Riverine plastic pollution from fisheries: insights from the Ganges River system

Sarah E Nelms[a, b*], Emily M Duncan[a], Surshti Patel[c], Ruchi Badola[d], Sunanda Bhola[d], Surfarsha Chakma[e], Gawsia Wahidunnessa Chowdhury[f, g], Brendan J Godley[a], Alifa Bintha Haque[f, h], Jeyaraj Antony Johnson[d], Hina Khatoon[d], Sumit Kumar[d], Imogen E Napper[i], MD. Nazmul Hasan Niloy[f], Tanjila Akter[f], Srishti Badola[d], Aditi Dev[d], Sunita Rawat[d], David Santillo[j], Subrata Sarker[k], Ekta Sharma[d], Heather Koldewey[a, c]

AUTHOR AFFILIATIONS

[a]Centre for Ecology and Conservation, University of Exeter, Cornwall, TR10 9EZ, UK
[b]Centre for Circular Economy, University of Exeter, Cornwall, TR10 9EZ, UK
[c]Zoological Society of London, Regent's Park, London, NW1 4RY, UK
[d]Wildlife Institute of India, Chandrabani Road, Dehradun 248001, Uttarakhand, India
[e]Isabela Foundation, Road-15 (new), Dhanmondi-R/A, Dhaka 1209, Bangladesh
[f]Department of Zoology, University of Dhaka, Dhaka 1000, Bangladesh
[g]WildTeam 69/1 New Circular Road, Dhaka 1217, Bangladesh
[h]Nature-based Solutions Initiative, Department of Zoology, University of Oxford, Oxford, OX1 3SZ, UK
[i]International Marine Litter Research Unit, University of Plymouth, Plymouth, PL4 8AA, UK
[j]Greenpeace Research Laboratories, Innovation Centre Phase 2, University of Exeter, Devon, EX4 4RN, UK
[k]Department of Oceanography, Shahjalal University of Science and Technology, Sylhet-3114, Bangladesh

*Corresponding author: s.nelms@exeter.ac.uk

HIGHLIGHTS

- Fishing gear is a significant source of plastic pollution in the Ganges River system.
- Fisher knowledge provided insights into behavioural drivers of gear disposal.
- Waste gear poses a risk to aquatic species of conservation concern.
- Targeted and practical solutions are needed to reduce gear input.
- Future work should examine plastic pollution from fisheries in other major rivers.

ABSTRACT

Abandoned, lost or otherwise discarded fishing gear represents a substantial proportion of global marine plastic pollution and can cause significant environmental and socio-economic impacts. Yet little is known about its presence in, and implications for, freshwater ecosystems or its downstream contribution to plastic pollution in the ocean. This study documents fishing gear-related debris in one of the world's largest plastic pollution contributing river catchments, the Ganges. Riverbank surveys conducted along the length of the river, from the coast in Bangladesh to the Himalaya in India, show that derelict fishing gear density increases with proximity to the sea. Fishing nets were the main gear type by volume and all samples examined for polymer type were plastic. Illegal gear types and restricted net mesh sizes were also recorded. Socio-economic surveys of fisher communities explored the behavioural drivers of plastic waste input from one of the world's largest inland fisheries and revealed short gear lifespans and high turnover rates, lack of appropriate end-of-life gear disposal methods and ineffective fisheries regulations. A biodiversity threat assessment identified the air-breathing aquatic vertebrate species most at risk of entanglement in, and impacts from, derelict fishing gear; namely species of threatened freshwater turtle and otter, and the endangered Ganges river dolphin. This research demonstrates a need for targeted and practical interventions to limit the input of fisheries-related plastic pollution to this major river system and ultimately, the global ocean. The approach used in this study could be replicated to examine the inputs, socio-economic drivers and ecological impacts of this previously uncharacterised but important source of plastic pollution in other major rivers worldwide.

KEYWORDS: Abandoned, lost or otherwise discarded fishing gear (ALDFG); Behavioural drivers; Entanglement; Inland fisheries; Fishers' knowledge; River catchments

1. INTRODUCTION

Globally, abandoned, lost or otherwise discarded fishing gear (ALDFG) is a significant source of plastic pollution within the marine environment, and concern is growing over its potential to cause ecological and socio-economic harm (Richardson et al., 2019a, 2019b). Transported by winds and currents, this 'ghost gear' can drift over large distances for many years, during which time it can continue to trap and entangle commercially important and vulnerable species, smother sensitive habitats, and cause damage to active fishing gear and maritime equipment (Gilman, 2015; Richardson et al., 2019b; Valderrama Ballesteros et al., 2018; Wilcox et al., 2013). Though rivers are known to play a key role in transporting anthropogenic debris from inland communities to the marine environment, and have been identified as plastic pollution hotspots in their own right (Emmerik and Schwarz, 2020; Jambeck et al., 2015; Lebreton and Andrady, 2019; Owens and Kamil, 2020; Windsor et al., 2019), few studies examine inputs of waste fishing gear to riparian environments.

The Ganges River system (known as the Ganga in India, and Padma and Meghna in Bangladesh, hereafter referred to as the Ganges) has been identified as one of 14 continental rivers into which over a quarter of global waste is discarded, and is considered the second largest plastic pollution contributing catchment in the world (0.12 million tonnes plastic discharged per year), after the Yangtze River in China (0.33 million tonnes; Lebreton and Andrady, 2019; Lebreton et al., 2017; Schmidt et al., 2017). Originating in the Himalaya in India and discharging into the Bay of Bengal from Bangladesh, the 2,500 km long Ganges is of high religious, cultural, socio-economic and ecological significance and sustains over 655 million people, many of whom live below the poverty line (Rahman et al., 2020; Sharma et al., 2010; Singh and Singh, 2020). Inland fisheries provide key income and nutrition for people in the lower parts of the Ganges, and India and Bangladesh are two of the world's major inland fisheries producers (Sharma et al. 2010, Blettler et al. 2018, FAO 2020). The region is also globally important for biodiversity and hosts a number of endemic aquatic species, many of which are of conservation concern due to pressure from dam construction, habitat degradation, pollution and fisheries bycatch (Braulik and Smith, 2019; Dewhurst-Richman et al., 2019; Mansur et al., 2008).

The prevalence of fishing activities and lack of formal waste management systems in many areas (FAO, 2020; Ferronato and Torretta, 2019) means fishing gear likely contributes significantly to the overall plastic pollution burden of the Ganges and downstream in the marine environment, and may pose a risk to species of conservation concern through entanglement or ingestion (Senko et al., 2020). Yet little or no research has been carried out to assess its distribution and abundance or the associated risks to biodiversity, or to understand the socio-economic drivers of ALDFG leakage into the environment. Gathering such evidence is essential for developing effective management strategies aimed at addressing the issue of plastic pollution in both freshwater and marine environments (González-Fernández and Hanke, 2017; Owens and Kamil, 2020; Richardson et al., 2019a), particularly as the integration of fishers' knowledge and experience into environmental management is known to lead to improved decision-making (Funk et al., 2020).

This study sought to: 1) assess the abundance, distribution and characteristics of ALDFG on riverbanks along the entire main Ganges channel in Bangladesh and India, 2) examine the behavioural drivers of ALDFG leakage into the environment, 3) explore the potential risks of entanglement to biodiversity, and 4) recommend potential solutions and areas requiring further research.

2. MATERIAL AND METHODS

2.1 Sampling location selection

During the National Geographic Sea to Source Ganges Expedition (hereafter the Sea to Source Expedition), nine sampling locations situated along the length of the mainstream river were selected *a priori* (Fig. 1a). The selection criteria were; a) relatively equidistant locations along the entire main river channel; b) a range of population densities, including some major cities; c) availability of existing data from local partners; and d) local community and other stakeholder contacts to facilitate the research and ensure results could effectively contribute to evidence-based recommendations.

2.2 ALDFG riverbank surveys

2.2.1 Data collection

Riverbank surveys for ALDFG began during the Sea to Source Expedition in late October 2019 (post-monsoon season) at sampling location one (Bhola) on the Bangladesh coast in the Bay of Bengal, and continued upstream to sampling location nine in the Himalaya (Rishikesh, India) in early December 2019 (Fig. 1a). Data were collected from two fish landing sites per sampling location (Fig. 1b and c), which were chosen whilst in the field following discussion with local experts and community members, informed by pre-expedition scoping.

To maintain a consistent level of sampling effort throughout, the number of people systematically searching landing sites for ALDFG was always four (lead author, at least one local language speaker and two others). While walking in parallel lines with their team members at a slow pace, each person visually scanned the ground in front and approximately one metre either side of their path (total transect width = 8 m). The transect (one per landing site) generally followed the edge of the riverbank, although the length and specific route were determined by the topography and accessibility. To further standardise effort, the time spent searching was limited to 30 minutes and monitored using a stopwatch, which was paused when a fishing related item (net, float, string, rope or line) was encountered. An initial assessment of whether the item was derelict or active was carried out. Assessment criteria included factors such as, whether it was lying randomly on the ground (or buried) or organised with other similar items; if it appeared old (e.g. weathered or dirty); or was only a small part of a whole item (e.g. a fragment of net or a short piece of string). If it was not clear, nearby fishers were consulted. The survey route was tracked and ALDFG items recorded as waypoints using a handheld global positioning system (GPS) device (Garmin eTrex 10). The length of transect was calculated using the GPS data after the survey. Aside from location, other characteristics of the ALDFG items were recorded (gear type; height, width and length of item; mesh size if relevant), and a photograph was taken. Maximum stretched mesh size (diagonal distance between opposite knots) was measured using a ruler. When gear items new to each survey were encountered, physical samples were collected for further analysis to confirm polymer composition (see section 2.2.2). No more than two minutes were spent at each waypoint so if multiple items were observed, only those that could be processed within this consistent time-period were recorded. This was to facilitate broad spatial coverage whilst gaining an estimate of discarded fishing gear density, particularly for sites with high densities of waste gear.

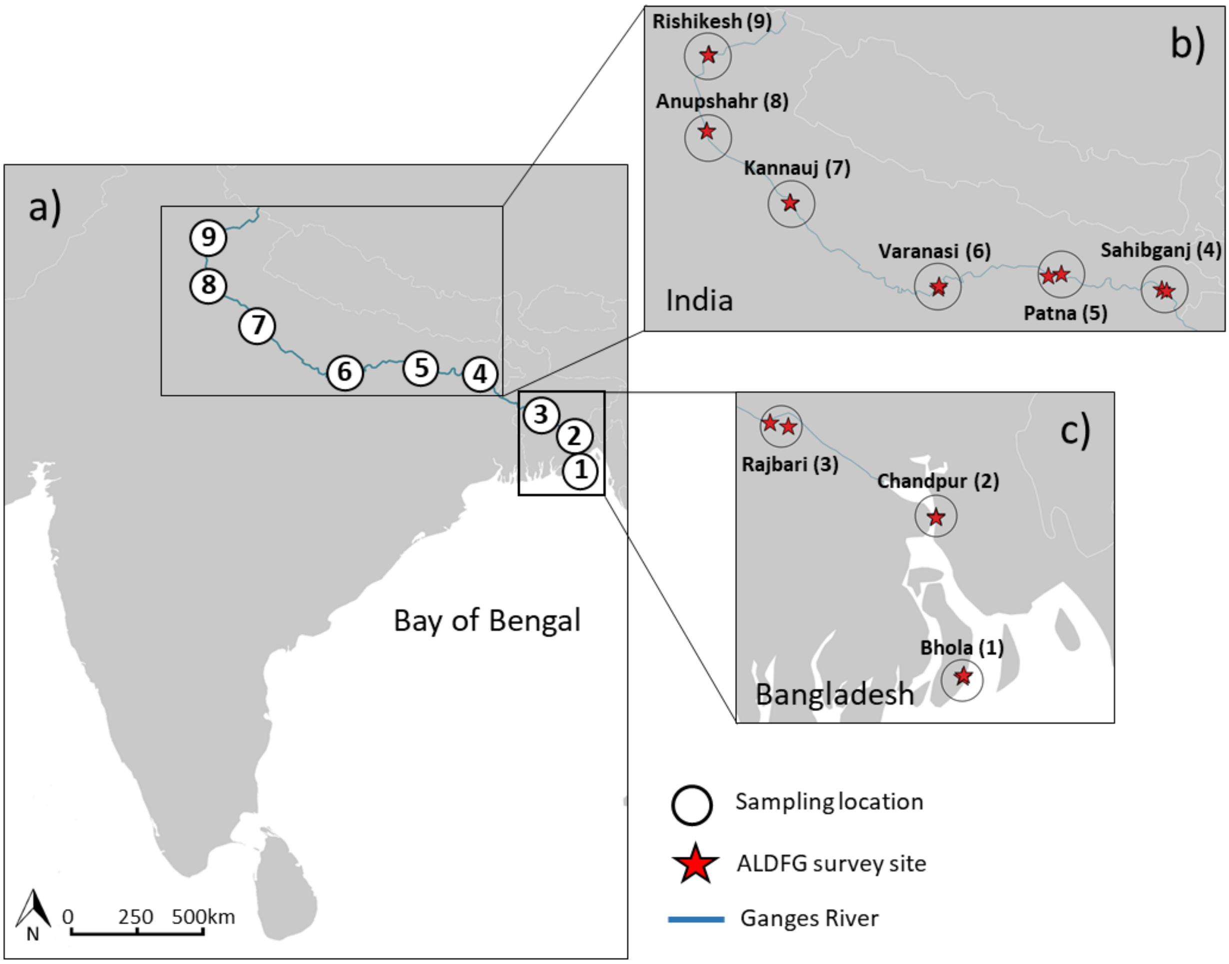

Fig. 1 Maps showing **a)** expedition sampling locations (numbered 1-9) and fish landing sites (red star symbols) where ALDFG surveys took place in **b)** India and **c)** Bangladesh. The Ganges is depicted in blue. Note: Some landing sites are very close to others, and therefore, some symbols overlap.

2.2.2 Data analysis

To ensure that our results are comparable with those of existing and future studies, abundance of items is documented using two metrics – frequency of occurrence (%FO) and volume (m^3). The proportions of each gear type (net, string, rope, float, line), colour and polymer types are also presented in this manner. Volume was calculated by multiplying the three size dimensions: length, width and height.

ALDFG density (*items per m^2*) was calculated by dividing the number of items by the total area surveyed (transect width of 8 m multiplied by length according to the GPS track).

The relationship between ALDFG density at each sampling location and variables that may drive the observed pattern (distance from the sea and local population size) was investigated using a Generalized Linear Model (GLM; R Core Team 2020). The distance of each sampling location from the sea was estimated by measuring the straight-line distance between locations using the ruler function in Google Earth. Population estimate data were accessed via the Center for International Earth Science Information Network (CIESIN, Center for International Earth Science Information Network - CIESIN - Columbia University. 2018. Gridded Population of the World, Version 4 (GPWv4): Population Count, Revision 11. Palisades, NY: NASA Socioeconomic Data and Applications Center. https://doi.org/10.7927/H4JW8BX5; Last accessed 12 May 2020). The distribution of the dependent variable data (ALDFG density) was checked for normality using a Q–Q plot and deemed not normal (zero-bounded, asymmetrical). Further examination of the data using model selection revealed the Gamma error family and 'log' link function combination to be the most appropriate. Model selection to identify which variables may act as potential drivers of ALDFG density was based on Akaike's Information Criterion (AIC) and *p*-value, where the model with lowest AIC score was deemed the most reliable. The null hypothesis was rejected if $p \leq 0.05$.

The variation in net mesh size among sampling locations was examined using a Kruskall-Wallis test and Wilcox test (R Core Team, 2020) following data normality checks (Q-Q plot and Shapiro-Wilcox test), which revealed non-normality of data.

The samples of ALDFG collected during the surveys (see section 2.2.1; *n*=180; 26% of the 701 items recorded) were subjected to further analysis using Fourier transform infra-red spectroscopy (FTIR; PerkinElmer UATR Two) to confirm their polymer composition. Samples were scanned at a resolution of 4 cm^{-1} (wavelength range = 4000–650 cm^{-1}). The resulting spectra were compared to a spectral database from a number of polymer libraries using SpectrumTM (PerkinElmer). Spectra match hits were accepted when the search score was ≥ 0.70 and visual inspection of the spectrum confirmed the reliability of the match.

2.3 Socio-economic surveys

2.3.1 Data collection and analysis

Interviews were conducted within villages at or near the ALDFG riverbank survey sites during the same three days in which the riverbank surveys took place. In the absence of village census data, key informant interviews were held with village officials to identify fisher households. Team members, accompanied by in-country volunteers and researchers who were familiar with the target villages, visited households to validate information, and snowball sampling was employed to recruit further participants (Goodman, 2011). Alongside this, opportunistic encounters with fishers along riverbanks maximised participant recruitment in the three-day sampling period per site. Interviews were undertaken in local languages, using a structured questionnaire, and led by in-country researchers. This helped minimise the potential of information withholding on sensitive subjects, and at certain sites, illegal activities, and to minimise perception bias. Local permissions were obtained from respective village leaders on arrival at each site. In-country researchers were recruited through partner organisations and trained by the lead social science researcher.

Questionnaires were piloted and refined prior to commencement, with support from in-country researchers. Prior to the interview commencing, the purpose of the survey was explained to the participant and they were informed that their involvement in the survey was voluntary, they would receive no direct benefit from participating and would incur no sanctions should they choose not to. They were also told that their personal data would be kept confidential and their responses anonymised. The participants were able to stop the interview and withdraw from this study at any time.

For the purposes of this study, participants were asked a series of questions relating to fishing gear use, disposal, observed interactions with biodiversity and knowledge of fisheries regulations:

- What type of fishing gear do you use?
- How often do you replace it?
- How do you dispose of old gear?
- Do you ever see animals other than fish caught in nets?
- If yes, what kinds of animals do you see?
- Are animals in the nets usually dead or alive?
- Were the animals caught in active nets (currently in use for catching fish) or derelict nets (no longer in use for catching fish)?
- Are you aware of any rules and regulations related to fishing gears that can be used?

Team member knowledge and expertise was employed to translate local names for gear types and animals into more widely recognised classifications. A visual species identification guide was provided during the interviews to enhance accuracy of species interaction observations and anecdotes.

2.4 Biodiversity threat assessment

A threat assessment to examine the relative vulnerability of aquatic air-breathing Gangetic vertebrate species to entanglement in ALDFG was conducted to inform research prioritisation and mitigation efforts. Although ingestion of debris can pose a risk to fauna, the threat assessment focused on entanglement because it is known to cause high instances of injury and mortality across a range of taxa, with clear welfare implications (Good et al., 2010).

Species of conservation concern, as identified by the Wildlife Institute for India (WII; www.wii.gov.in/nmcg/priority-species; last accessed 28 July 2020), with ranges that overlap with the sampling locations, were investigated (*n*=21; Supp. Mat. Tables S1 and S2). A scoring system using three criteria was implemented: gear density at sampling locations where species may be present, IUCN Red List status of species, and evidence of impacts based on existing literature. Details of which are provided below.

2.4.1 Gear density at sampling locations

The nine sampling locations were ranked based on gear densities observed during the ALDFG riverbank surveys, as a proxy for the relative abundance of gear likely to be entering the river itself, and reflect the differing degrees of potential biodiversity interaction risk among the locations (Supp. Mat. Table S1). For example, sampling location eight (Anupshahr) exhibited the lowest gear density so was given the rank of one. Sampling site two (Chandpur) exhibited the highest gear density and was therefore given the rank of nine. Each species was then assessed for its potential presence at each of the sampling locations. As fine-scale species distribution data are scarce for the region, broad species information was garnered from the IUCN Red List of Threatened Species database (www.iucnredlist.org; last accessed 08 July 2020). The ranks of all locations where the species may be present were summed to provide a cumulative score. For example, if a species range covers all sampling locations (one to nine), the maximum score relating to gear density would be 45 (Supp. Mat. Table S2).

2.4.2 IUCN Red List Status

The conservation status of each species was obtained by searching the IUCN Red List of Threatened Species database (www.iucnredlist.org; last accessed 08 July 2020). The six categories - *Data Deficient*, *Least Concern*, *Near Threatened*, *Vulnerable*, *Endangered*, *Critically Endangered* - were allocated scores from one to five, respectively (Data Deficient and Least Concern were both allocated the score of one; Supp. Mat. Table S3 and S4).

2.4.3 Literature-based evidence

A database of available literature on ALDFG entanglement relating to each species was established using a semi-structured systematic literature review. Initially, Web of Science (WoS) and Google Scholar were explored using key search terms (ghost gear, derelict, fishing net/gear, ALDFG, entangle, plus the genus and taxa name, including alternatives). In view of the challenges in differentiating between entanglement in ALDFG and active fishing equipment (bycatch; Asmutis-Silvia et al. 2017), only peer-reviewed research where the entangling gear was explicitly described as abandoned, lost or otherwise discarded (including terms such as 'derelict', 'ghost' or 'debris') was accepted. Studies that did not specify whether the gear was active or derelict, were ambiguous or discuss only active gear were excluded, as was grey literature (e.g. reports and conference proceedings). Following the WoS and Google Scholar searches, relevant literature cited within reviews was also explored. Studies concerning the Gangetic species of interest or related species were included. Here, related species are defined as those classified in the same biological family or as marine equivalents to those taxa found in the Ganges. Information, such as observed impacts of ALDFG entanglement (e.g. injury or mortality) and type of entangling gear were examined but, to limit bias, studies were not excluded if this information was not reported. The literature-based evidence status for each species was organised into three categories; no evidence (score = 1), moderate (score = 2) or major (score =3; Table 1).

Table 1 Scoring criteria for the literature-based evidence status

Literature-based evidence status	**No evidence**	**Moderate**	**Major**
Score	1	2	3
Description	No current evidence of entanglement with, or impacts from, ALDFG on the given or related species.	Some evidence that; a) Interactions between the Gangetic species and ALDFG have resulted in non-lethal effects. OR b) ALDFG interactions have resulted in severe injury or mortality of a related species.	Multiple sources of evidence demonstrate that interactions between the Gangetic species and ALDFG have resulted in severe injury or mortality.

2.4.4 Overall vulnerability score

The scores from each of the above three criteria were multiplied to give an overall score of vulnerability to entanglement with, and impacts from, ALDFG for each species (Eq. 1, where S^V is the final vulnerability score, S^D is the gear density score, S^R is the IUCN Red List score and S^L is the literature-based evidence score).

$$S^V = S^D \times S^R \times S^L \quad (1).$$

3. RESULTS

3.1 ALDFG riverbank surveys

The total number of ALDFG items recorded on the 6,761 m of Ganges riverbank surveyed was 701. Of these, the most common by frequency was string (41.2%FO; *n*=289) followed by net (40.2%FO; *n*=282), rope (10.1%FO; *n*=71), float (8.0%FO; *n*=56) and line (0.4%FO; *n*=3; Fig. 2 and Fig. 3a).

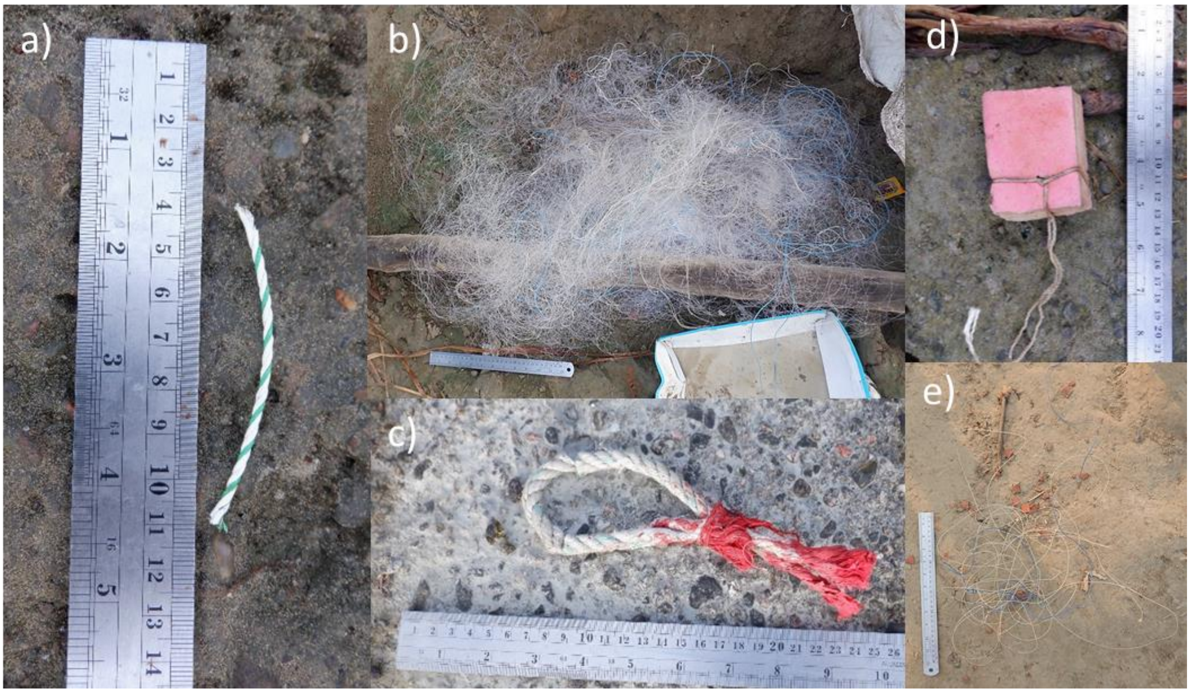

Fig. 2 Photographic examples of abandoned, lost or discarded fishing gear encountered during surveys of the Ganges riverbank in Bangladesh and India. The five ALDFG types found were **a)** string **b)** net **c)** rope **d)** float and **e)** line.

The combined volume of all items was 23.9 m^3 and net represented the highest proportion (99.7%; 23.886 m^3), followed by rope (0.13%; 0.031 m^3), string (0.09%; 0.021 m^3), floats (0.05%; 0.013 m^3) and line (0.01%; 0.002 m^3; Fig. 3b).

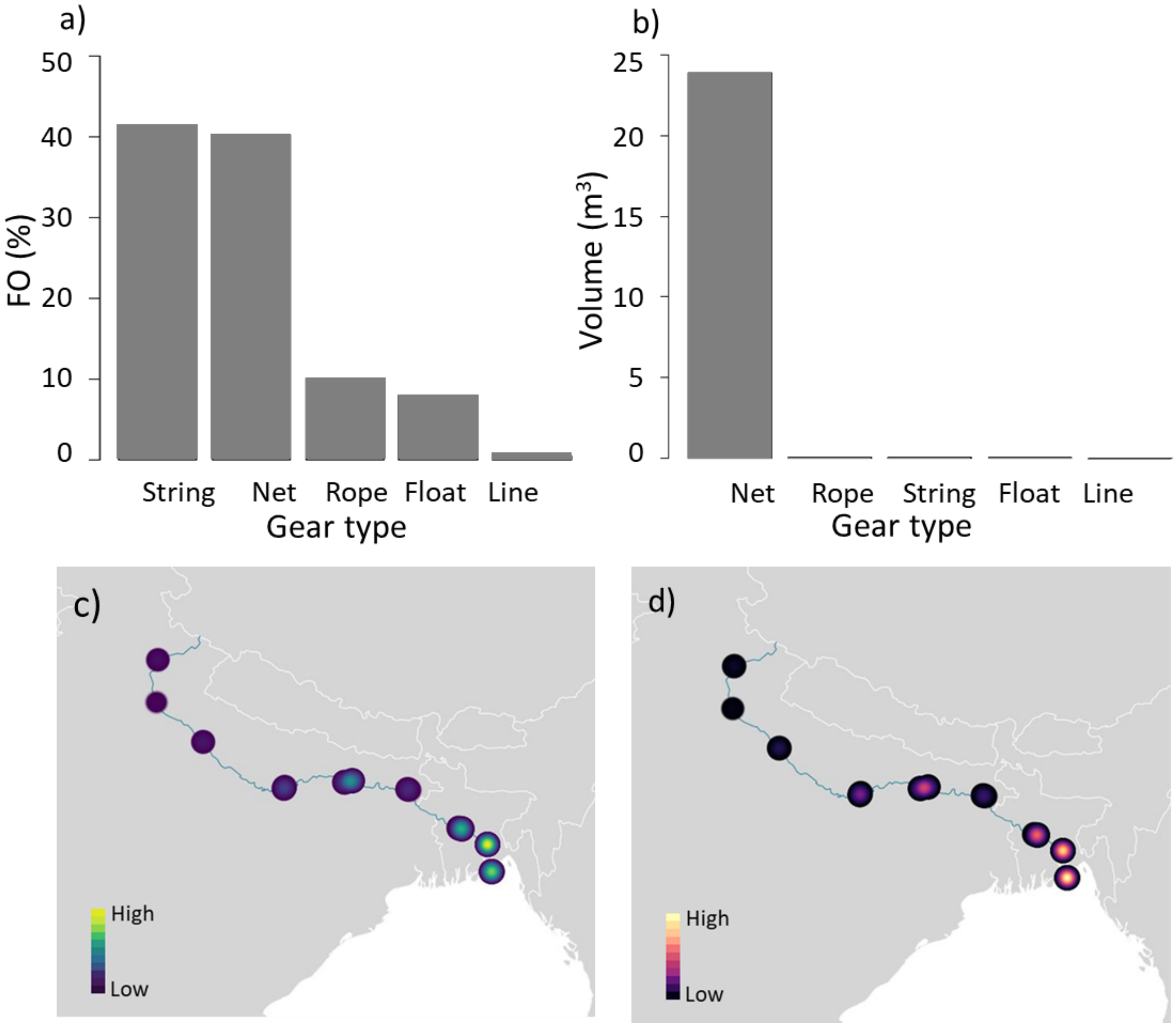

Fig. 3 Barplots showing the **a)** frequency occurrence (%) and **b)** volume (m^3) of the gear types recorded during ALDFG riverbank surveys. Heatmaps showing relative density of **c)** discarded fishing gear (all types) in each sampling site. Yellow = highest density (0.076 items per m^2), dark purple = lowest density (0.0002 items per m^2) and **d)** discarded fishing nets only in each sampling site. Yellow = highest density (0.030 nets per m^2), dark purple = lower density (0.0002 nets per m^2).

3.1.1 ALDFG density

The riverbank surveys covered an area of 54,088 m^2. The mean ALDFG item density (± SD) across all sampling locations (one to nine) was 0.013 (± 0.038) items per m^2. Chandpur in Bangladesh (sampling location two) had the highest mean density of 0.076 (± 0.069) items per m^2 and Anupshahr in northern India (sampling location eight) had lowest of 0.0002 (± 0.0003) items per m^2 (Fig. 3c).

As nets made up over 99% of the overall composition by volume, are known to pose a direct risk to biodiversity and can cause economic harm to communities (Beaumont et al., 2019; Wilcox et al., 2013), their density was also examined separately. Overall, 282 nets (whole or fragments) were recorded. The mean density (± SD) across all sampling locations was 0.005 (± 0.015) nets per m^2. Bhola in Bangladesh (sampling location one) had the highest mean density of 0.030 (± 0.027) nets per m^2 and Anupshahr (sampling location eight) had the lowest of 0.0002 (± 0.0002) nets per m^2 (Fig. 3d).

Model simplification of the GLM indicated that local population size is not a significant predictor of ALDFG density ($p > 0.05$) but distance from the sea is (one-way ANOVA; $F_{1,7}= 15.847$, $p = 0.005$), and there was a significant exponential decay in gear density with sampling location distance from the sea ($p = 0.001$; Fig. 4a).

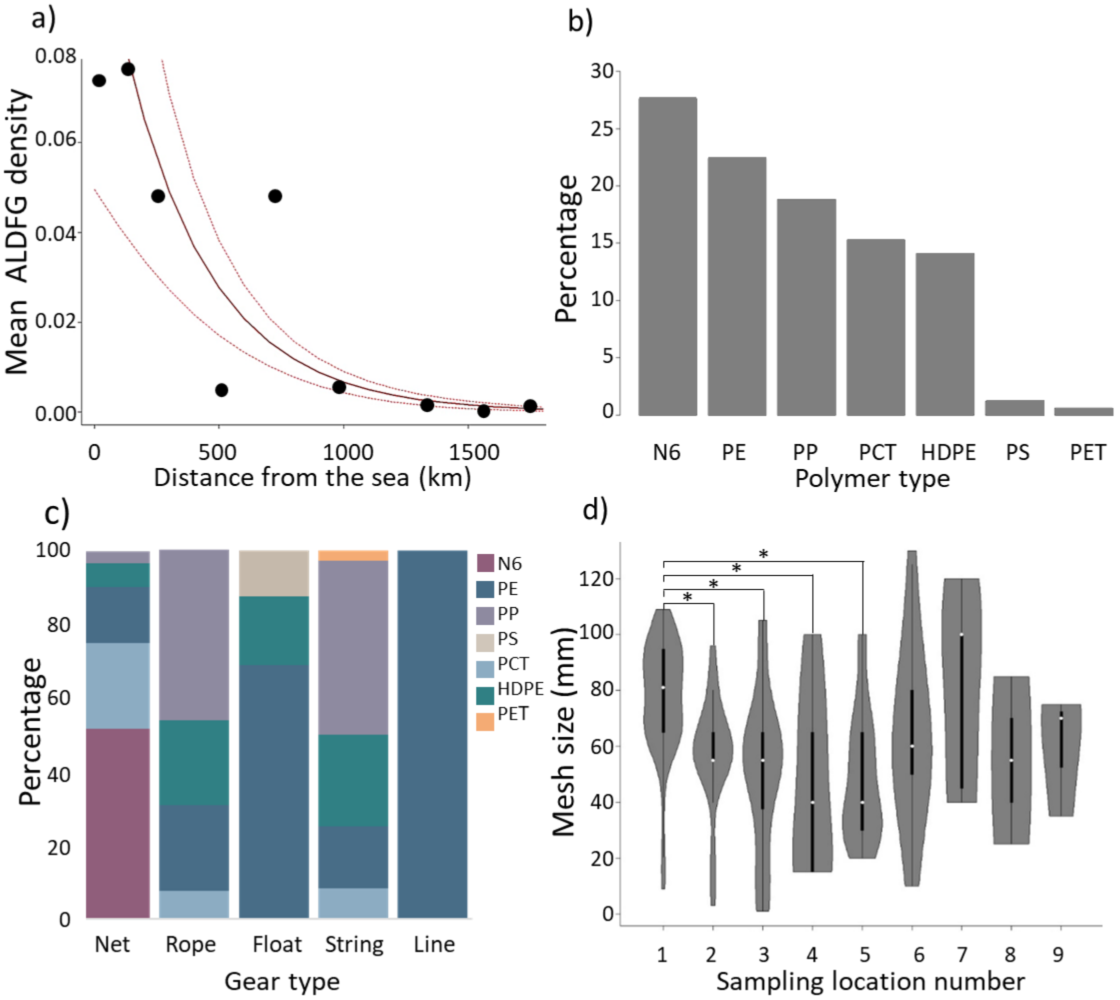

Fig. 4 a) Scatterplot showing the correlation between ALDFG density and sampling location distance from the sea as investigated using a generalized linear model (GLM). Red solid line represents fitted model and dashed red lines represent +/- 1 standard error; **b)** Barplot showing the composition (%) of riverbank ALDFG items by polymer. N6; Nylon 6, PE; polyethylene, PP; polypropylene, PCT; poly(1,4-

cyclohexanedimethylene terephthalate), HDPE; high density polyethylene, PS; polystyrene, PET; polyethylene; **c)** Stacked barplot showing the polymer composition (%) of ALDFG items in each gear type category; **d)** Violin plot showing mesh size (mm) of nets recorded in each sampling location (1 - 9). Asterisks indicate those locations with significant differences in mesh sizes.

3.1.2 Gear characteristics

3.1.2.1 Polymer type

It was possible to obtain reliable FTIR spectra matches (search score ≥ 0.70) for 94% (*n*=170) of the gear samples tested. Overall (all gear types), the most common polymer type was Nylon 6 (27.6%), followed by polyethylene (22.4%), polypropylene (18.8%), poly(1,4-cyclohexanedimethylene terephthalate) or PCT (15.3%), high-density polyethylene (14.1%), polystyrene (1.2%) and polyethylene terephthalate (PET; 0.6%; Fig. 4b).

Of the net samples analysed (*n*=91), 51.6% were predominantly comprised of Nylon 6, while the rest were made from PCT (23.1%), polyethylene (15.4%), high-density polyethylene (6.6%), polypropylene (3.3%; Fig. 4c). Ropes (*n*=26 analysed) were predominantly made from polypropylene (46.2%) followed by regular and high-density polyethylene (both 23.1%; Fig. 4c). Floats (*n*=16 analysed) predominantly comprised of polyethylene (68.8%) followed by high-density polyethylene (18.8%) and polystyrene (12.5; Fig. 4c). As with rope, string (*n*=36 analysed) was mainly made from polypropylene (47.2%), high-density and regular polyethylene (25.0 and 16.7% respectively). One piece of line was analysed (of three recorded) and comprised of polyethylene (Fig. 4c).

3.1.2.2 Net mesh size

Of the 282 nets observed, an accurate mesh size measurement could be recorded for 238. The remaining 44 nets were too degraded and fragile to measure. Mesh sizes ranged from 1 mm (mosquito net) to 130 mm (monofilament gill net) with a mean (± SD) of 61 mm (± 27 mm). Mesh size varied significantly among the sampling locations (Kruskal-Wallis test, $p < 0.001$; Fig. 4d), specifically between sampling location one (Bhola) and two (Chandpur; Wilcox test; $p < 0.001$), three (Rajbari; Wilcox test, $p < 0.001$), four (Sahibganj; Wilcox test; $p < 0.05$) and five (Patna; Wilcox test; $p < 0.01$). Sampling location four (Sahibganj) had the smallest mean mesh size (45 mm) and seven (Kannauj) had the largest (81 mm).

3.2 Socio-economic surveys

3.2.1 Socio-demographics of households

Seventy-nine interviews were conducted with members from households that were previously or actively engaged with fishing. Most lead respondents were male (*n*=66; 84%) and of those, the majority (*n*=47; 71%) were the household heads. The primary occupations reported for household heads were fishing/fishing-related business (*n*=66; 84%), daily labour (*n*=4; 5%), agriculture, riverbed farming, other business and retired (each *n*=2; 3%). Most fishers reported going out fishing seven days a week, during both the summer *'March-May'* (*n*=35; 44%), and monsoon/rainy season *'June-September'* (*n*=27; 34%). The number of fishers going out during the winter season *'December-February'* decreases, with most (*n*=29; 37%) only fishing one to three days a week, with reports of fewer fish during this period.

3.2.2 Gear type, replacement frequency and end-of-life gear outcomes

The most commonly used gear type across the sampling locations was gill nets (*n*=179 responses; 74.9%), followed by mosquito nets (*n*=30; 12.6%), drag nets (*n*=12; 5.0%), bamboo traps (*n*=6; 2.5%), seine nets (*n*=4; 1.7%), Chinese traps (*n*=3; 1.3%), set-bag nets (*n*=2; 0.8%), fry fish nets, long-line hooks and unspecified traps (each *n*=1; 0.4%; Fig. 5a; see Supp. Mat. Fig. S1 for glossary of terms). It should be noted that some participants gave more than one answer due to multiple gear type usage, thus the number of responses is greater than the number of interviews.

When asked how often fishers replace their nets, a range of answers were given, from every month or less, to every 10 years. Of the 209 responses, a third (34%; *n*=71) said they replace their nets every one to six months and a quarter (25%; *n*=52) replace them every six months to a year Fig. 5b). Factors affecting gear turnover rates include quality (e.g. poor durability) and cost (e.g. cheaper to replace than repair). When asked what happens to the gear they replace, respondents listed between one and three end-of-life gear outcomes that occurred immediately after use as fishing gear (total responses *n*=289). The repurposing of old gear into other items, such as fencing and ropes, was the most commonly listed outcome overall (44%; *n*=126), followed by discarding in the environment (e.g. throwing it into the river or leaving it on the riverbank; 22%; *n*=64). Other outcomes included selling (17%; *n*=49), burning (16%; *n*=47) and burying (1%; *n*=3) old gear (Fig. 5c). The prevalence of each end-of-life outcome varied among sampling locations. For example, repurposing was the most common outcome in Kannauj, Varanasi and Patna (93%, 65% and 60% of primary responses, respectively). Discarding was most common in Sahibganj, Rajbari and Chandpur (75%, 50% and 48%, respectively). Selling was most common in sampling location one (Bhola; 77% of responses) and burning most common in sampling location eight (Anupshahr; 73%). No end-of-life gear outcome data were obtained in sampling location nine (Rishikesh) due a local religious fishing ban and consequent scarcity, and reticence, of survey participants.

Of 79 respondents, 48% (*n*=38) said they had seen old nets on the riverbank and 52% (*n*=41) said they had not. Again, the proportion varied among sampling locations. For example, more than 90% of respondents said they had seen nets on the riverbank in four of the nine sampling locations (Anupshahr; 100%, Sahibganj; 100%, Rajbari; 100% and Bhola; 92% of respondents).

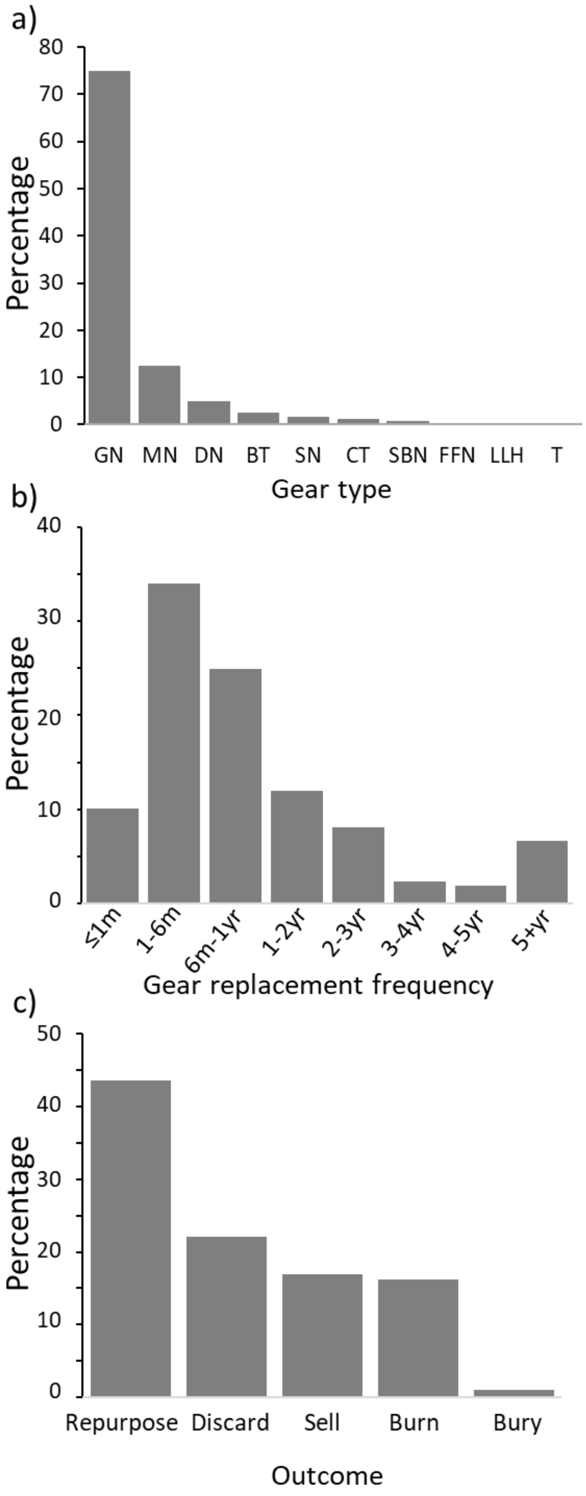

Fig. 5 Plots showing percentage of responses for **a)** gear type (GN=gill net, MN = mosquito net, DN = drag net, BT = bamboo trap, SN= seine net, CT = Chinese trap, SBN = set-bag net, FFN = fry fish net, LLH = long-line hook, T = trap (type unspecified); **b)** frequency of gear replacement; and **c)** end-of-life gear outcomes.

3.2.3 Interactions with animals

Of the 53 individuals who responded to the question of whether they had seen animals other than fish caught in nets, 55% (*n*=29) said they had. Species included crabs, crocodiles, dolphins, frogs, lizards, otters, rays, sawfish, sharks, snails, snakes, turtles and domestic animals. When asked if the animals were alive or dead when encountered, 73 observations were recorded (some individuals reported more than one observation). Of which, 42% (*n*=31) said the animals were alive, 30% (*n*=22) said they did not know, 16% (*n*=12) said both (alive and dead) and 11% (*n*=8) said dead. Most of the animals were caught in active nets (67%; *n*=48) but 33% (*n*=24) of respondents said they did not know whether the gear was active or derelict.

3.2.4 Legislation

When asked whether any rules and regulations exist regarding fishing gear type, 57% (*n*=43) of the respondents who answered said no, 42% (*n*=32) said yes and 1% (*n*=1) said they did not know. Respondents from the same communities often gave opposing answers. Examples of regulations were sometimes listed and included bans on certain net types, such as, *current jal* (local term for monofilament gill net) and mosquito net, as well as restrictions on mesh sizes.

3.3 Biodiversity threat assessment

The results of the biodiversity threat assessment are described in sections 3.3.1 to 3.3.4 with further detail presented in Table 2. See Supp. Mat. Table S2 for species presence at sampling locations, S4 for IUCN Red List status and Tables S5 and S6 for literature-based evidence.

Table 2 Biodiversity threat assessment of Gangetic species most at risk from entanglement with, and impacts from, ALDFG. Species are ranked by vulnerability score, from highest (430) to lowest (4).

Taxa	Species	Sampling location gear density score	IUCN Red List status score	Literature-based evidence score	Vulnerability score
Reptile	Three-striped roofed turtle (*Batagur dhongoka*)	43	5	2	430

Mammal	Ganges river dolphin (*Platanista gangetica gangetica*)	43	4	2	344
Reptile	Black spotted turtle (*Geoclemys hamiltonii*)	37	4	2	296
Reptile	Northern river terrapin (*Batagur baska*)	24	5	2	240
Mammal	Smooth coated otter (*Lutrogale perspicilata*)	35	3	2	210
Reptile	Red-crowned roofed turtle (*Batagur kachuga*)	19	5	2	190
Bird	Black-bellied tern (*Sterna acuticauda*)	21	4	2	168
Bird	River tern (*Sterna aurantia*)	37	2	2	148
Reptile	Marsh crocodile (*Crocodylus palustris*)	21	3	2	126
Bird	Sarus crane (*Antigone antigone*)	21	3	2	126
Bird	Indian skimmer (*Rynchops albicollis*)	19	3	2	114
Bird	River lapwing (*Vanellus duvaucelii*)	19	2	2	76
Reptile	Gharial (*Gavialis gangeticus*)	7	5	2	70
Mammal	Asian small-clawed otter (*Aonyx cinereus*)	11	3	2	66
Reptile	Salt-water crocodile (*Crocodylus porosus*)	24	1	2	48
Amphibian	Indian bullfrog (*Hoplobatrachus tigerinus*)	45	1	1	45
Amphibian	Marbled toad (*Duttaphrynus stomaticus*)	45	1	1	45

Amphibian	Jerdon's bullfrog (*Hoplobatrachus crassus*)	39	1	1	39
Amphibian	Tytler's pond frog (*Hylarana tytleri*)	24	1	1	24
Amphibian	Nepal Paa frog (*Nanorana minica*)	2	3	1	6
Mammal	Eurasian otter (*Lutra lutra*)	1	2	2	4

3.3.1 Amphibians

Of the five amphibian species assessed, the Indian bullfrog and marbled toad had the highest vulnerability score (both 45), followed by Jerdon's bullfrog (39) Tytler's pond frog (24) and Nepal Paa frog (6; Table 2). No literature-based evidence of entanglement in ALDFG was found for these Gangetic or related species.

3.3.2 Reptiles

Of the four freshwater turtle species assessed, the three-striped roofed turtle had the highest vulnerability score (430), which was also the highest overall score of all species assessed, followed by black spotted turtle (296), northern river terrapin (240) and red-crowned roofed turtle (190; Table 2). No literature was identified that presents evidence of entanglement by these species but 12 studies reported entanglements in or capture by ALDFG for a number of related species - five of the seven marine turtle species and a brackish-water terrapin (diamondback terrapin; *Malaclemys terrapin*). Of these studies, 10 reported animal mortality resulting from ALDFG entanglement (two did not specify any impacts). Nets (gill, trawl, unspecified) were responsible for all marine turtle entanglements (Adelir-Alves et al., 2016; Barbosa-Filho et al., 2020; Chatto, 1995; Gunn et al., 2010; Jensen et al., 2013; Santos et al., 2012; Stelfox et al., 2019; Wilcox et al., 2013), whereas terrapins were observed in derelict crab pots and traps (Anderson and Alford, 2014; Bilkovic et al., 2014; Grosse et al., 2009).

Of the three crocodilian species assessed, marsh crocodile had the highest vulnerability score (126), followed by gharial (70) and saltwater crocodile (48; Table 2). One study reported entanglement of a saltwater crocodile in ALDFG in Australia, but with undetermined impacts (Gunn et al., 2010). Another study described a false gharial (*Tomistoma schlegelii*) which had 'debris of fishing net entangled in its mouth' and several injuries consistent with attempts to escape from the net.

3.3.3 Birds

Of the five bird species assessed, black-bellied tern had the highest vulnerability score of 168, followed by river tern (148), sarus crane (126), Indian skimmer (114) and river lapwing (76; Table 2).

No studies relating to these Gangetic species were identified, however evidence of entanglement in ALDFG by related species of the Laridae Family (terns, skimmers and gulls) was found. For example, Gochfeld (1973) reported three common terns (*Sterna hirundo*) and four black skimmers (*Rhynchops nigra*) with nylon fishing line entangling their legs, causing permanent damage in some through obstructed blood supply. In India, Nisanth & Kumar (2019) observed a lesser crested tern (*Thalasseus bengalensis*), brown-headed gull (*Chroicocephalus brunnicephalus*) and lesser black-backed gull (*Larus fuscus*) entangled in discarded gill nets, which caused injuries, prevented normal feeding behaviour and hampered flight. Bergmann et al. (2017) present citizen scientists' photographic evidence of a dead Arctic tern (*Sterna paradisaea*) entangled in fishing net, although the cause of death cannot be ascertained from the imagery. Taylor (1996) reported a southern black-backed gull (*Larus dominicanus*) that died from entanglement in discarded fishing line, although it was not clear how the discarded status was determined.

Though no studies were found that demonstrate evidence of entanglement in ALDFG by Gangetic species of cranes, one study did report observations of three whooping cranes (*Grus americana*) and a sandhill crane (*Grus canadensis*) with monofilament line wrapped around the feet and legs which caused injuries (Folk et al., 2001). The authors surmise the entangling material to be fishing line but as they do not discuss whether it was derelict or active gear, the report was not included in the species assessment.

A number of studies demonstrate the impacts of entanglement in ALDFG in other species of aquatic bird species. For example, Good et al. (2009) documented 514 dead individuals from at least 15 marine bird species in derelict gill nets in Puget Sound (Canada and the United States of America; USA) and Degange & Newby (1980) reported 99 dead seabirds from at least five species in 1,500 m of salmon drift net.

In the Sulidae family, gannets and boobies have also been found to use fishing and shipping debris to build their nests which can result in both adults and young becoming entangled (Lavers et al., 2013; Rodríguez et al., 2013; Votier et al., 2011).

3.3.4 Mammals

One species of cetacean was assessed, the Ganges river dolphin (*Platanista gangetica gangetica*), which had the second highest overall vulnerability score (344; Table 2). No literature reporting entanglement in ALDFG by this species was found but one study described mortality from entanglement in abandoned gill nets by two species of river dolphins in the Brazilian Amazon (boto; *Inia geoffrensis* and tucuxi; *Sotalia fluvia-tilis;* Iriarte & Marmontel 2013). An additional three studies reporting injury and mortality of marine dolphin and porpoise species were also found. For example, Good et al. (2010) reported a dead harbour porpoise (*Phocoena phocoena*) trapped in a derelict gill net in Puget Sound. A study by Quintana-Rizzo (2014) presented observations from fisher interviews in Guatemala where three dead bottlenose dolphins (*Tursiops truncatus*) were found entangled in a 'ghost' fishing gill net approximately 200 m long. Similarly, Barbosa-filho et al. (2020) interviewed Brazilian fishers who reported finding dolphins in ghost nets. Additionally, Hong et al. (2013) reported the injury of a finless porpoise (*Neophocaena phocaenoides*) in Korea by a commercial fishing hook embedded in its tail fluke. Though the hook was classified as 'marine debris', it is not clear how the differentiation between active and derelict status was determined.

Of the three otter species assessed, the smooth-coated otter had the highest vulnerability score of 210, followed by small-clawed otter (66) and Eurasian otter (4; Table 2).
No evidence of entanglement in ALDFG for these Gangetic species was identified but two studies reported entanglement by river otters (*Lontra canadensis*) in North America. Good et al. (2010) reported a dead otter recovered from a derelict gill net in Puget Sound and Anderson & Alford (2014) reported river otters among the species found in derelict crab traps in Louisiana, USA, without specifying the number of animals. An anecdotal report of three dead and two living sea otters (*Enhydra lutris*) recovered from a monofilament gillnet was cited by Degange & Newby (1980), but was not included in the threat assessment.

4. DISCUSSION

Abandoned, lost or otherwise discarded fishing gear represents a substantial proportion of global marine debris and can cause significant environmental and socio-economic impacts (Richardson et al., 2019b). Yet little is known about its presence in, and implications for, freshwater ecosystems, such as rivers. Evidence is emerging, however, which demonstrates that 'ghost gear' is not only a marine issue, but can pollute freshwater habitats too (Spirkovski et al., 2019). For example, Kappenman & Parker (2007) recovered 33 lost gill nets from the Columbia River (USA) and found 126 white sturgeon (*Acipenser transmontanus*), which had been 'fished' by this ghost gear. Additionally, Spirkovski et al. (2019) reported 116 fish and four birds entangled in ghost nets retrieved from Lake Ohrid (Macedonia and Albania). The Ganges River catchment supports some of the world's largest inland fisheries but no research has yet been conducted to examine the input of debris from this industry. Additionally, no studies have investigated the potential movement of ALDFG from rivers into the sea. Our study is the first to investigate the distribution, abundance and characteristics of ALDFG on riverbanks along the length of a major river, explore the behavioural drivers of waste gear environmental input, and assess the threat posed to air-breathing aquatic vertebrate species.

4.1 ALDFG riverbank surveys

Riverbanks are important riparian ecotones that are an understudied interface between terrestrial and freshwater systems where plastic pollution, such as ALDFG, is periodically stored, retained and transported as a result of flooding, deposition and retention in vegetation (Windsor et al., 2019). Despite growing research attention, sources of riverine plastic pollution are poorly understood. Where input estimates exist, they are often based on models from extrapolated data that predict the magnitude and spatial distribution on a global scale (Jambeck et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017). Empirical field observations, such as those presented in this study, are essential for garnering fine-scale information to inform management strategies aimed at reducing input. The methods used here to assess the abundance, distribution, and characteristics of waste fishing gear in the Ganges could be replicated in other major rivers, worldwide.

Though there are few studies that can be directly compared to our riverbank survey results, a number reporting litter items in freshwater habitats were identified. Owens & Kamil (2020) conducted riverbank litter surveys of the Karamana River, Kerala (India), the methods of which were similar but not the same as those employed in the present study. For example, their suggested protocol of surveying standardised transects of 100 m long and 5 m deep was not possible at the landing sites where our ALDFG riverbank surveys were conducted due to logistical challenges (e.g. health and safety considerations, such as riverbank stability due to erosion), time constraints (e.g. availability of fishers for consultation on gear type) and topography (e.g. width of riverbank). Instead, a flexible transect was adopted that followed the water’s edge where possible (for a standardised time limit), while the route was tracked using handheld GPS units. A litter density of 3.26 pieces per m^2 was recorded for the Karamana River, of which the majority of items originated from litter and human household waste, not fishing or other industries (Owens and Kamil, 2020). This may be due to a range of factors, including site selection. Shoreline surveys of a remote mountain lake in Mongolia found 0.008 fishing items per metre (62 items recorded in transects totalling 7800 m in length; Free et al. 2014). Due to varying transect widths, however, the authors do not report the total area surveyed so it is not possible to compare fishing gear density with those reported in this study.

When potential drivers of ALDFG distribution and abundance were investigated, no relationship between ALDFG density and local population size was identified, but sampling location distance from the sea appears to be linked to ALDFG density (density increased with proximity to the coast). This relationship could be caused by a range of factors, the effects of which could not be further investigated in this study due to scarcity of data but would be worthy of future investigation. Firstly, the lack of influence of population size on ALDFG density may be due to the presence of alternative livelihoods and subsequent lower reliance on fishing in areas of high population density. For example, large urban areas, such as Patna and Varanasi, likely offer greater levels of employment in alternative industries, including manufacturing and tourism (Geetika Verma and Shrivastav, 2018; Kumar et al., 2012). Secondly, density of ALDFG is likely related to the level of fishing effort at the sampling locations. For example, commercial fishing activity is very low in upland waters due to inaccessibility (FAO, 2011) where fewer ALDFG items were observed. Additionally, dietary differences (e.g. due to religious beliefs) among the sampling locations likely influence the degree of fishing effort. Thirdly, the extent, and enforcement, of fisheries management restrictions differ among the various regions of Bangladesh and India and likely influence the temporal trends and spatial patterns of ALDFG, and types of gear found. For example, the government of Bangladesh implement seasonal hilsa (*Tenualosa ilisha*) bans and area closures in an effort to prevent stock decline (Dewhurst-Richman et al., 2019; Nahiduzzaman et al., 2018). Additionally, monofilament fixed gill nets (*current jal*) and mosquito nets are illegal or restricted in Bangladesh and India but their presence as observed during the riverbank surveys suggest that fishers are not adhering to the restrictions (Nahiduzzaman et al., 2018). Lastly, the greater densities of ALDFG at the downstream sampling locations may be related to the accumulation of debris as it moves towards the sea. It is not clear, however, what proportion of riverine fishing debris reaches the ocean and how dams and other obstructions influence the spatial distribution and any subsequent accumulation of ALDFG. As the riverbank surveys conducted in this study occurred in the post-monsoon season only, it was not possible to investigate the effect of fluxes in water levels on ALDFG distribution and abundance. Water level, velocity and riverbank vegetation (type, coverage and roughness) are factors which are highly variable between pre- and post-monsoon seasons and are key to regulating the storage, release and transport of plastic debris in rivers, such as the Ganges (Windsor et al., 2019).

Of the ALDFG samples analysed using FTIR (n = 170), all were found to be made from synthetic polymers. The three most common types were nylon, polyethylene and polypropylene. Nylon, or polyamide, is negatively buoyant in water and likely sinks to the mid-water column or benthos (Andrady, 2015). It is probable, therefore, that the nylon ALDFG items observed during the riverbank surveys were abandoned *in situ* or nearby, rather than deposited during flooding events. Conversely, polyethylene (PE) and polypropylene (PP) are less dense and therefore more likely to float and be deposited elsewhere when they enter the water (Andrady, 2015). These differences in polymer type characteristics may therefore affect ALDFG transport and deposition. They may also mean that different types of ALDFG occur in different habitats and affect different species. For example, nylon nets may be more likely to be encountered by species that inhabit the mid-water column or benthic environment.

Due to the variation in fishing techniques employed throughout the Ganges (Sinha and Sinha, 2013), a wide-range of net mesh-sizes was observed (1 mm; mosquito net to 130 mm; monofilament gill net). Mosquito net fishing is prevalent in sub-Saharan Africa but evidence of its use outside of this region is limited (Short et al., 2018). The small mesh size of mosquito nets means they are unselective and often have high capture rates of juvenile fish, with implications for fishery sustainability (Short et al., 2018). Mesh size may also have implications for risk of entanglement by non-target aquatic taxa, such as the Ganges river dolphin. For example, Dewhurst-Richman et al. (2019) found that the risk of dolphin bycatch (active gear) in Bangladesh increased with larger mesh sizes. The relationship between mesh size and entanglement risk is likely to be species-specific, and relative to animal morphology and behaviour (Dewhurst-Richman et al., 2019).

4.2 Socio-economic surveys

Interviews with fishers revealed that gill nets are the most commonly used gear type and that gear turnover rates are high, with the majority being replaced every one to six months. A substantial proportion of the old gear is then discarded into the environment (by leaving on the riverbank or throwing into the river itself), burnt or buried. Three sampling locations in particular were identified where discarding into the environment is the most common end-of-life gear outcome (Sahibganj in India, and Rajbari and Chandpur in Bangladesh; 75%, 50% and 48%, respectively). This behaviour illustrates one potential driver of the observed ALDFG abundances but the reasons for differences in disposal methods among the sampling locations requires further research. In addition, there are a number of other behaviours that were not explored here but would be worthy of future investigation. For example, the recent introduction of imported monofilament nets may influence the rate of net disposal because the cheap nets break easily and are often more expensive and time-consuming to repair than replace (authors pers. obs.). Additionally, it is not known how riverside activities, such as net alteration, float preparation and attachment, repurposing of old net into string or rope, and use of old net as fencing contributes to plastic pollution levels on riverbanks. The high abundance of string recorded in this study indicates such activities may be a potential source and focus for input prevention measures. Furthermore, though it is clear that a large amount of old gear is repurposed or sold on, the ultimate fate of those items is not understood. For example, old nets used as fences were observed but some were collapsed/ no longer in use and liable to leak into the environment. Further work should examine the circularity of this system and how it can be improved (see section 4.4).

In addition to discarded and abandoned gear, further investigation into the factors affecting accidental loss of gear is needed. In a marine setting, rates of loss are increased when nets are unattended and fishing grounds overcrowded (Richardson et al., 2019b, 2019a). It is therefore possible that appropriate fisheries management could reduce incidences of gear loss.

4.3 Biodiversity threat assessment

A biodiversity threat assessment was carried out to identify species most vulnerable to the risk of, and impacts from, entanglement in ALDFG, based on their distribution, conservation status and literature-based evidence. This priority-setting exercise may help to guide future research and direct conservation resources to where they are most needed.

While there is evidence that entanglement in active fishing gear (bycatch) poses a risk for some Gangetic vertebrate species, such as river dolphins (Dewhurst-Richman et al., 2019; Mansur et al., 2008), no published research was found which demonstrates evidence of entanglement in ALDFG for any of the 21 species assessed. This dearth of literature does not demonstrate an absence of impact, rather a need to carry out more research and gather evidence. Though socio-economic observations documented animals entangled in nets, it is not clear how many occurred due to interactions with ALDFG. Nisanth & Kumar (2019) suggest that many incidences of entanglement of seabirds in ALDFG often go unnoticed due to the limited number of seabird studies in India, and even fewer that focus on anthropogenic debris. In addition, compared to bycatch, entanglement in derelict gear is rarely documented, and incidences of entanglement are likely to be under-reported (Matsuoka et al., 2005; Parsons et al., 2010). For example, fishers do not monitor non-active fishing gear and any entangled animals are less likely to be encountered than those occurring in active gear. Drifting gear can cover large distances and enter remotes areas where the evidence of impacts (e.g. animal carcasses) are not observed. When observations of entanglement do occur, they may not be published in peer-reviewed literature, particularly in the case of single incidences. The mining of social media platforms for posts relating to animal entanglements may reveal some insights (Hart et al., 2018; Parton et al., 2019). Differentiating between bycatch in active gear and entanglement in ALDFG is a major challenge and caution should be applied when documenting and interpreting evidence of fishing gear interactions (Asmutis-Silvia et al., 2017; Quirós et al., 2018). Here, only those studies that explicitly discussed entanglement in ALDFG were included in our assessment. This conservative approach may under-estimate the prevalence and impacts of fishing debris entanglement but it was deemed appropriate given the concerns that lack of rigorous differentiation may have implications for policy and management of both bycatch and ALDFG. This is particularly important as bycatch in active gear remains one of the most significant threats to many aquatic species, worldwide (Asmutis-Silvia et al., 2017; Quirós et al., 2018).

The biodiversity threat assessment conducted here demonstrates the theoretical risk posed by ALDFG, but a lack of empirical evidence means this potential threat is absent from existing conservation management plans for at-risk species. To better understand the impacts of ALDFG on biodiversity, and develop effective mitigation measures, an urgent assessment is needed and should be incorporated into existing monitoring programmes.

4.4 Potential solutions

Although the socio-economic surveys revealed some re-use and re-purposing of old plastic fishing gear by fishers in Bangladesh and India, a substantial proportion is discarded or abandoned in the environment. Practical, local-level disposal solutions are required to reduce ALDFG inputs and mitigate the potential for harm. Circular economy approaches, such as ‘extending product value’, where plastic waste from fishing is used as a resource for creating new products, can be effective at addressing both the environmental and social issues relating to ALDFG pollution (Bocken et al., 2016; Luqmani et al., 2017; OSPAR Commission, 2020). For example, *‘Net-Works’* (www.net-works.com; last accessed 02 July 2020) is a social enterprise, which currently operates in the Philippines and Cameroon, where members of partnering communities directly sell end-of-life fishing gear and Nylon 6 nets recovered from the marine environment into a global supply chain. They are then recycled into yarn for manufacture of products, such as carpet tiles, that are themselves recycled at end of life, moving the material into a circular economy. This approach reduces ALDFG in the environment whilst simultaneously offering financial incentives to marginalised communities and is underpinned by an inclusive and sustainable business model (Luqmani et al., 2017). Given that a high proportion of nets recorded during the Ganges riverbank surveys were made of Nylon 6, it is possible a similar approach could be feasible, particularly where net densities were highest and/or discarding behaviour is most common (e.g. sampling locations one to three, in Bangladesh and four in India). Further examples of fishing net recycling enterprises can be found in OSPAR Commission (2020).

Bycatch mitigation devices, such as acoustic ‘*pingers*’, are widely used in the marine environment (Omeyer et al., 2020), but their application in freshwater fisheries is limited (Campbell et al., 2020). The efficacy of employing such approaches in important foraging/ breeding areas of high-risk species (e.g. Ganges river dolphin) should be evaluated.

Enhancing environmental awareness and knowledge is considered key to increasing support for solutions, and catalysing behaviour change (Ashley et al., 2019; Derraik, 2002). Social marketing frameworks offer a flexible approach to design behaviour change programmes, motivate and incentivise recycling, reduce the impact of plastic pollution on biodiversity, and have been shown to be an effective tool for fostering sustained change across a range of behaviours in fishing communities (Andriamalala et al., 2013; Brodbeck, 2016; Eagle et al., 2016; Haldeman and Turner, 2009; Thompson, 2008). Community-based social marketing campaigns, coupled with circular economy approaches, offer strong potential to facilitate better management of fishing-related activities such as net repairs, as well as end-of-life gear disposal.

5. CONCLUSION

In conclusion, this research demonstrates that waste fishing gear likely contributes significantly to the plastic pollution burden of the Ganges River and potentially downstream into the global ocean. The multifaceted approach used here combines fishers’ knowledge and experience with an environmental assessment to gain an in-depth understanding of this previously uncharacterised but important source of plastic pollution, and provides novel insights for improved decision-making and sustainable management. Globally, further research and targeted interventions are needed to assess the extent of waste gear input to major rivers and ameliorate the associated ecological and socio-economic impacts. Intercepting waste at source is crucial if we are to turn off the tap and prevent further leakage of plastic into our environment.

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REFERENCES

Adelir-Alves, J., Rocha, G.R.A., Souza, T.F., Pinheiro, P.C., Freire, K. de M.F., 2016. Abandoned, lost or otherwise discarded fishing gears in rocky reefs of Southern Brazil. Brazilian J. Biol. 64, 427–434.

Anderson, J.A., Alford, A.B., 2014. Ghost fishing activity in derelict blue crab traps in Louisiana. Mar. Pollut. Bull. 79, 261–267. https://doi.org/10.1016/j.marpolbul.2013.12.002

Andrady, A.L., 2015. Persistence of plastic litter in the oceans, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. SpringerLink, Springer Cham Heidelberg New York Dordrecht London, pp. 57–72.

Andriamalala, G., Peabody, S., Gardner, C.J., Westerman, K., 2013. Using social marketing to foster sustainable behaviour in traditional fishing communities of southwest Madagascar. Conserv. Evid. 10, 37–41.

Ashley, M., Pahl, S., Glegg, G., Fletcher, S., 2019. A change of mind: Applying social and behavioral research methods to the assessment of the effectiveness of ocean literacy initiatives. Front. Mar. Sci. 6. https://doi.org/10.3389/fmars.2019.00288

Asmutis-Silvia, R., Barco, S., Cole, T., Henry, A., Johnson, A., Knowlton, A., Landry, S., Mattila, D., Moore, M., Robbins, J., van der Hoop, J., 2017. Rebuttal to published article "A review of ghost gear entanglement amongst marine mammals, reptiles and elasmobranchs" by M. Stelfox, J. Hudgins, and M. Sweet. Mar. Pollut. Bull. 117, 554–555. https://doi.org/10.1016/j.marpolbul.2016.11.052

Barbosa-Filho, L. V, In, C., Siciliano, S., Hauser-davis, R.A., Mour, S., 2020. Artisanal fisher perceptions on ghost nets in a tropical South Atlantic marine biodiversity hotspot: Challenges to traditional fishing culture and implications for conservation strategies. Ocean Coast. Manag. 192. https://doi.org/10.1016/j.ocecoaman.2020.105189

Beaumont, N.J., Aanesen, M., Austen, M.C., Börger, T., Clark, J.R., Cole, M., Hooper, T., Lindeque, P.K., Pascoe, C., Wyles, K.J., 2019. Global ecological, social and economic impacts of marine plastic. Mar. Pollut. Bull. 142, 189–195. https://doi.org/10.1016/j.marpolbul.2019.03.022

Bergmann, M., Lutz, B., Tekman, M.B., Gutow, L., 2017. Citizen scientists reveal: Marine litter pollutes Arctic beaches and affects wild life. Mar. Pollut. Bull. 125, 535–540. https://doi.org/10.1016/j.marpolbul.2017.09.055

Bilkovic, D.M., Havens, K., Stanhope, D., Angstadt, K., 2014. Derelict fishing gear in Chesapeake Bay, Virginia: Spatial patterns and implications for marine fauna. Mar. Pollut. Bull. 80, 114–123. https://doi.org/10.1016/j.marpolbul.2014.01.034

Blasi, M.F., Mattei, D., 2017. Seasonal encounter rate, life stages and main threats to the loggerhead sea turtle (Caretta caretta) in the Aeolian Archipelago (southern Thyrrenian Sea). Aquat. Conserv. Mar. Freshw. Ecosyst. https://doi.org/10.1002/aqc.2723

Blettler, M.C.M., Abrial, E., Khan, F.R., Sivri, N., Espinola, L.A., 2018. Freshwater plastic pollution: Recognizing research biases and identifying knowledge gaps. Water Res. 143, 416–424. https://doi.org/10.1016/j.watres.2018.06.015

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124

Braulik, G.T., Smith, B.., 2019. South Asian River Dolphin (Platanista gangetica) (amended version of 2017 assessment). IUCN Red List Threat. Species 2019 8235.

Brodbeck, L., 2016. Mechanisms to support the recycling/reuse of fishing gear and the prevention of gear becoming lost/abandoned at sea. Barrier assessment 43.

Campbell, E., Mangel, J.C., Alfaro-Shigueto, J., Mena, J.L., Thurstan, R.H., Godley, B.J., 2020. Coexisting in the Peruvian Amazon: Interactions between fisheries and river dolphins. J. Nat. Conserv. 56, 125859. https://doi.org/10.1016/j.jnc.2020.125859

Chatto, R., 1995. Sea turtles killed by flotsam in northern Australia. Mar. Turt. Newsl. 69, 17–18.

Degange, A.R., Newby, T.C., 1980. Mortality of seabirds and fish in a lost salmon driftnet. Mar. Pollut. Bull. https://doi.org/10.1016/0025-326X(80)90049-1

Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44, 842–852. https://doi.org/10.1016/S0025-326X(02)00220-5

Dewhurst-Richman, N.I., Jones, J.P.G., Northridge, S., Ahmed, B., Brook, S., Freeman, R., Jepson, P., Mahood, S.P., Turvey, S.T., 2019. Fishing for the facts: river dolphin bycatch in a small-scale freshwater fishery in Bangladesh. Anim. Conserv. https://doi.org/10.1111/acv.12523

Eagle, L., Hamann, M., Low, D.R., 2016. The role of social marketing, marine turtles and sustainable tourism in reducing plastic pollution. Mar. Pollut. Bull. 107, 324–332. https://doi.org/10.1016/j.marpolbul.2016.03.040

Emmerik, T., Schwarz, A., 2020. Plastic debris in rivers. WIREs Water 7. https://doi.org/10.1002/wat2.1398

FAO, 2020. The State of World Fisheries and Aquaculture 2020, in: Sustainability in Action. Rome. https://doi.org/https://doi.org/10.4060/ca9229en

FAO, 2011. Review of tropical reservoirs and their fisheries the cases of Lake Nasser, Lake Volta and Indo-Gangetic Basin reservoir. (No. 557), FAO Fisheries and Aquaculture Technical Paper. Rome.

Ferronato, N., Torretta, V., 2019. Waste mismanagement in developing countries: A review of global issues. Int. J. Environ. Res. Public Health 16. https://doi.org/10.3390/ijerph16061060

Folk, M.J., Nesbitt, S.A., Spalding, M.G., 2001. Interactions of sandhill cranes and whooping cranes with foreign objects in Florida. Proc. North Am. Crane Work. 8, 195–197.

Free, C.M., Jensen, O.P., Mason, S.A., Eriksen, M., Williamson, N.J., Boldgiv, B., 2014. High-levels of microplastic pollution in a large, remote, mountain lake. Mar. Pollut. Bull. 85, 156–163. https://doi.org/10.1016/j.marpolbul.2014.06.001

Funk, S., Krumme, U., Temming, A., Möllmann, C., 2020. Gillnet fishers' knowledge reveals seasonality in depth and habitat use of cod (Gadus morhua) in the Western Baltic Sea. ICES J. Mar. Sci. https://doi.org/10.1093/icesjms/fsaa071

Geetika Verma, A., Shrivastav, K., 2018. Finding the Causes of Water Pollution in Ghats of Varanasi City. Int. Res. J. Eng. Technol. Volume: 05, 891–896.

Gilman, E., 2015. Status of international monitoring and management of abandoned, lost and discarded fishing gear and ghost fishing. Mar. Policy 60, 225–239. https://doi.org/10.1016/j.marpol.2015.06.016

Gochfeld, M., 1973. Effect of artefact pollution on the viability of seabird colonies on Long Island, New York. Environ. Pollut. 4, 1–6. https://doi.org/10.1016/0013-9327(73)90025-6

González-Fernández, D., Hanke, G., 2017. Toward a harmonized approach for monitoring of riverine floating macro litter inputs to the marine environment. Front. Mar. Sci. 4, 1–7. https://doi.org/10.3389/fmars.2017.00086

Good, T.P., June, J.A., Etnier, M.A., Broadhurst, G., 2010. Derelict fishing nets in Puget Sound and the

Northwest Straits: Patterns and threats to marine fauna. Mar. Pollut. Bull. 60, 39–50. https://doi.org/10.1016/j.marpolbul.2009.09.005

Good, T.P., June, J.A., Etnier, M.A., Broadhurst, G., 2009. Ghosts of the Salish Sea Threats to marine birds in puget sound and the northwest straits from derelict fishing gear. Mar. Ornithol. 37, 67–76.

Goodman, L.A., 2011. Comment: On respondent-driven sampling and snowball sampling in hard-to-reach populations and snowball sampling not in hard-to-reach populations. Sociol. Methodol. 41, 347–353. https://doi.org/10.1111/j.1467-9531.2011.01242.x

Grosse, A.M., Dijk, J.D., Holcomb, K.L., Maerz, J.C., 2009. Diamondback Terrapin Mortality in Crab Pots in a Georgia Tidal Marsh. Chelonian Conserv. Biol. 8, 98–100. https://doi.org/10.2744/ccb-0729.1

Gunn, B.R., Hardesty, B.D., Butler, J., 2010. Tackling ‘ghost nets ’: Local solutions to a global issue in northern Australia. Ecol. Manag. Restor. 11. https://doi.org/10.1111/j.1442-8903.2010.00525.x

Haldeman, T., Turner, J.W., 2009. Implementing a community- based social marketing program to increase recycling. Soc. Mar. Q. 15, 114–127. https://doi.org/10.1080/15245000903154618

Hart, A.G., Carpenter, W.S., Hlustik-Smith, E., Reed, M., Goodenough, A.E., 2018. Testing the potential of Twitter mining methods for data acquisition: Evaluating novel opportunities for ecological research in multiple taxa. Methods Ecol. Evol. 9, 2194–2205. https://doi.org/10.1111/2041-210X.13063

Hassan, R., Ahmad, R., Amirul, M., Adzhar, A., Izwan, M., Abdul, Z., Ayob, A., Zainudin, R., 2016. Notes on the Wild Tomistoma Populations in Western Sarawak , Malaysian Borneo 2016.

Hong, S., Lee, J., Jang, Y.C., Kim, Y.J., Kim, H.J., Han, D., Hong, S.H., Kang, D., Shim, W.J., 2013. Impacts of marine debris on wild animals in the coastal area of Korea. Mar. Pollut. Bull. 66, 117–124. https://doi.org/10.1016/j.marpolbul.2012.10.022

Iriarte, V., Marmontel, M., 2013. Insights on the use of dolphins (boto, Inia geoffrensis and tucuxi, Sotalia fluviatilis) for bait in the piracatinga (Calophysus macropterus) fishery in the western Brazilian Amazon. J. Cetacean Res. Manag. 13, 163–173.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science (80-.). 347, 768–771. https://doi.org/10.1126/science.1260352

Jensen, M., Limpus, C., Whiting, S., Guinea, M., Prince, R., Dethmers, K., Adnyana, I., Kennett, R., FitzSimmons, N., 2013. Defining olive ridley turtle Lepidochelys olivacea management units in Australia and assessing the potential impact of mortality in ghost nets. Endanger. Species Res. 21, 241–253. https://doi.org/10.3354/esr00521

Kappenman, K.M., Parker, B.L., 2007. Ghost Nets in the Columbia River: Methods for Locating and Removing Derelict Gill Nets in a Large River and an Assessment of Impact to White Sturgeon. North Am. J. Fish. Manag. 27, 804–809. https://doi.org/10.1577/m06-052.1

Kumar, S., Jha, P., Baier, K., Jha, R., Azzam, R., 2012. Pollution of Ganga River Due to Urbanization of Varanasi: Adverse Conditions Faced by the Slum Population. Environ. Urban. Asia 3, 343–352. https://doi.org/10.1177/0975425312473229

Lavers, J.L., Hodgson, J.C., Clarke, R.H., 2013. Prevalence and composition of marine debris in Brown Booby (Sula leucogaster) nests at Ashmore Reef. Mar. Pollut. Bull. 77, 320–324. https://doi.org/10.1016/j.marpolbul.2013.09.026

Lebreton, L., Andrady, A., 2019. Future scenarios of global plastic waste generation and disposal. Palgrave Commun. 5, 1–11. https://doi.org/10.1057/s41599-018-0212-7

Lebreton, L.C.M., Van Der Zwet, J., Damsteeg, J.W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world’s oceans. Nat. Commun. 8, 1–10. https://doi.org/10.1038/ncomms15611

Luqmani, A., Leach, M., Jesson, D., 2017. Factors behind sustainable business innovation: The case of a global carpet manufacturing company. Environ. Innov. Soc. Transitions 24, 94–105. https://doi.org/10.1016/j.eist.2016.10.007

Mansur, E.F., Smith, B.D., Mowgli, R.M., Diyan, M.A.A., 2008. Two incidents of fishing gear entanglement of Ganges River dolphins (Platanista gangetica gangetica) in waterways of the Sundarbans mangrove forest, Bangladesh. Aquat. Mamm. 34, 362–366. https://doi.org/10.1578/AM.34.3.2008.362

Matsuoka, T., Nakashima, O., Nagsawa, N., 2005. Review of Ghost-Fishing; Scientific Approaches to Evaluation and Solution. Fish. Sci. 71, 7–11.

Nahiduzzaman, M., Monirul Islam, M., Wahab, M.A., 2018. Impacts of fishing bans for conservation on hilsa fishers livelihoods: Challenges and Opportunities, in: Nishat, B., Mandal, S., Pangare, G. (Eds.), Conserving Ilish, Securing Livelihoods: Bangladesh-India Perspectives. Academic Foundation, New Delhi.

Nisanth, H.P., Kumar, B., 2019. Observations on the Entanglement of Plastic Debris in Seabirds of the Family Laridae Along Kerala Coast, India. Kerala J. Aquat. Biol. Fish. | 7, 115–119.

Omeyer, L.C.M., Doherty, P.D., Dolman, S., Enever, R., Reese, A., Tregenza, N., Williams, R., Godley, B.J., 2020. Assessing the Effects of Banana Pingers as a Bycatch Mitigation Device for Harbour Porpoises (Phocoena phocoena). Front. Mar. Sci. 7, 1–10. https://doi.org/10.3389/fmars.2020.00285

OSPAR Commission, 2020. OSPAR scoping study on best practices for the design and recycling of fishing gear as a means to reduce quantities of fishing gear found as marine litter in the North-East Atlantic.

Owens, K.A., Kamil, P.I., 2020. Adapting Coastal Collection Methods for River Assessment to Increase Data on Global Plastic Pollution: Examples From India and Indonesia. Front. Environ. Sci. 7, 1–11. https://doi.org/10.3389/fenvs.2019.00208

Parsons, E.C.M., Clark, J., Warham, J., Simmonds, M.P., 2010. The conservation of british cetaceans: A review of the threats and protection afforded to whales, dolphins, and porpoises in UK waters, part 1. J. Int. Wildl. Law Policy 13, 1–62. https://doi.org/10.1080/13880291003705145

Parton, K.J., Galloway, T.S., Godley, B.J., 2019. A global review of shark and ray entanglement in anthropogenic marine debris. Endanger. Species Res. 39, 173–190. https://doi.org/10.3354/esr00964

Quintana-Rizzo, E., 2014. Harpooning and entanglement of wild dolphins in the Pacific coast of Guatemala. Lat. Am. J. Aquat. Mamm. 9, 179–182.

Quirós, Y.B. De, Hartwick, M., Rotstein, D.S., Garner, M.M., Bogomolni, A., Greer, W., Niemeyer, M.E., Early, G., Wenzel, F., Moore, M., 2018. Discrimination between bycatch and other causes of cetacean and pinniped stranding. Dis. Aquat. Organ. 127, 83–95.

R Core Team, 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rahman, M.M., Ghosh, T., Salehin, M., Ghosh, A., Haque, A., Hossain, M.A., Das, S., Hazra, S., Islam, N., Sarker, M.H., R. J. Nicholls, Hutton, C.W., 2020. Ganges-Brahmaputra-Meghna Delta, Bangladesh and India: A Transnational Mega-Delta, in: Deltas in the Anthropocene. Springer International Publishing, pp. 23–51.

Richardson, K., Asmutis-Silvia, R., Drinkwin, J., Gilardi, K.V.K., Giskes, I., Jones, G., O'Brien, K., Pragnell-Raasch, H., Ludwig, L., Antonelis, K., Barco, S., Henry, A., Knowlton, A., Landry, S., Mattila, D., MacDonald, K., Moore, M., Morgan, J., Robbins, J., van der Hoop, J., Hogan, E., 2019a. Building evidence around ghost gear: Global trends and analysis for sustainable solutions at scale. Mar. Pollut. Bull. 138, 222–229. https://doi.org/10.1016/j.marpolbul.2018.11.031

Richardson, K., Hardesty, B.D., Wilcox, C., 2019b. Estimates of fishing gear loss rates at a global scale: A literature review and meta-analysis. Fish Fish. 20, 1218–1231. https://doi.org/10.1111/faf.12407

Rodríguez, B., Bécares, J., Rodríguez, A., Arcos, J.M., 2013. Incidence of entanglements with marine debris by northern gannets (Morus bassanus) in the non-breeding grounds. Mar. Pollut. Bull. 75, 259–263. https://doi.org/10.1016/j.marpolbul.2013.07.003

Santos, A.J.B., Bellini, C., Bortolon, L.F., Coluchi, R., 2012. Ghost nets haunt the olive ridley turtle (Lepidochelys olivacea) near the Brazilian Islands of Fernando de Noronha and Atol das Rocas. Herpetol. Rev. 43, 245–246.

Schmidt, C., Krauth, T., Wagner, S., 2017. Export of Plastic Debris by Rivers into the Sea. Environ. Sci. Technol. 51, 12246–12253. https://doi.org/10.1021/acs.est.7b02368

Senko, J., Nelms, S., Reavis, J., Witherington, B., Godley, B., Wallace, B., 2020. Understanding individual and population-level effects of plastic pollution on marine megafauna. Endanger. Species Res. 43, 234–252. https://doi.org/10.3354/esr01064

Sharma, B., Amarasinghe, U., Xueliang, C., de Condappa, D., Shah, T., Mukherji, A., Bharati, L., Ambili, G., Qureshi, A., Pant, D., Xenarios, S., Singh, R., Smakhtin, V., 2010. The indus and the ganges: River basins under extreme pressure. Water Int. 35, 493–521. https://doi.org/10.1080/02508060.2010.512996

Short, R., Gurung, R., Rowcliffe, M., Hill, N., Milner-Gulland, E.J., 2018. The use of mosquito nets in fisheries: A global perspective. PLoS One 13, 1–14. https://doi.org/10.1371/journal.pone.0191519

Singh, R., Singh, G.S., 2020. Integrated management of the Ganga River: An ecohydrological approach. Ecohydrol. Hydrobiol. 20, 153–174. https://doi.org/10.1016/j.ecohyd.2019.10.007

Sinha, Rajesh K, Sinha, R K, 2013. Diversity of Selective and Non-Selective Fishing Gears and Their Impact on Ganga Fishery in Bihar. Int. J. Bioassays 739–750.

Spirkovski, Z., Ilik-Boeva, D., Ritterbusch, D., Peveling, R., Pietrock, M., 2019. Ghost net removal in ancient Lake Ohrid: A pilot study. Fish. Res. 211, 46–50. https://doi.org/10.1016/j.fishres.2018.10.023

Stelfox, M., Bulling, M., Sweet, M., 2019. Untangling the origin of ghost gear within the Maldivian archipelago and its impact on olive ridley (Lepidochelys olivacea) populations. Endanger. Species Res. https://doi.org/10.3354/ESR00990

Taylor, G.A., 1996. Beach patrol scheme: Seabirds found dead on New Zealand beaches, 1997-1999. Notornis 43, 187–196.

Thompson, M.H., 2008. Fostering sustainable behaviours in community-based co-managed fisheries. Mar. Policy 32, 413–420. https://doi.org/10.1016/j.marpol.2007.08.005

Valderrama Ballesteros, L., Matthews, J.L., Hoeksema, B.W., 2018. Pollution and coral damage caused by derelict fishing gear on coral reefs around Koh Tao, Gulf of Thailand. Mar. Pollut. Bull. 135, 1107–1116. https://doi.org/10.1016/j.marpolbul.2018.08.033

Votier, S.C., Archibald, K., Morgan, G., Morgan, L., 2011. The use of plastic debris as nesting material by a colonial seabird and associated entanglement mortality. Mar. Pollut. Bull. 62, 168–172. https://doi.org/10.1016/j.marpolbul.2010.11.009

Wilcox, C., Hardesty, B.D., Sharples, R., Griffin, D.A., Lawson, T.J., Gunn, R., 2013. Ghostnet impacts on globally threatened turtles, a spatial risk analysis for northern Australia. Conserv. Lett. 6, 247–254. https://doi.org/10.1111/conl.12001

Windsor, F.M., Durance, I., Horton, A.A., Thompson, R.C., Tyler, C.R., Ormerod, S.J., 2019. A catchment-scale perspective of plastic pollution. Glob. Chang. Biol. https://doi.org/10.1111/gcb.14572