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# Estimates of fishing gear loss rates at a global scale: A literature review and meta-analysis

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## Abstract

Abandoned, lost or otherwise discarded fishing gear (ALDFG) represents a significant, yet ultimately unknown amount of global marine debris, with serious environmental and socioeconomic impacts. This study reviews 68 publications from 1975 to 2017 that contain quantitative information about fishing gear losses. Gear loss estimates reported by the studies ranged widely, with all net studies reviewed reporting annual gear loss rates from 0% to 79.8%, all trap studies reporting gear loss rates from 0% to 88%, and all line studies reporting gear loss rates from 0.1% to 79.2%. Information obtained from this review was used to perform a meta-analysis that provides the first synthetic, statistically robust estimates of global fishing gear losses. The meta-analysis estimates global fishing gear losses for different major gear types. We estimate that 5.7% of all fishing nets, 8.6% of all traps, and 29% of all lines are lost around the world each year. Furthermore, we identified key gear characteristics, operational aspects and environmental contexts that influence gear loss. These estimates can be used to support sustainable fisheries development through informing risk assessments for fisheries and monitoring and assessment efforts to reduce gear losses.

KEYWORDS
abandoned, lost or otherwise discarded fishing gear (ALDFG), derelict fishing gear, gear loss rates, marine debris, marine litter, sustainable fisheries

## 1 | INTRODUCTION

Sustainable fisheries provide food security, are important for income and livelihoods and promote economic growth. With fish estimated to provide nearly 20% of the animal protein consumed by humans around the world, ensuring global seafood security becomes increasingly important as the world's population continues to grow (FAO, 2018). Abandoned, lost or otherwise discarded fishing gear (ALDFG) is a growing issue of concern for sustainable fisheries due to its subsequent effects on target and non-target species, habitats and human users in marine systems. Fisheries impacts from ALDFG include damage to and loss of fishing gear and catch, and hazards to navigation and safety at sea (Gilman, 2015; Macfadyen, Huntington, & Cappell, 2009; Scheld, Bilkovic, & Havens, 2016). These impacts can exacerbate existing pressures on fishers experiencing diminishing economic returns, as fish stocks are depleted and illegal fishing is on the rise (Watson & Tidd, 2018).

As a significant source of litter in the ocean, ALDFG is a key and distinct part of the global marine debris issue (Macfadyen et al., 2009), with disproportionately higher impacts to marine wildlife compared to other types of debris through its potential to entangle, ensnare or be ingested (Gilardi et al., 2010; Laist & Wray, 1995;

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Wilcox, Mallos, Leonard, Rodriguez, & Hardesty, 2016). This gear can also damage marine habitats (Lewis, Slade, Maxwell, & Matthews, 2009; NOAA, 2016), and recovery and clean-up are expensive, complicated and time intensive (Good, June, Etnier, & Broadhurst, 2010; NOAA, 2015; Uhrin, 2016).

Given the adverse socioeconomic and environmental impacts from ALDFG, United Nations General Assembly and United Nations Environment Assembly resolutions have encouraged States to reduce amounts of and impacts from ALDFG (Gilman, Chopin, Suuronen, & Kuemlangan, 2016; UNEA, 2014, 2016, 2017). The Food and Agriculture Organization of the United Nations (FAO)'s Committee on Fisheries, the FAO Code of Conduct for Responsible Fisheries and FAO's Voluntary Guidelines for the Marking of Fishing Gear have also highlighted the importance of fishing gear marking and ALDFG reporting and recovery (Food & Agriculture Organization of the United Nations, 2019; Gilman et al., 2016). Under the United Nations 2030 Agenda for Sustainable Development, which works to promote global social, economic and environmental development through 17 goals and 169 targets, goal 14.1 importantly includes a commitment by all member countries to significantly reduce marine pollution of all kinds, including marine debris, by 2025 (UNSDG, 2018).

While significant progress has been made in quantifying amounts of land-based sources of marine debris, progress has been considerably more limited for sea-based sources including ALDFG (Derraik, 2002; Jambeck et al., 2015; Lebreton et al., 2018; Sheavly & Register, 2007). To date, no statistically rigorous estimates have been provided for fishing gear losses on a global scale, largely due to challenges arising from differing data types, fisheries and geographic areas represented by the variety of ALDFG studies.

Because fishing gears are specific to target species and vary across geographic areas, the studies which quantify fishing gear losses that have been undertaken since the 1970s have been limited to specific gear types and/or geographic areas (Al-Masroori, Al-Oufi, & McShane, 2009; Ayaz, Ünal, Acarli, & Altinagac, 2010; Bilkovic, Havens, Stanhope, & Angstadt, 2014; Breen, 1987; Hareide et al., 2005; Kim, Park, & Lee, 2014; Maufroy, Chassot, Joo, & Kaplan, 2015; Shainee & Leira, 2011; Uhrin, 2016; Webber & Parker, 2012). Generally, studies of gear loss from the literature that are among the more comprehensive in geographic scope were also conducted a decade or more ago and no longer comprehensively represent information about gear losses today (Breen, 1990; Brown & Macfadyen, 2007; Chopin, Inoue, Matsushita, Arimoto, & Wray, 1995; Macfadyen et al., 2009; MacMullen, 2002; NRC, 1990; O'Hara & Ludicello, 1987).

We summarize fishing gear losses from 1975 to 2017 to provide the first statistically rigorous, quantitative gear loss estimates for major gear types around the world. We included nets, traps, lines and fish aggregating devices in our analysis. We also identify variables that affect loss rates, such as the type of fishing gear used, its configuration and operations, and environmental variables such as benthic habitat types. Data gaps in the literature and priority areas for future research are also highlighted. The global estimates of fishing gear losses and associated trends summarized here can be used as baselines by stakeholders such as fisheries managers, government and intergovernmental agencies, non-governmental organizations and researchers to inform sustainable fisheries development. The information can further be applied to risk assessments for fisheries and monitoring and assessment of interventions aimed at decreasing ALDFG.

## 2 | METHODS

### 2.1 | Literature review

A literature search was undertaken using Web of Science, Google Scholar and Google to identify published works about fishing gear losses from 1950 to May 2018. By reviewing literature cited in the works identified, we were able to include grey literature that would otherwise have been missed (e.g. technical reports). We used FAO's International Standard Statistical Classification of Fishing Gear

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(ISSCFG) to identify and classify all fishing gear types (Nédélec & Prado, 1990). Major gear types we considered included nets, traps, lines and fish aggregating devices. If a paper referenced a quantitative estimate of lost gear from another study, every attempt was made to recover the original study referenced as the primary source for the gear loss estimation.

Literature was only included if it contained information about amounts of fishing gear lost over a specific time interval. Search terms were designed to capture commonly used terminology such as "abandoned, lost or otherwise discarded fishing gear (ALDFG)," "derelict fishing gear (DFG)," "ghost gear" and "ghost fishing." These terms and keywords were combined with words about quantitative estimations such as "rate," "amount," "estimat*" and "los*." Search terms included combinations of quantitative terms with: "fish*," "gear," "net," "gillnet," "seine," "trammel," "trawl," "fish aggregating device," "FAD*," "trap," "pot," "longline," "derelict," "abandoned," "discarded," "ALDFG," "DFG" and "ghost."

Within nets, we reviewed studies that reported data on gillnets and entangling nets (including set, drifting and fixed gillnets and trammel nets), purse seine nets, seine nets (including beach and boat seine), trawl nets (including bottom otter trawls, midwater otter trawls and midwater pair trawls), cast and other miscellaneous nets. Miscellaneous nets included dip nets, as well as a variety of unidentified nets and reef nets, depending on the study (Matthews & Glazer, 2010; NRC, 1990).

Within traps, we reviewed studies that reported data on pots and traps, fyke and pound nets. Within lines, we reviewed studies that reported data on handlines and pole-lines (both hand operated and mechanized), longlines (set and drifting) and trolling lines. We also considered fish aggregating devices, though with only three studies (Macfadyen et al., 2009; Maufroy et al., 2015; Shainee & Leira, 2011) there was little analysis we were able to undertake. For a full summary of gear types included in the studies, we reviewed see Table S1. For more information about these individual gear types see Figure S1.

## 2.2 | Summary statistics

Information retrieved and summarized from the studies reviewed included: the amount of gear lost, scale of gear loss (e.g. across an entire fleet or per vessel), time frame for gear loss, geography, target species, fishing effort, gear characteristics, depth ranges, benthic habitat and causes of gear loss, including the type of gear conflict in instances where gear conflict was reported. When fishing depths and benthic habitat types were unavailable from the studies, this information was determined by the target species and gear type reported by each study, and retrieved from the online databases FishBase (Froese & Pauly, 2019) and SeaLifeBase (Palomares, Pauly, & Editors., 2019).

If information about the scale of loss was limited to one variable, such as per vessel or across an entire fleet, when possible this information was generalized to include more scales, such as by dividing the fleet level of loss by total vessels in the fleet to represent vessel-level loss, or by multiplying the vessel-level loss by the total vessels in the fleet to represent fleet-level loss. When total gear used was reported, we divided the amount of gear lost by the amount of gear used to obtain percentages of loss. Alternatively, we multiplied reported percentages of gear lost by reported total gear used to obtain numbers, lengths or weights of gear lost. Time frames for gear loss were similarly generalized to annual levels of gear loss, if reported only by fishing season, day or set for comparison purposes.

To identify variables that might affect loss rates, each type of lost gear was also assigned to categories based on whether the gear was attended, whether it actively moved through the water, if it was attached to a fixed point or fishing vessel, and if the gear touched the bottom, as well as the corresponding bottom type (hard, soft, mixed or unknown).

## 2.3 | Statistical analysis

We took a meta-analysis approach to the data, treating the reported loss estimates from each study as a replicate in our dataset. Meta-analysis approaches would typically incorporate a measure of uncertainty of the estimates into the analysis, down-weighting records with large uncertainty and up-weighting those with relatively smaller uncertainty. However, very few of the gear loss studies we found reported standard errors or other measures of uncertainty.

Since direct measures of uncertainty were often unavailable, we used the number of vessels and/or fishers in the study as a measure of uncertainty, assuming that the more replication that occurred in an individual study the smaller the uncertainty there should be in their estimates. Some studies, however, did not include information about the number of vessels and/or fishers surveyed. To include estimates from these studies, we assigned them the median number of replicates from the studies that did provide a sample size. The level of replication in each study was used as a regression weight for that observation in the analysis.

We used the data obtained from the literature to develop statistical models to analyse two measures of gear loss rates: (a) the percentage (proportion) of gear lost and (b) the number of units of gear lost per vessel per year (count). These analyses were carried out across three major gear classes: nets, traps and lines. The percentage of gear lost is unitless, and this measure was the most common metric available across the studies. For analysis purposes, we converted the percentages reported by studies to proportions.

We used generalized additive models (GAMs) to analyse the data, as implemented in the mgcv package (Wood, 2017) in the R statistical language (R Core Team, 2017). We analysed the proportion data by using a beta distribution to represent the likelihood of gear loss (Wood, Pya, & Säfken, 2016), and modelled the data based on the expectation, with the second term in the beta distribution fitted with no covariates. We analysed the number of units of gear lost data by treating it as a count, and adopted a Tweedie distribution for the likelihood as it allows flexible modelling of count data, which

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typically contain outliers that are difficult to fit otherwise (Wood et al., 2016).

For the analyses of the two metrics of loss (proportion, number of units of gear) across the three major gear types (nets, traps, lines), we posed a number of possible statistical models that included a measure of loss as the response variable, the study sizes as the regression weights, and possible driving variables that could affect loss rates. We used Akaike's Information Criterion (AIC) (Burnham & Anderson, 2003) to select the best model among these candidates for each combination of loss and gear type metric. The AIC score of a model measures the quality of its fit to the data, adjusted for the complexity of the model to allow for comparison of different models for the same dataset.

The use of AIC requires that the models under comparison be fitted to the exact same dataset. Given this requirement, the most complex model under consideration will define the observations that can be included in the analysis, as each possible explanatory variable must have a value for every observation. While it would be ideal to include a wide range of driving variables in the analysis of each loss—gear type metric dataset, the variation in the studies means that many of the necessary observations are missing. Thus, the models we explored for each of the loss— gear type metric analyses varied slightly, depending on the available data.

The data available for nets supported analyses for the proportion of loss with disaggregated gear types (*N* = 279 observations) and the proportion of loss with gear, operational and benthic habitat characteristics (*N* = 172 observations), as well as analysis of the number of units of gear lost per vessel per year with benthic habitat characteristics (*N* = 64 observations). Data on the number of units of gear lost were only available for gillnets and trammel nets, and we were unable to examine the effect of other net gear types for this loss metric (Table S4).

The data available for traps supported analyses for both the proportion of gear loss with disaggregated gear type and benthic habitat characteristics (*N* = 202 observations) and number of units of gear lost per vessel per year with benthic habitat and depth characteristics (*N* = 24 observations). While we were able to explore the effects of bottom type on numbers of units of pot and trap losses per vessel per year, we were not able to explore these effects on fyke and pound nets due to only one study in 1990 reporting losses for these gear types (NRC, 1990).

The data available for lines only supported analysis for the proportion of gear loss (*N* = 92 observations). Due to the limited number of line gear loss studies and detail provided in those studies, we could not incorporate gear, operational, benthic habitat or depth characteristics. With only three studies containing quantitative information about gear loss from fish aggregating devices, not enough information was available to undertake a statistical analysis for this gear type.

After identifying the best model for each loss—gear type combination, we used that model to understand the driving variables for loss. We then predicted the global gear loss rates standardized to the year 2017 and included a confidence interval based on the standard errors of the terms in our best fitted model for each metric.

## 3 | RESULTS

### 3.1 | Literature review

We identified 68 publications that met our criteria for containing quantitative information about fishing gear loss over time. These included 52 primary literature and 16 technical reports, from 1975 to 2017 (Table S1). Publications focusing on gear loss for traps were most numerous (*N* = 49 publications), followed by nets (*N* = 20 publications), lines (*N* = 8 publications) and fish aggregating devices (*N* = 3 publications). Some studies included information about more than one gear type (NRC, 1990; Yıldız & Karakulak, 2016).

The publications spanned 32 countries and territories across the Atlantic, Indian, Pacific and Southern Oceans and the Baltic, Caribbean and Mediterranean Seas (Figure 1). Most of the information about gear loss was from North America, with the bulk of these studies from the USA (Figure 1, Figure S2). The number of studies available for review and diversity of geographic areas represented increased over time, with almost two-thirds of the studies undertaken since 2000 (61%). Prior to 2000, almost all of the studies reviewed were from the United States and Canada (94%). While more than a third of the studies from 2000 to 2017 were still from the United States (38%), almost a third were also from Europe and the Middle East (28%), with the final third (34%) representing a wide range of additional individual studies from the Caribbean, the Indian Ocean, Antarctica, Australia, Mexico, Indonesia and South Korea (Figure 1).

Most studies reported gear loss annually (75%), while some reported gear loss seasonally (12%), monthly, daily or nightly (7%) or by set (6%). Studies reported gear loss mostly in percentages (75%) and numbers of units of gear lost (18%), as well as in lengths (6%) and weights (1%) (Figures 2 – 4). These differences in gear loss reporting complicate analysis as conversion is then required to compare across equivalent categories, fisheries and geographic areas.

When we investigated target species, depths and benthic habitat (bottom types) across the studies reviewed, a large and diverse range of target species, depths and bottom types were retrieved for the net and line gear types. This is likely a reflection of the larger number of sub-gear types available for each of these categories, which are designed to fish for specific target species, with corresponding ranges of depths and bottom types. For example, sub-gear types for nets included gillnets and entangling nets, trawl nets, purse seine, seine and miscellaneous nets. By contrast, the bulk of literature reviewed for traps, which only had three sub-gear types (pots and traps, and fyke and pound nets) targeted mostly crab and lobster in coastal regions, with mostly rocky reef bottom types for lobster and soft bottom types for crabs (Figure 3, 75%).

While the focus of this meta-analysis is the quantification of global fishing gear loss rates, we were also interested in the causes for gear loss reported by the studies reviewed. Fishing gear loss due to bad weather was the most commonly reported cause of gear loss

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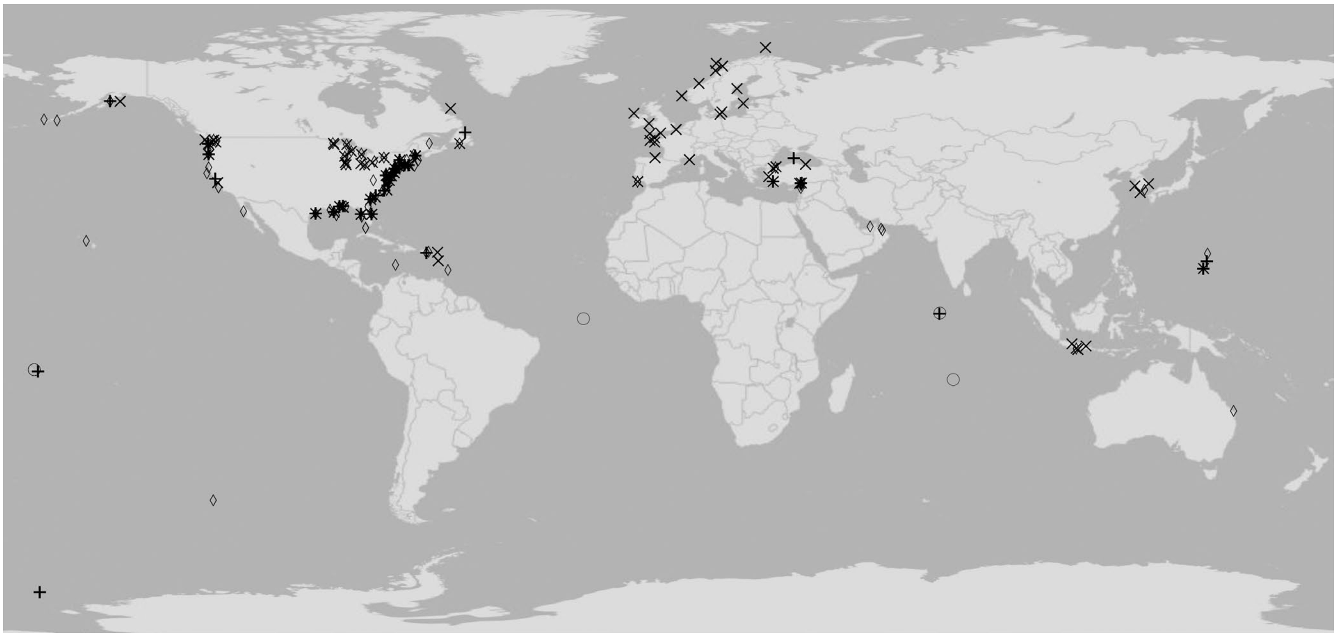

**FIGURE 1** Geographic areas for studies included in our analyses. Studies focusing on net fisheries are indicated by X; traps: ◊, lines: ○, fish aggregating devices (FADs): +

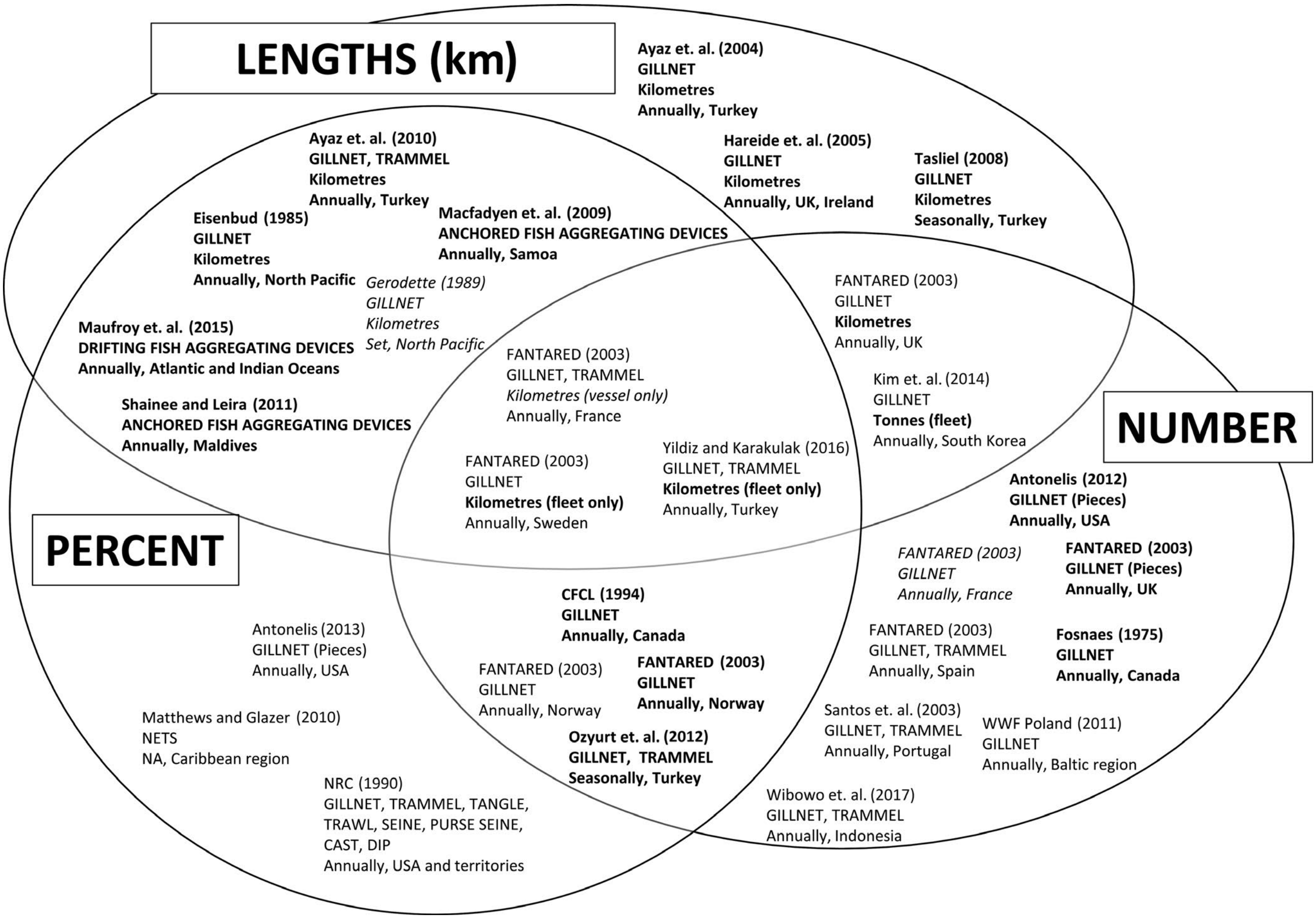

**FIGURE 2** Studies reporting on abandoned, lost or discarded nets. Each record includes, in order: the study, net type (uppercase letters), length type of net loss (if available), time frame for net loss (annually, seasonally, daily or by set) and location by country or region. Bold records represent net loss across an entire fleet, italicized records represent net loss by vessel, and non-bold, non-italicized records represent net loss information at both fleet and vessel scales

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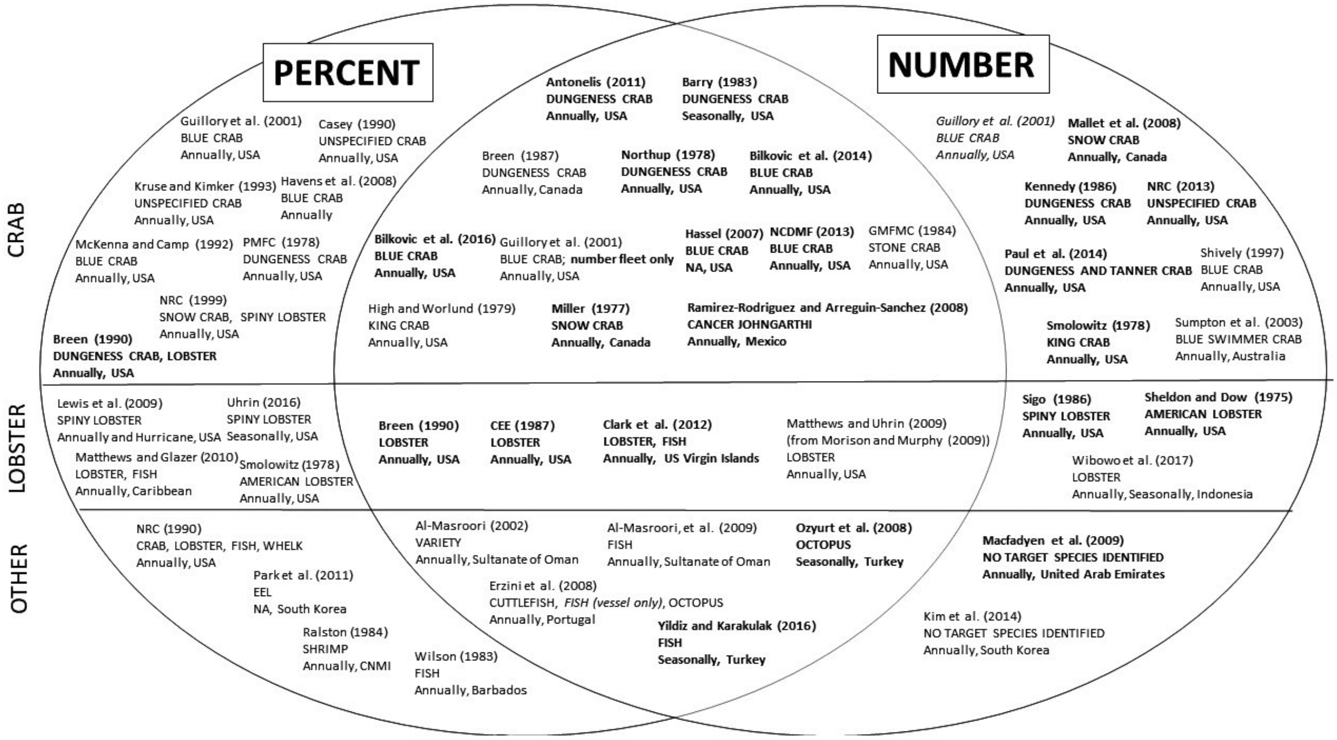

**FIGURE 3** Studies reporting on abandoned, lost or discarded traps. Each record includes, in order, the study, target fishery (uppercase letters), time frame for gear loss (annually, seasonally, daily or by set) and location by country or region. Bold records represent trap loss across an entire fleet, italicized records represent trap loss by vessel, and non-bold, non-italicized records represent trap loss information at both fleet and vessel scales. Scientific names of species mentioned can be found in Appendix S1

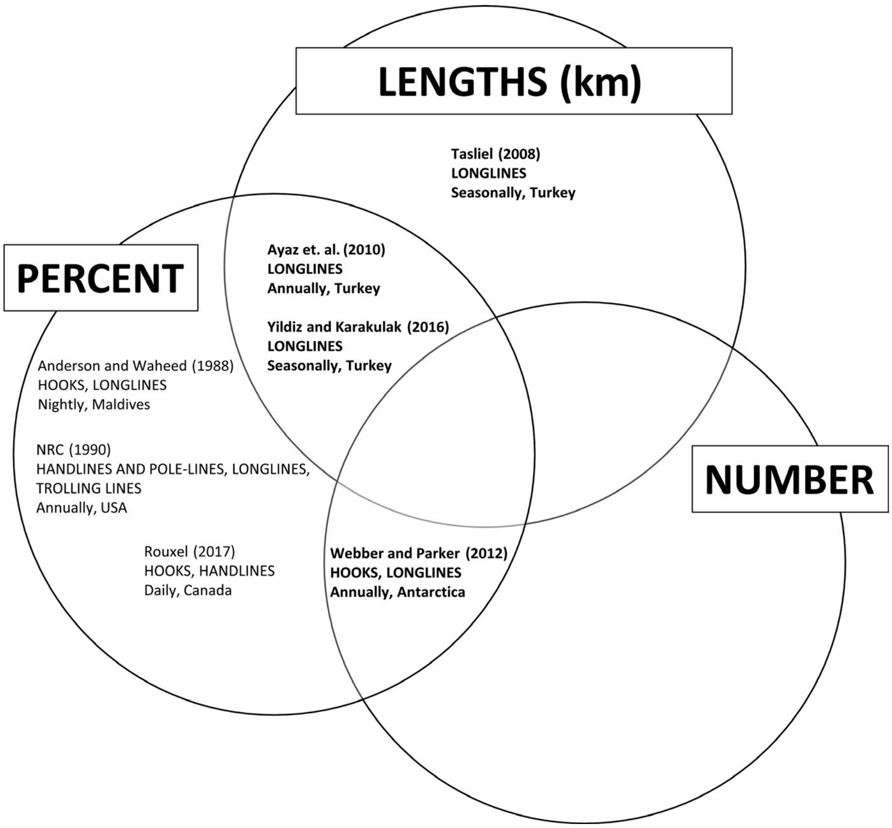

**FIGURE 4** Studies reporting on abandoned, lost or discarded lines. Each record, in order, includes the study, line type (uppercase letters), length of line lost (if available), time frame for line loss (annually, seasonally, daily or by set) and location by country or region. Bold records represent lines lost across an entire fleet, italicized records represent lines lost by vessel, and non-bold, non-italicized records represent line loss information at both fleet and vessel scales

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across all studies (69%). Gear conflict was the second most common cause of gear loss (57%), with 22% of all studies (regardless of gear type used by fishers) reporting loss due to conflict between towed and static gears. Ensnarement of fishing gear on bottom obstructions was the third most common cause for gear loss reported across all studies (31%).

## 3.2 | Meta-analyses

### 3.2.1 | Analysis of net loss metrics

Gear loss rates reported by the studies reviewed ranged from 0% to 79.8% (Figure 5), and number of units of gear lost per vessel ranged from 0 to 800 (Figure S3).

The models for proportion and number of units of gear lost revealed that there was an overall increasing trend in gear losses with time (Figure 5; Figure S3; Tables S2–S4). The outliers to this trend are seen in the high 80% loss rate reported for a variety of nets in the Caribbean (Figure 5; Matthews & Glazer, 2010), as well as a study in Indonesia which reported annual losses of 800 set gillnets per vessel for an inshore lobster fishery (Figure S3; Wibowo et al., 2017).

There was also a greater proportion and number of units of gear lost per vessel when nets touched the bottom (Tables S2–S4). The influence of specific bottom types was different between the proportion and number of units of gear lost per vessel models, however, using “hard bottom type” as the intercept term. Soft, mixed and unknown bottom types had a greater proportion of net loss, while the number of units of gear lost per vessel was lower with these same bottom types (Tables S2–S4).

Proportions of gear losses also differed significantly across all net types, with the exception of trawl nets which were not statistically significant (Table S2). Gillnets and trammel nets had the highest proportion of net loss, followed by purse seine nets, seine nets and miscellaneous nets (Table S2).

When examining gear characteristics that differ among gear types, proportion of loss was lower when nets were not attached to a vessel and when nets were attached to a fixed point (Tables S2 and S3). Attended nets and active nets had lower proportions of gear loss compared to unattended nets and passive nets (Table S3).

### 3.2.2 | Predictions of percentages of net losses and numbers of nets lost annually

Based on the fitted regression model for the proportion of loss by gear type (Table S2), we estimated loss rates for the year 2017 assuming the median study size for each gear type in the context in which it is used (Table 1). Purse seine, seine and trawl net losses are conservatively reported as fragments of nets lost, as opposed to whole net loss. Whole net loss is rare for these gear types while the incidence of net tear offs is more common.

Our regression for the proportion of nets lost revealed an average percentage of overall net loss of 5.7%. More specific net losses were 5.8% for gillnets and entangling nets, 1.2% for miscellaneous nets (includes mostly dip nets as well as unidentified and reef nets), 6.6% for purse seine net fragments, 2.3% for seine net fragments and 12% for trawl net fragments (Table 1). Proportions of net losses are also differentiated for different bottom types (hard, soft, mixed and unknown) for nets that touch the bottom (Table 1).

Our regression for the number of units of gear lost per vessel annually predicted that an average of 26 units of net gear were lost annually per vessel (Table S5). An average of 47.4 gillnets and entangling nets were lost annually per vessel, which was comprised

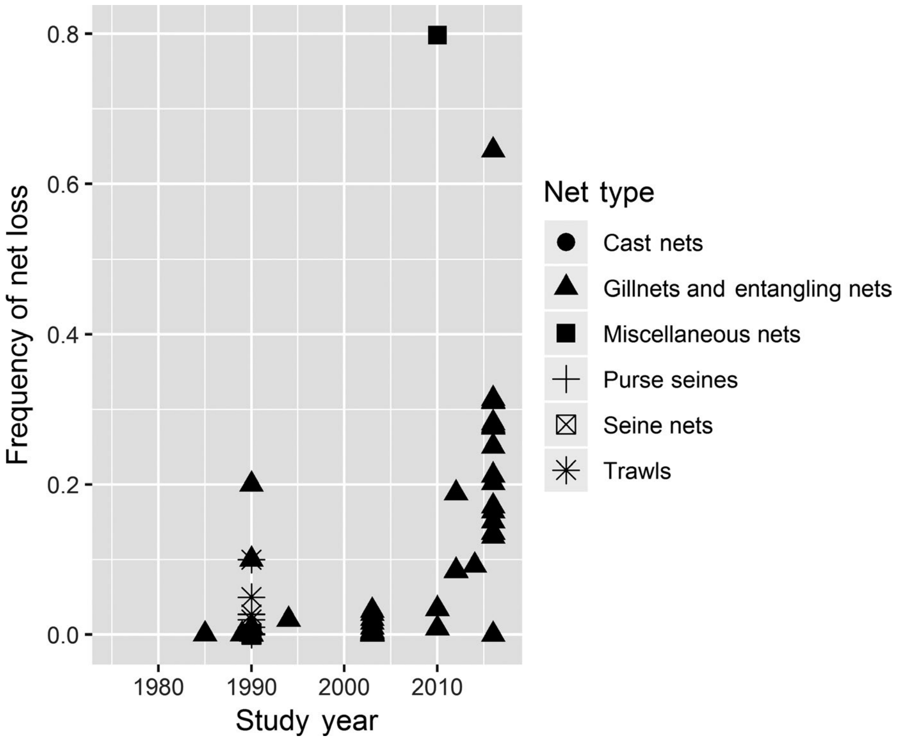

**FIGURE 5** Frequency of net loss by study year

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**TABLE 1** Average proportion of nets lost globally, for gillnets and entangling nets, miscellaneous, purse seine, seine and trawl nets. Average lower and upper 95% confidence intervals (CIs) are presented. Purse seine, seine and trawl net losses are conservatively reported as fragments of nets lost, as opposed to whole net loss. Average proportion of net loss predictions for set and fixed gillnets and bottom trawls on hard, soft, mixed and unknown bottom substrates are presented in italics. Major gear types are presented in bold, with corresponding sub-gear types and bottom types below

| Net type | Average proportion of net loss | Lower 95% CI | Upper 95% CI |
|---|---|---|---|
| **Gillnets and entangling nets** | 0.058 | 0.050 | 0.065 |
| Drifting gillnets | 0.031 | 0.027 | 0.035 |
| Set and fixed gillnets | 0.084 | 0.073 | 0.095 |
| *Hard bottom* | 0.027 | 0.021 | 0.033 |
| *Soft bottom* | 0.072 | 0.062 | 0.083 |
| *Mixed bottom* | 0.049 | 0.042 | 0.057 |
| *Bottom type unknown* | 0.19 | 0.17 | 0.21 |
| **Miscellaneous Nets** | 0.012 | 0.008 | 0.016 |
| **Purse Seines Nets** (net fragments) | 0.066 | 0.059 | 0.073 |
| **Seine Nets** (net fragments) | 0.023 | 0.019 | 0.028 |
| **Trawl Nets** (net fragments) | 0.12 | 0.11 | 0.14 |
| Midwater trawls | 0.070 | 0.058 | 0.082 |
| Bottom trawls | 0.18 | 0.16 | 0.19 |
| *Soft bottom* | 0.10 | 0.094 | 0.11 |
| *Bottom type unknown* | 0.26 | 0.24 | 0.28 |
| **All net types** | 0.057 | 0.050 | 0.064 |

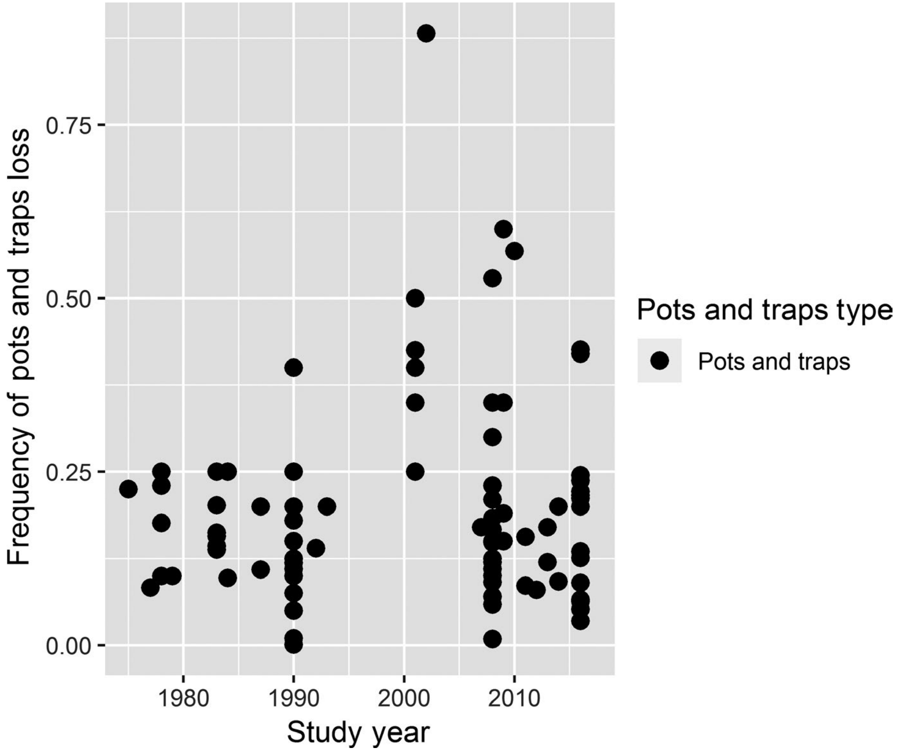
of an average of 6.2 drifting gillnets and 88.56 set or fixed gillnets. More than three and a half miscellaneous nets were lost annually per vessel (includes mostly dip nets as well as unidentified nets and reef nets), 51.49 purse seine net fragments/pieces were lost annually per vessel, 6.88 seine net fragments/pieces were lost annually per vessel and 20.94 trawl net fragments/pieces were lost annually per vessel (Table S5).

### 3.2.3 | Analysis of trap loss metrics

Gear loss rates reported by the studies reviewed ranged from 0% to 88% (Figure 6), and number of units of gear lost per vessel ranged from 6 to 400 (Figure S4).

Similar to the nets analyses, models for the proportion of gear loss and number of units of gear lost per vessel annually revealed

**FIGURE 6** Frequency of pots and traps loss by study year



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| Trap type | Average proportion of trap loss | Lower 95% CI | Upper 95% CI |
|---|---|---|---|
| **Pots and traps** | 0.19 | 0.18 | 0.20 |
| *Hard bottom* | 0.25 | 0.24 | 0.26 |
| *Soft bottom* | 0.18 | 0.18 | 0.19 |
| *Mixed bottom* | 0.22 | 0.21 | 0.22 |
| *Bottom type unknown* | 0.11 | 0.11 | 0.12 |
| *Fyke nets* | 0.041 | 0.038 | 0.045 |
| *Hard bottom* | 0.059 | 0.055 | 0.064 |
| *Bottom type unknown* | 0.024 | 0.022 | 0.025 |
| **Pound nets** | 0.026 | 0.024 | 0.028 |
| **All traps** | 0.086 | 0.082 | 0.089 |

**TABLE 2** Average proportion of traps lost globally, for pots and traps, fyke and pound nets. Average lower and upper 95% confidence intervals (CIs) are presented. The average proportion of trap loss predictions for pots and traps and fyke nets on hard, soft, mixed and unknown bottom substrates is presented in italics. Major gear types are presented in bold, with corresponding bottom types below

that there is a greater proportion and number of units of gear lost through time, with especially high (88%) loss rates for fish traps reported by one study (Figure 6; Figure S4; Tables S6 and S7; Al-Masroori, 2002). In contrast to the estimates for nets lost, there was a lower proportion of traps lost and more units of pots and traps lost per vessel for traps fishing over soft, mixed and unknown bottom types, in comparison with hard bottom types (Tables S6 and S7). Loss proportions were highest for pots and traps, followed by pound nets and fyke nets (Table S6). Numbers of units of gear lost for pots and traps increased with depth (Table S7).

### 3.2.4 | Prediction of percentages of trap losses and numbers of traps lost annually

Our regression model for the proportion of trap losses estimates an average overall loss of 8.6% across the gear types in this category. Loss percentages by gear type are estimated to be 19% for all pots and traps, 4.1% for fyke nets and 2.6% for pound nets (Table 2). We estimate higher loss proportions on hard bottoms, across all gear types.

Our regression model for the number of units of gear lost per vessel per year predicted the loss of 259.8 units of pots and traps lost annually per vessel (Table S8).

### 3.2.5 | Analysis of line loss metrics

Gear loss rates reported by the studies reviewed ranged from 0.1% to 79.2% (Figure 7). Similar to nets and traps, there is a greater frequency of hook and line losses with time (Figure 7; Table S8). The proportion of gear loss differed significantly between gear types. Proportions of gear losses for pole-lines were the highest, followed by handlines, trolling lines, longlines and hooks from longlines (Table S9).

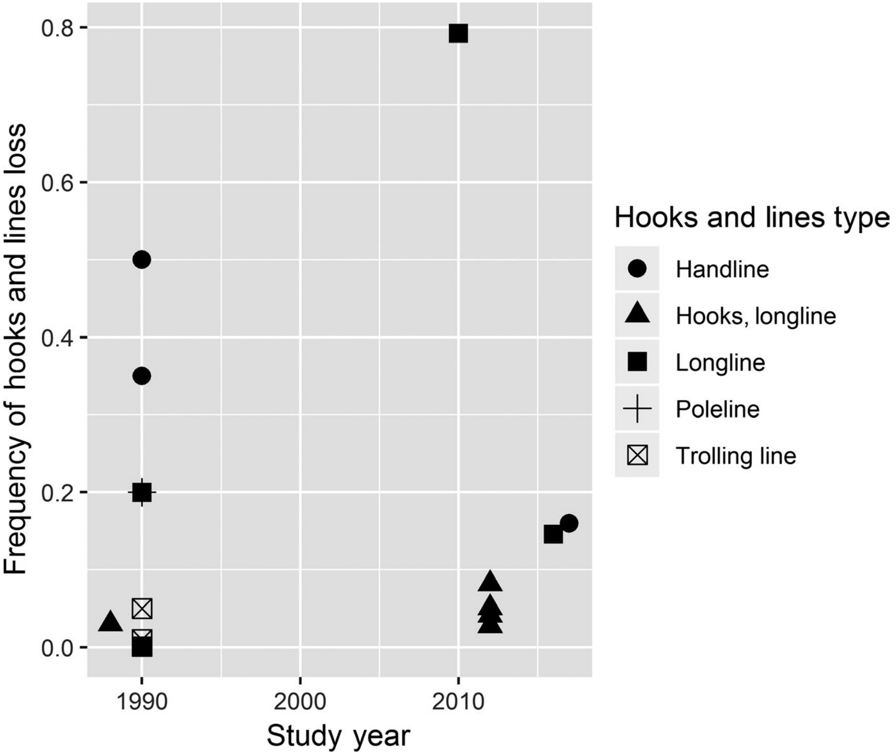

**FIGURE 7** Frequency of hooks and lines loss by study year

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### 3.2.6 | Predictions of percentages of line losses

Our regression for the percentage of gear loss for the line category predicted an overall loss of 29%. Predicted percentages of gear loss across the subcategories were 23% for handlines, 65% for pole-lines, 20% for longlines including 17% loss for hooks from longlines and 22% for trolling lines (Table 3).

### 3.2.7 | Fish Aggregating Device (FAD) losses

While we were unable to undertake a statistical analysis for this gear type, gear loss summary statistics are provided from the studies reviewed. One study recovered for drifting FADs used FAD GPS tracking information from French purse seine vessels to report a conservative 9.9% gear loss estimate, or 1,500 FADs lost in the Atlantic and Indian Oceans each year (Maufroy et al., 2015). Average annual loss rates of 82% and 79% for anchored FADs in the Maldives and Samoa, respectively, were determined from the other two studies reviewed (Macfadyen et al., 2009; Shainee & Leira, 2011).

## 4 | DISCUSSION

### 4.1 | Key findings

This literature review and meta-analysis based on published literature from 1975 to 2017 provides the first statistically rigorous estimates of global fishing gear losses across a range of nets, traps and line types under varying operational and environmental conditions. We predicted a 6% overall net loss rate for the year 2017 (range of 0%–79.8% reported by all studies); a 9% overall trap loss rate (range of 0%–88% reported by all studies) representing a 19% overall pots and traps loss rate, 3% overall pound net loss rate and 4% overall fyke nets loss rate; and a 29% overall line loss rate (range of 0.1%–79.2% reported by all studies). Because these estimates are global, it is relevant to recognize that regional variation may exist. Furthermore, we acknowledge the studies geographically over-represent North America and Europe from commercial fisheries.

**TABLE 3** Average proportion of lines lost globally, for handlines, pole-lines, longlines and hooks from longlines and trolling lines. Average lower and upper 95% confidence intervals (CIs) are presented

| Line types | Average proportion of lines lost | Lower 95% CI | Upper 95% CI |
|---|---|---|---|
| **Handlines** | 0.23 | 0.22 | 0.24 |
| **Pole-lines** | 0.65 | 0.62 | 0.69 |
| **Longlines** | 0.20 | 0.19 | 0.22 |
| Hooks, longlines | 0.17 | 0.16 | 0.18 |
| **Trolling lines** | 0.22 | 0.20 | 0.23 |
| **All line types** | 0.29 | 0.28 | 0.31 |

### 4.2 | The findings in context and additional considerations

While the numbers are summary statistics, it is important to consider the detail behind them, both in what they imply and in how they arise. For example, while line losses are high, these losses are likely comprised of a mix of entire gears and fragments due to breakage. In contrast, while trap and net losses are lower, in the case of pot gear or gillnets, these losses are likely comprised of entire gears.

It is also helpful to have a basic understanding of the application of the meta-analysis approach, which is the general term for a study of studies. Meta-analyses evolved from the literature on medical trials, with typically highly prescribed and nearly identical methods across studies that are underpinned by well developed conceptual frameworks (Garg, Hackam, & Tonelli, 2008; Gurevitch, Koricheva, Nakagawa, & Stewart, 2018). The studies of fishing gear losses that we compiled are far more variable in methods, data collected, analysis and reporting structure, and even purpose than is typical in the medical literature. Given the strong variability across studies and lack of uncertainty measures provided, standard meta-analysis methods are not particularly well adapted to this study. While we were able to capture some uncertainty in the estimates by incorporating sample sizes as regression weights in our analyses, the samples sizes remain only a proxy for uncertainty and are unlikely to capture the full uncertainty.

### 4.3 | Geographic representation

These estimates can be particularly useful as baseline estimates for under-represented gear types and geographic areas where little to no information about amounts of ALDFG exist. These include data gaps around amounts of gear loss in Africa, Asia and South America, and for lines and purse seine, seine and trawl nets more generally.

In contrast, significant work has been undertaken around fishing gear loss estimates in North America and Europe for gillnets, trammel nets and traps and in the Atlantic and Indian Oceans for drifting FADs (Figure 1). In countries and regions where more extensive work has already occurred to estimate fishing gear loss rates, the estimates provided here can be used as a complement and comparison, and should not be used as a substitution for already existing estimates.

We also observed a geographic shift in the studies over time, with early gear loss studies mostly from North America, followed by later studies more widely spread around the world. As a consequence, later studies included a larger proportion of less industrialized fisheries with less well developed management regimes, where gear loss rates can typically be higher. The interaction between geography and study date is likely the main driver in the consistent increases observed in gear losses with time (Figures 5–7; Figures S3 and 4; Tables S2–S4, S6 and S7). We explored using country metrics to capture this confounding effect; however, as most countries in the literature review are only represented by one or a few studies, it was not possible to disentangle these effects.

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A possible additional and/or alternative explanation for the increase in gear losses with time is the significant increase in global fishing effort from the 1970s through 2010 and the stabilizing of this effort over the last decade (Bell, Watson, & Ye, 2017; Watson & Tidd, 2018). Perhaps unsurprisingly, a correlation between fishing effort and quantities of gear lost has been found (Richardson, Gunn, Wilcox, & Hardesty, 2018; Yıldız & Karakulak, 2016). Increased fishing effort, if inadequately managed, has the potential to result in gear conflicts arising from overcrowding, increased competition and risk-taking behaviours among fishers, all of which can act as drivers for fishing gear loss (Macfadyen et al., 2009; Richardson et al., 2018). Gear conflict was noted as a cause of gear loss across more than half of all the studies reviewed. Fisheries management improvements that include reductions in fishing effort and improvements in spatial management measures could reduce gear conflict and the associated loss of fishing gear (Richardson et al., 2018).

## 4.4 | Influences from environmental and operational variables for net and trap gear types

In the case of net gear, losses can also result from nets snagging or becoming ensnared upon obstructions when they make contact with the seafloor (Richardson et al., 2018). Our results showed a greater proportion of loss for nets that fish along the bottom. Concordantly, almost a third (32%) of the studies we reviewed cited nets being snagged on bottom obstructions as a major cause of gear loss.

The high proportions of loss for nets fishing on soft bottoms is likely a reflection of a mix of loss from all gears including high losses from trawl vessels, while losses on hard bottoms are almost solely due to gillnets and trammel nets. While we found cases where there was a greater proportion of net loss for soft, mixed and unknown bottom types, our results also showed that fewer nets by count are lost overall for these same bottom types. This discrepancy is likely due to limitations in the datasets available, as the proportion estimates are based on a larger dataset covering all net types while the number of units of nets lost (count) per vessel is based on a much smaller dataset that only includes gillnets and trammel nets.

Gear becoming ensnared on the bottom was also a common cause of lobster, octopus and cuttlefish trap loss. This corresponds to the higher proportion of pot and trap losses shown in our results for rocky and reef hard bottoms where many of these traps are fished, compared to often muddy soft bottoms where crabs are fished. Pot and trap loss also increased with the depth of fishing grounds; it is likely that if a pot is lost or damaged, it becomes harder to find and recover in deeper water.

Our results also showed that nets that are attended and/or active are less likely to be lost, compared to unattended and/or passive nets. If a situation arises that might result in lost fishing gear, such as bad weather or vessels fishing too close to one another, fishers who are attending their gear can respond by making adjustments to their fishing practices to avoid gear loss. By contrast, if similar situations arise for unattended and/or passive gear and no change is made due to no fishers being present or aware of the gear loss threat, it is more likely that this gear will be lost.

We also observed a lower proportion of gear loss for nets that are attached to a fixed point or not attached to a vessel compared to nets that are attached to a vessel. It is possible that by nets being affixed to specific, non-moving objects, this ensures they will not drift away from their fishing grounds after damage is incurred. By contrast, if net damage or a loss event occurs for a net attached to a vessel without the vessel realizing this event as the vessel is underway or drifting, it is possible that these nets or portions of nets can drift away from the vessel and become lost gear.

These results for attendance, activity and attachment as drivers of loss can be used to predict relative differences in amounts of gear losses across gears based on their mode of operation. When integrated with other operational variables, such as bottom contact or relevant environmental variables, such as the bottom type, it is feasible to make recommendations as to the gears that will result in the lowest amounts of loss in a given situation.

## 4.5 | Areas for future research

Compared to nets and traps, the review reveals few studies on gear loss from line fisheries. For studies reporting on generalized losses from longline fisheries, however, incidences of bait and hook bite-offs are commonly reported for shark catch and by-catch (Afonso, Santiago, Hazin, & Hazin, 2012; Branstetter & Musick, 1993; Hannan et al., 2013). While bite-off rates are not typically used for the purpose of gear loss estimations, bite-off rates for hooks from line fisheries could be useful proxy data to estimate gear losses where data is otherwise unavailable (Ward, Lawrence, Darbyshire, & Hindmarsh, 2008).

Significant data gaps also exist in the gear loss literature for fish aggregating devices (FADs). With tens of thousands of drifting FADs (DFADs) deployed each year by tuna purse seine fisheries (Gershman, Nickson, & O'Toole, 2015), even relatively small rates of gear loss can result in large numbers of lost FADs globally (Maufroy et al., 2015). Abandoned, lost or otherwise discarded DFADs can have serious impacts on the surrounding marine environment including entangling and ensnaring marine wildlife, damaging fragile benthic habitats, and can be expensive and complicated to clean-up (Balderson & Martin, 2015; Stelfox, Hudgins, Ali, & Anderson, 2015). Because of the potential for large amounts of DFAD losses and the associated threats to marine wildlife and ecosystems, research around gear loss from DFADs should be prioritized. The Parties to the Nauru Agreement (PNA) in the Western and Central Pacific Ocean requires DFAD reporting and tracking, and the Inter-American Tropical Tuna Commission (IATTC) requires vessels to provide FAD data and marking information (Criddle, Amos, & Carroll, 2009; Escalle, Muller, Brouwer, Pilling, & the PNA Office., 2018; Gershman et al., 2015). Tracking programs like the one supported by PNA and FAD data from PNA and the IATTC could be potential sources of information for gear loss estimates for this gear type.

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Due to the differences in data reporting across studies (Figures 2–4), not all studies reviewed could be used in all analyses. One recommendation, therefore, is for future gear loss estimation work to include information that improves the ability to contextualize gear loss estimates and to compare losses across other fisheries and geographic areas. Helpful information includes measures of uncertainty, the amount of gear used, number of vessels per fleet and relevant fishing effort information.

While these global gear loss estimates are understandably limited by the availability of the published literature, these estimates can be updated using unpublished data sources from fishery management organizations, fishery observers, vessel logbooks, fisher mail-in surveys and gear loss reporting databases (Gilman, 2015; Lewis et al., 2009; O'Hara & Ludicello, 1987; Richardson, Haynes, Talouli, & Donoghue, 2017; Uhrin, 2016; Washington State Derelict Fishing Gear Database, 2018). Future gear loss research that includes interviews with fishers and fisheries managers, especially for under-represented geographic areas and gear types, would additionally assist in filling knowledge gaps around fishing gear losses.

## 5 | CONCLUSIONS

We estimated that 5.7% of all fishing nets, 8.6% of all traps and 29% of all lines were lost to the world's oceans for the year 2017. These estimates can be refined as more detailed studies provide empirical information about fishing gear losses. Future research that includes under-represented gear types (such as fish aggregating devices and lines) and geographic areas (such as Africa, Asia and South America) where major data gaps exist will improve our regional understanding of gear losses.

While these estimates are limited by the availability of the published literature, the quantitative estimates of fishing gear loss and associated trends provided here can be used to fill data gaps about sea-based sources of global marine debris. The information on effects of gear configuration, gear use and environmental conditions can facilitate the evaluation of risks from existing gears and improvements on gear changes to reduce loss rates across fisheries. This work has broad relevance for stakeholders including fisheries managers, government and intergovernmental agencies, NGOs and researchers who seek to better understand, monitor, assess and ultimately decrease amounts of and impacts from abandoned, lost and derelict fishing gear.

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## DATA AVAILABILITY STATEMENT

All publications referred to and used in analysis are referenced and information used is provided in the Table 1.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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