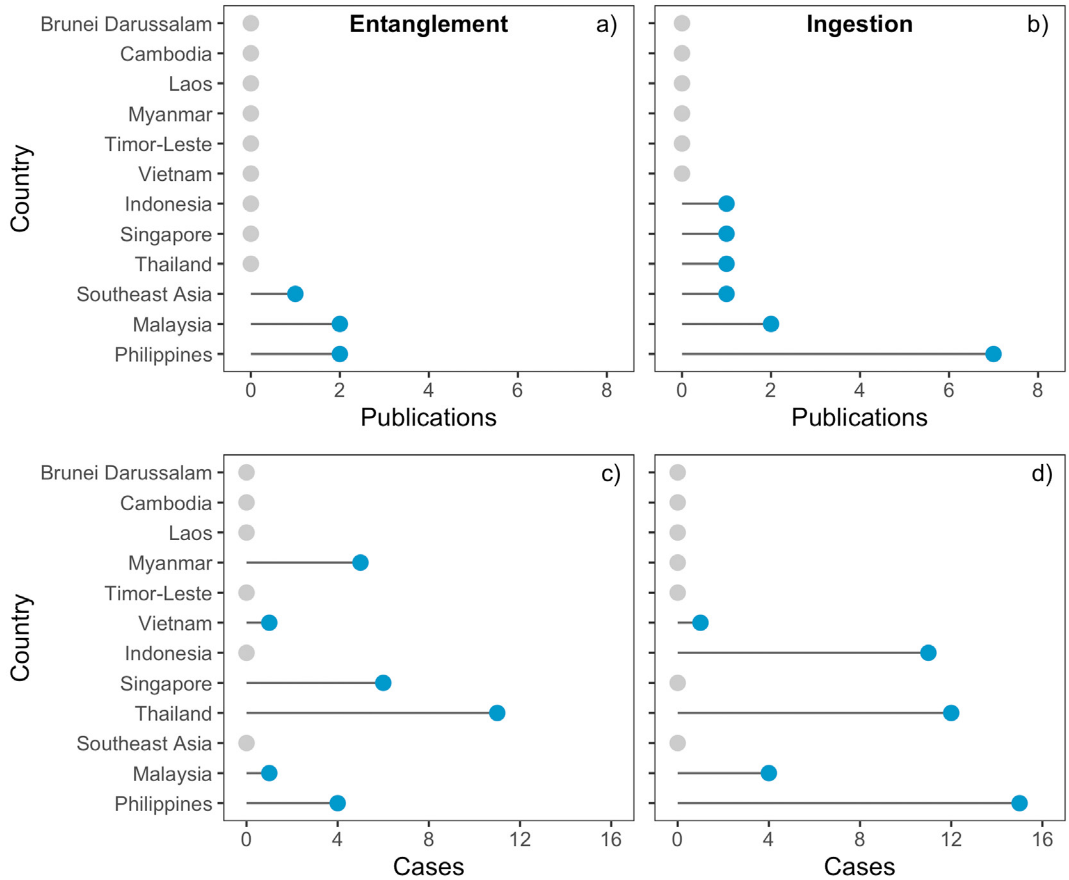


Fig. 7. Geographical location for publications (panels: a-b) and cases resulting from expert elicitation (panels: c-d) conducted in SE Asian countries for plastic entanglement (panels: a, c) and ingestion (panels: b, d) for cartilaginous fishes, marine mammals, marine reptiles, and seabirds present in SE Asia identified during the filtering of the IUCN Red List of Threatened Species. Two publications covered plastic ingestion and entanglement for multiple countries in SE Asia. The grey circles highlight the lack of publications and cases in the various countries. Publications covering both entanglement and ingestion are included in both panels a and b.

Investigation of marine vertebrate strandings provides scientists with opportunities to explore the impacts of plastic pollution (Abreo et al., 2019a; Lusher et al., 2018; Nelms et al., 2019; Prampramote et al., 2022). Entanglement can be established through visual observations of animals using images from social media, for example (e.g. Abreo et al., 2019b; Coram et al., 2021; Parton et al., 2019; Peter et al., 2022), while determining whether individuals have ingested plastics is more challenging as it often requires a necropsy. In most SE Asian countries, necropsies need to be performed by a veterinarian or someone with specific necropsy training (Mustika et al., 2022). However, the extensive coastline and often remote stranding locations mean that trained personnel are often unavailable. For example, in the Philippines, only a third of dead stranded marine mammals recorded by the Philippine Marine Mammal Stranding Network were necropsied between 2005 and 2021 (Aragones et al., in review). In addition, postmortems in SE Asia might not be conducted (1) as dead animals are used as a source of food (e.g. sea turtles, Fendjalang et al., 2019; and marine mammals, Porter and Lai, 2017), (2) cultural considerations limit necropsies (e.g. whale worship in Vietnam; Lantz, 2009), (3) necropsies are not recognised as standard procedure when dealing with dead stranded animals (Acebes et al., 2022), and finally (4) there is limited funding available to carry out such work (Neil Abreo, *pers. obs.*) and to cover publication fees (Jo Marie Acebes, *pers. obs.*). Furthermore, in cases where necropsies are performed, data are often kept as strandings reports held by local governments, non-profit organisations, and other institutions, remaining unpublished or only reported in the media. For example, the Marine Wildlife Watch of the Philippines has been performing standardised necropsies on marine mammals and cartilaginous fishes, including recording stomach content, for almost a decade, yet the analysis of these data is still forthcoming (Jovanie Garay, *pers. obs.*). While SE Asia might appear as a data-poor region at face value when only considering literature published in English, it is clear that data do exist on plastic ingestion and entanglement in the region as emphasised by the expert elicitation. Getting these data published in English to enhance their global reach will likely require an increased awareness of local stakeholders of the importance of stranded individuals for data collection on a regional level (Mustika et al., 2022; Tiongson et al., 2021), coupled with collaborative research, led by regional scientists, using international funding to facilitate capacity building and knowledge exchange.

4.2. Taxonomic groups

Publications were unequally distributed among the four taxonomic groups of interest in this literature review for both plastic ingestion and entanglement on a global scale. Marine reptiles, primarily sea turtles, were the group with the most entanglement and ingestion publications for species present in SE Asia, despite comprising only five species in the region. However, when considering all species, seabirds were the taxonomic group the most widely studied for both entanglement and ingestion, due to the scarcity of data for sea snakes, as previously highlighted by similar reviews (Kühn and van Franeker, 2020; Provencher et al., 2017). On the other hand, cartilaginous fishes remain particularly understudied at the family and species level for both ingestion (Provencher et al., 2017) and entanglement (Parton et al., 2019). While cartilaginous fishes appear to show the lowest frequency occurrence of plastic ingestion compared to the other taxonomic groups investigated here, this likely, is at least in part, resultant of the scarcity of studies published (Kühn and van Franeker, 2020), rather than their lack of interaction with marine plastics (Abreo et al., 2019a; Haetrakul et al., 2009; Parton et al., 2019; Yong et al., 2021). Although not always lethal, ingested plastics are known to impact physiological functioning and can lead to reduced body condition, through reduced growth or energy assimilation efficiency linked to the satiating impacts of plastics (Marn et al., 2020; Puskic et al., 2020).

On a regional scale, there were few cases of marine plastic-wildlife interactions, underpinning the lag in our understanding of the impacts of plastic pollution in SE Asia compared to other parts of the world within the published literature (Lyons et al., 2020). It transpired through the expert elicitation that cases exist as unpublished for far more species than is currently described in the published literature, although new publications filling in those gaps have emerged since our literature search was performed (e.g. Gajanur and Jaafar, 2022; Ng et al., 2022; Prampramote et al., 2022; Yong et al., 2021). Green and leatherback turtles were the only two species for which published cases of both entanglement and ingestion were available from the SE Asian countries. The high number of published and unpublished cases from SE Asian countries for all sea turtle species present in the region is likely due to the fact that they represent (1) a source of food (e.g. Fendjalang et al., 2019) and/or (2) hold a monetary value in the illegal wildlife trade (e.g. Joseph et al., 2019) and through eco-tourism (e.g. Willard et al., 2022), a sector which is a major source of livelihood in the region (Pascoe et al., 2014; Tamayo et al., 2018). Like sea turtles, marine mammals appear particularly well studied, with published plastic ingestion cases being available for over a third of the species present in SE Asia. Marine mammals, although more generally whales, hold a particular place in the culture of some SE Asian countries, such as Vietnam, where whale strandings are seen as a sign of good fortune by fishers, who, out of respect, bury, exhume, and then expose the bones of dead individuals in whale temples (Lantz, 2009; McGowen et al., 2021). In addition, monitoring programmes for marine mammals have been running for decades in countries such as the Philippines (e.g. Aragones et al., 2010; Obusan et al., 2016; Tiongson et al., 2021), and marine mammal legislation exists for multiple SE Asian countries, such as Indonesia (Sahri et al., 2020), Malaysia (Tetley et al., 2022), and the Philippines (UNEP/CMS Secretariat, 2015). By contrast, despite being the most widely studied taxon globally (Kühn and van Franeker, 2020; Provencher et al., 2017), no published cases were available for seabirds in the region, while a few cases exist as unpublished from Indonesia and the Philippines. Seabird colonies are confined to rocky outcrops and small, often remote islands in the region (e.g. Hamza et al., 2016), making their montoring logistically challenging, which has led to considerable knowledge gaps existing in multiple areas of research in SE Asia, including in global studies on biologging (Bernard et al., 2021) and bycatch in fisheries (Pott and Wiedenfeld, 2017), for example. For cartilaginous fishes, whale sharks appear to be the main species of interest, with published and unpublished cases of entanglement and ingestion being available for the species in the region (Germanov et al., 2019; Yong et al., 2021). However, unlike marine mammals, dead stranded cartilaginous fishes are almost never necropsied in the Philippines, for example (Jo Marie Acebes, *pers. obs.*), limiting the scope for publications for this species group in the region. Although this literature review did not include more coastal species, such as shorebirds, herons, egrets, and other marine snakes, inhabitating mangrove forests, which are known plastic-trapping habitats (Luo et al., 2021) and particularly abundant in SE Asia (Spalding et al., 2010), we note that the Marine Plastic Research Inventory (https://mapla-riv.web.app/), a database of information extracted from the publications on marine plastics in the seas of East Asia, did not include records of ingestion and entanglement for such species from SE Asian countries, with data focusing instead on microplastic ingestion in bony fishes and invertebrates.

4.3. Marine plastic governance

Marine plastic pollution is a global issue with detrimental biological, ecological, and socioeconomic consequences (Beaumont et al., 2019), which has resulted in its prominent position on international policy agendas and has prompted the United Nations (UN) Global Assembly to dedicate one target of SDG 14 to marine pollution of all kinds, including plastics (Walker, 2021). Policy documents, some of which are legally binding instruments, primarily focus on establishing various regional and global governance frameworks (French and Kotzé, 2018), or on specific taxonomic groups. For example, in October 2022, a majority of parties that are signatories to the International Whaling Commission voted to better tackle plastic pollution. Similarly, in March 2022, the UN adopted a resolution to negotiate a legally binding instrument to end global plastic pollution (United Nations Environment Assembly, 2022). While negotiations are likely to take several years, this resolution signifies the global urgency by which the flow of plastics into the marine environment needs to be stopped. At the regional level of SE Asia, the ASEAN Regional Action Plan for Combating Marine Debris (2021–2025) (ASEAN Secretariat, 2021) and Coordinating Body on the Seas of East Asia (COBSEA) Regional Action Plan on Marine Litter (COBSEA, 2019) offer essential instruments for a coordinated response to combat the various aspects of marine debris considering their transboundary nature, as well as provide solutions for their effective management in the region (ASEAN Secretariat, 2021; SEA Circular, 2019; UNEP, 2017). Numerous studies have highlighted the multi-faceted, species-specific, and spatially variable impacts of marine plastics on marine megafauna (Duncan et al., 2021; Høiberg et al., 2022; Puskic et al., 2020; Senko et al., 2020), emphasising the importance of monitoring plastic ingestion and entanglement on a regional scale and across taxonomic groups. The structured literature review, coupled with the regional expert elicitation, brought to light that knowledge on the impacts of marine plastic pollution on marine megafauna in the region lags behind other parts of the world. Going forward, research could be prioritised in SE Asia by focusing on (1) endemic species, (2) those listed as (Critically) Endangered and Data Deficient, or (3) species with small, genetically distinct, and/or genetically isolated populations, for which the removal of a single individual due to the negative interaction with marine plastics could greatly affect genetic diversity and increase local extinction risk, such as the Irrawaddy dolphin (Sonne et al., 2022). Increasing our understanding of the types of plastics ingested by, or entangling, marine megafauna in SE Asia will help guide policy development, targeting items having the largest impacts (Roman et al., 2021).

4.4. Conclusion

Considering the scale of the plastic problem in SE Asia, there is great potential for research into the ecological impacts of plastic pollution on marine vertebrate species. While the literature search highlighted the scarcity of publications in English from SE Asian countries, the regional expert elicitation emphasised the disparity between the two data sources, with novel records found for numerous species through this process. Additional funding to help collate baseline data, presently absent for most of the region and taxonomic groups, are critically needed to inform management and to develop mitigation strategies. Long-term monitoring of the impacts of plastics on marine megafauna and marine organisms more widely will help inform policies and solutions towards limiting the interactions of marine species and plastics in SE Asia.

CRediT authorship contribution statement

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Data availability

None of the data used in this manuscript is primary data

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

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