frontiers in Marine Science

ORIGINAL RESEARCH
published: 09 July 2021
doi: 10.3389/fmars.2021.690447

Global Causes, Drivers, and Prevention Measures for Lost Fishing Gear

Kelsey Richardson[1,2,3]*, *Britta Denise Hardesty*[1,2], *Joanna Zofia Vince*[2,3] *and Chris Wilcox*[1,2]

[1] Commonwealth Scientific and Industrial Research Organisation (CSIRO), Hobart, TAS, Australia, [2] Centre for Marine Socioecology, Institute for Marine and Antarctic Studies, College of Sciences and Engineering, University of Tasmania, Hobart, TAS, Australia, [3] School of Social Sciences, College of Arts, Law and Education, University of Tasmania, Hobart, TAS, Australia

Abandoned, Lost or otherwise discarded fishing gear (ALDFG) comprises a significant part of global marine plastic pollution, with adverse consequences for fishers, the seafood industry, and marine wildlife and habitats. To effectively prevent and reduce ALDFG at source, an understanding of the major causes of and drivers behind fishing gear losses is required. We interviewed 451 fishers from seven countries around the world (Belize, Iceland, Indonesia, Morocco, New Zealand, Peru, and the United States of America) representing five key fishing gear types (gillnets, purse seine nets, trawl nets, longlines, and pots and traps) about why and under what circumstances they lose their gear. We also asked them their views on the most effective interventions to reduce gear losses. Across all major gear types and countries where interviews were undertaken, bad weather was the most common cause of gear loss, followed by interactions with wildlife (identified as a cause for loss by 81% and 65% of all fishers interviewed, respectively). Snagging gear on a bottom obstruction was a major cause of loss for gears that contact the seafloor, along with conflicts with other fishers, often via gear and vessel interactions, for gillnet and pot and trap fishers. Operational and behavioral characteristics such as gear type, trip length, and the party responsible to pay for gear repairs and replacements all significantly influenced gear losses. Gear maintenance was the most effective gear loss prevention measure across all gear types and countries reported by fishers, followed by training crew in gear management (identified as an effective prevention measure by 95% and 82% of all fishers interviewed, respectively). Actions available to fishers, managers and port operators to effectively prevent fishing gear losses include: gear maintenance; reducing active gear interactions with wildlife; reducing financial and administrative burdens for port reception facilities; reducing trip lengths; and targeting education and gear stewardship programs to fishers with limited ALDFG awareness, particularly those in low income fisheries and countries.

Keywords: abandoned lost or otherwise discarded fishing gear, derelict fishing gear, fisheries management, ghostfishing, marine debris, marine litter, plastic pollution, sustainable fisheries

Edited by:
Juan José Alava, University of British Columbia, Canada

Reviewed by:
Tomaso Fortibuoni, Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Italy
Nina Young, National Oceanic and Atmospheric Administration, United States

Correspondence:
Kelsey Richardson
kelsey.richardson@csiro.au; kelseypgr@gmail.com

Specialty section:
This article was submitted to Marine Pollution, a section of the journal Frontiers in Marine Science

Received: *02 April 2021*
Accepted: *02 June 2021*
Published: *09 July 2021*

Citation:
Richardson K, Hardesty BD, Vince JZ and Wilcox C (2021) Global Causes, Drivers, and Prevention Measures for Lost Fishing Gear. Front. Mar. Sci. 8:690447. doi: 10.3389/fmars.2021.690447

INTRODUCTION

Abandoned, lost or otherwise discarded fishing gear (ALDFG) represents a considerable component of global marine pollution, with adverse impacts to fishers, the seafood industry, coastal communities, and marine wildlife and habitats (Macfadyen et al., 2009; Richardson et al., 2019b). When fishing gear is abandoned, lost or discarded, it can sink to the seafloor where it can damage benthic habitats and organisms through abrasion, dragging, and entanglement (Pham et al., 2014; National Oceanic and Atmospheric Administration Marine Debris and Program, 2016; Du Preez et al., 2020). It may also drift with currents where it has the potential to interact with fish and other marine wildlife (Wilcox et al., 2013; Lebreton et al., 2018; Stelfox et al., 2020), provide habitat for invasive species (Miralles et al., 2018; Rech et al., 2018), and act as a hazard to navigation and safety at sea (Macfadyen et al., 2009; Hong et al., 2017). Often referred to as "ghost gear," ALDFG may continue to catch and entangle target and non-target species (National Oceanic and Atmospheric Administration Marine Debris and Program, 2015; Stelfox et al., 2016). Derelict gear can eventually be washed ashore with negative impacts to coastal communities including for coastline esthetics and tourism (Gunn et al., 2010; Matthews and Glazer, 2010; Marcou et al., 2016).

Fishing gear can be abandoned, lost or discarded following environmental, operational, behavioral or management pressures. Common environmental causes of gear loss include severe weather events and gear movement from currents, swells and tides (Santos et al., 2003; Uhrin, 2016; Dagtekin et al., 2019). Gear is also often lost because of gear snagging upon the seafloor (Brown et al., 2005; Ayaz et al., 2010) and interactions with wildlife (Nitta and Henderson, 1993; Gunarathna et al., 2019; Richardson et al., 2019a). Lack of fishing experience, awareness of issues surrounding ALDFG and operator error can all result in gear losses (Antonelis, 2013; Bilkovic et al., 2016). Towed and static gear interactions and conflicts, and vessels running over fishing gears are also commonly cited causes of gear loss (MacMullen et al., 2004; Al-Masroori et al., 2009; Yıldız and Karakulak, 2016). Insufficient fisheries management measures such as inadequate spatial management, enforcement, gear marking and loss reporting requirements, illegal, unregulated and unreported (IUU) fishing activities, and lack of limits on fishing effort can lead to chains of events that result in gear losses (Masompour et al., 2018; Richardson et al., 2018; Stelfox et al., 2020).

Prevention, mitigation, and curative measures for ALDFG vary depending upon the gear type, geography, and circumstances around gear losses and are most effective when the causes of and impacts from the ALDFG are understood. Prevention, mitigation and curative measures can be applied across a broad range of stakeholders including not only fishers but also gear designers, port operators, fisheries managers, seafood companies, and NGOs (Huntington, 2017). Preventative measures include governance and fisheries management measures around ALDFG, provisions of port reception facilities for end of life fishing gear and awareness raising initiatives (Huntington, 2017; Deshpande and Aspen, 2018; IMO, 2018). Mitigation measures include improvements in gear designs that reduce ghost fishing and other ALDFG impacts to marine habitats and wildlife (Wilcox and Hardesty, 2016; Huntington, 2017). Curative measures include ALDFG identification, reporting, removal and retrieval (Drinkwin, 2017; Huntington, 2017; He and Suuronen, 2018; FAO, 2019).

To better understand primary causes of and prevention measures for ALDFG at the global scale, we sought input from hook and line, net and pot and trap fishers from seven countries around the world. We asked questions that aimed to identify the main causes and drivers of fishing gear losses. We also asked fishers what they find to be effective ALDFG prevention measures, both onboard vessels and through management interventions. We analyzed data gleaned to identify major causes and drivers of and effective prevention measures for ALDFG globally across five different commonly used gear types. The work aims to contribute knowledge that can be used by fishers, managers and policy makers working to reduce ALDFG within the larger context of better seafood sustainability, food security and a healthier marine environments. This research represents the largest international survey of fishers around gear losses to date and provides the first global overview of major causes of and prevention measures for fishing gear losses using data obtained directly from fishers.

MATERIALS AND METHODS

Global Gear Loss Surveys

In total, we conducted an average of 15 surveys for each of five key fishing gear types (gillnets, purse seine nets, trawl nets, longlines, and pots and traps) in seven countries around the world (**Supplementary Table 1**). Countries were selected that employed most or all five gear types and had a combination of the highest amounts of capture production and fishing effort in their region relative to other countries in the region. Capture production and fishing effort (number of vessels and fishers) were determined using FAO's 2016 Fisheries and Aquaculture Statistics Yearbook (FAO, 2018a).

We selected Indonesia (ranked 2^{nd} globally for amounts of capture production and fishing effort in 2016)[1] from Asia, Belize[2] from the Caribbean; Iceland (19) from Europe; the United States (4) from North America; New Zealand (40) from Oceania; Peru (6) from South America, and Morocco (17) from Africa.

Interviews with all fishers used the same survey forms specific to each gear type in the native language(s) of the country surveyed (see **Supplementary Data Sheets 3–7** for survey form, English version). Some countries did not have major active commercial fisheries for all five gear types identified. In these cases, surveys were only conducted for the fisheries/gear types available. Fishers were selected randomly by interviewers at each

[1]Global rankings for amounts of capture production and fishing effort are indicated in the parentheses following each country selected in this paragraph.

[2]While Belize did not rank among the top countries globally for amounts of "capture production by principal producers in 2016," "number of fishing vessels" and "number of fishers," it was chosen for the Caribbean region given availability of and access to in country contacts.

port, dependent upon which fishers happened to be present at the port at the day(s) of the interview, and willing to spend between 5 and 15 min to answer survey questions. In rare instances where fisher presence at ports was limited and available fishers hard to find (e.g., typically long fishing trips away from port, small or remote fishery locations), the interviewer(s) employed a snowball sampling method, with research participants (fishers) suggesting other fishers available for interviews and sharing their contact information. Ethics approval by the Tasmania Social Sciences Human Research Ethics Committee for these surveys was received on July 13, 2018. Surveys were carried out from January 21, 2019 to December 03, 2019.

We conducted 451 interviews with fishers from Belize ($N = 50$), Iceland ($N = 73$), Indonesia ($N = 60$), Morocco ($N = 75$), New Zealand ($N = 47$), Peru ($N = 73$) and the United States of America ($N = 73$) for gillnets ($N = 94$), purse seine nets ($N = 75$), trawl nets ($N = 70$), longlines ($N = 107$), and pots and traps ($N = 105$) (**Figure 1** and **Supplementary Table 1**). Ports where interviews were conducted, and the associated major fishing areas are listed in **Supplementary Table 2**.

Causes and Drivers of and Prevention Measures for Gear Losses, and Issues of Concern to Fishers Related to ALDFG

Fishers were asked to identify major causes of gear losses, common prevention measures that they employ to avoid gear losses and issues of concern related to ALDFG. We summarized fishers' answers to these topics using Likert scale analyses, both across all countries and all gear types, combined; and across all countries for each gear type. A Likert scale is used to evaluate responses in which respondents are asked questions for closed-ended questions. It is one of the most reliable ways to measure opinions, perceptions, and behaviors (Nemoto and Beglar, 2014; Joshi et al., 2015). We used the likert package (Bryer and Speerschneider, 2016) in the R statistical programming language (R Core Team, 2019) to create the Likert figures presented in the section "Results."

Fishers were also asked about how much gear they lose, per trip, and annually. Data obtained from the surveys was used to determine driving variables behind fishing gear losses. We analyzed gear loss across all gear types and countries, combined; and across all countries for each gear type (**Table 1**).

We used a beta regression to analyse the relationship between reported loss rates and possible drivers of fishing gear losses (**Table 1**), as implemented in the betareg package (Cribari-Neto and Zeileis, 2010) in the R statistical language (R Core Team, 2019). We used a Beta distribution to represent the proportion of gear losses as the response variable and the possible drivers as the explanatory variables. We used Akaike Information Criterion (AIC) (Burnham and Anderson, 2003) to select the best model among all possible models derived from the driving variables by measuring the quality of the models' fits to the data, adjusted for model complexity. Given limited numbers of replicates due to missing values for some driving variables, we re-ran the beta regression analysis, the second time only including the variables that arose in the importance scores within 2 AIC points of the best model to increase the number of replicates available for analysis. When multiple models existed within 2 AIC points, we used model averaging across the similar models. In such instances, we used the full average estimate as a shrinkage estimator.

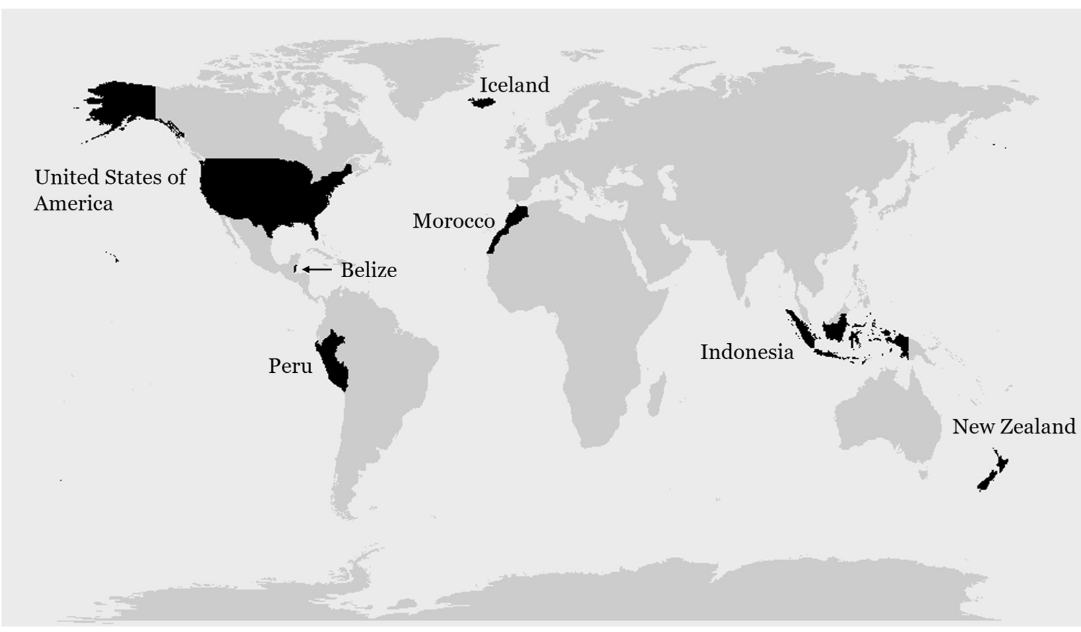

FIGURE 1 | Countries (in black) where interviews were conducted.

TABLE 1 | Driving variables examined across all gear types and countries, combined; and across all countries for each gear type (gillnets, purse seine nets, trawl nets, longlines, and pots/traps).

Scale of gear loss analysis	Driving variables examined in analysis
All gear types	Country, gear type, trip length, vessel length, depth, fishing time (day, night, both), gear contact with seafloor (Y/N), port reception facilities for end of life gear (Y/N), Dedicated onboard storage locations for end of life gear (Y/N), gear marking (Y/N), lifetime of gear, membership in a fishing organization/association (Y/N), years of fishing experience, lost gear reporting (Y/N), individual responsible for paying to repair or replace damaged and/or lost gear (e.g., company, captain, and crew), attempts to retrieve lost gear (Y/N), fishers concern levels around ALDFG, fisher awareness of any management measures specifically designed to prevent and/or reduce ALDFG (Y/N)
Gillnets	Soak time per set, number of sets per day, number of panels in a fleet, panel size, repair frequency
Purse seine nets	Time per set, number of sets per day, net size, repair frequency
Trawl nets	Time per shot, number of shots per day, number of nets used, net size, repair frequency
Longlines	Soak time per set, number of sets per day, mainline length, branchline length, repair frequency
Pots/Traps	Soak time per set, configuration (i.e., individually flagged, single or multiple in a fleet/line), Pot/trap size

RESULTS

Causes of Gear Losses

Bad weather was the top cause of gear loss reported by fishers across all gear types and countries, followed by damage by wildlife (**Figure 2**). When we reviewed causes of losses for specific gear types, snagging gear on a bottom obstruction was commonly reported by fishers whose gears make contact with the seafloor (**Supplementary Figures 1, 3, 4**), and conflicts with other fishers was commonly reported by gillnet and pot and trap fishers (**Supplementary Figures 1**, **5**).

Vessel Practices to Prevent Gear Losses

Gear maintenance was the most common gear loss prevention practice reported by fishers across all gear types and countries, followed by training crew in gear management (**Figure 3**). Fishers also commonly reported avoiding fishing in risky conditions for gear losses, such as in bad weather and in areas where gear might be snagged on obstructions, which varied according to the specific gear type (**Supplementary Figures 6–10**). Gillnet, trawl, longline and pot and trap fishers commonly reported communicating with other vessels about gear locations **Supplementary Figures 6, 8, 9, 10**) and pot and trap fishers commonly reported retrieving gear before storms (**Supplementary Figure 10**).

Fisher Concerns Around ALDFG

Most fishers reported being "very concerned" to "concerned" about the presence of ALDFG and its associated impacts, with trawl fishers expressing the highest levels of concern and longline fishers expressing the least amount of concern (**Figure 4**).

The most important issue of concern around ALDFG reported by fishers across all gear types and countries was economic losses, followed by harm to the environment (**Figure 5**). Net fishers reported more concern around a larger variety of impacts from ALDFG (**Supplementary Figures 11–13**).

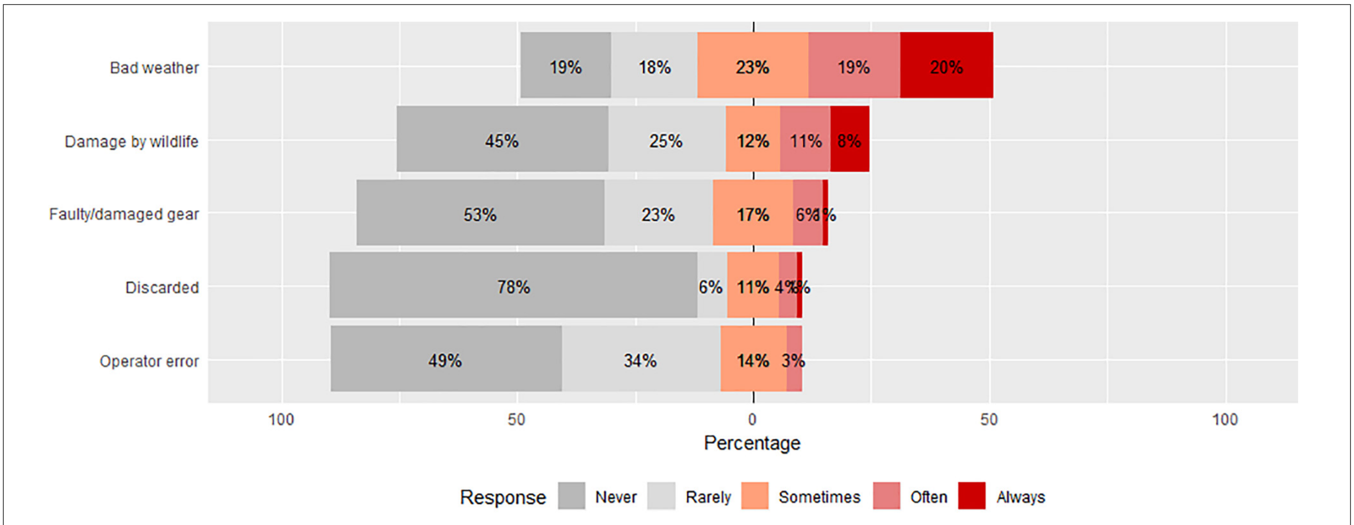

FIGURE 2 | Causes of fishing gear losses, for all gear types and countries combined. Less common causes are presented on the left side of the figure in dark to light grays, leading to more common causes as the reader moves right, and the colors warm from orange to salmon to red. Reading left to right, responses from fishers ranged from these causes "never," "rarely," "sometimes," "often," or "always" occurring. Total percentages are reported for each response and presented over the associated color code.

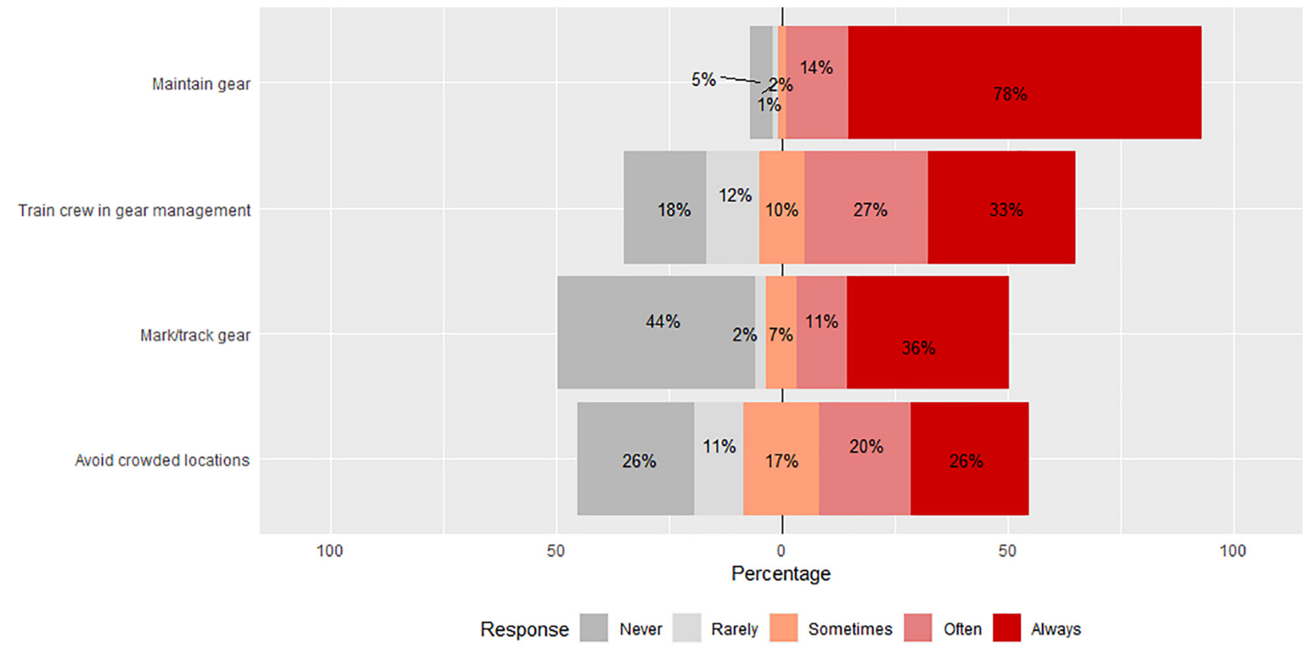

FIGURE 3 | Gear loss prevention practices, for all gear types and countries combined. Less common prevention practices are presented on the left side of the figure in dark to light grays, leading to more common prevention practices as the reader moves right and the colors warm from orange to salmon to red. Reading left to right, responses from fishers ranged from "never," "rarely," "sometimes," "often," or "always" engaging in these gear loss prevention practices. Total percentages are reported for each response and presented over the associated color code.

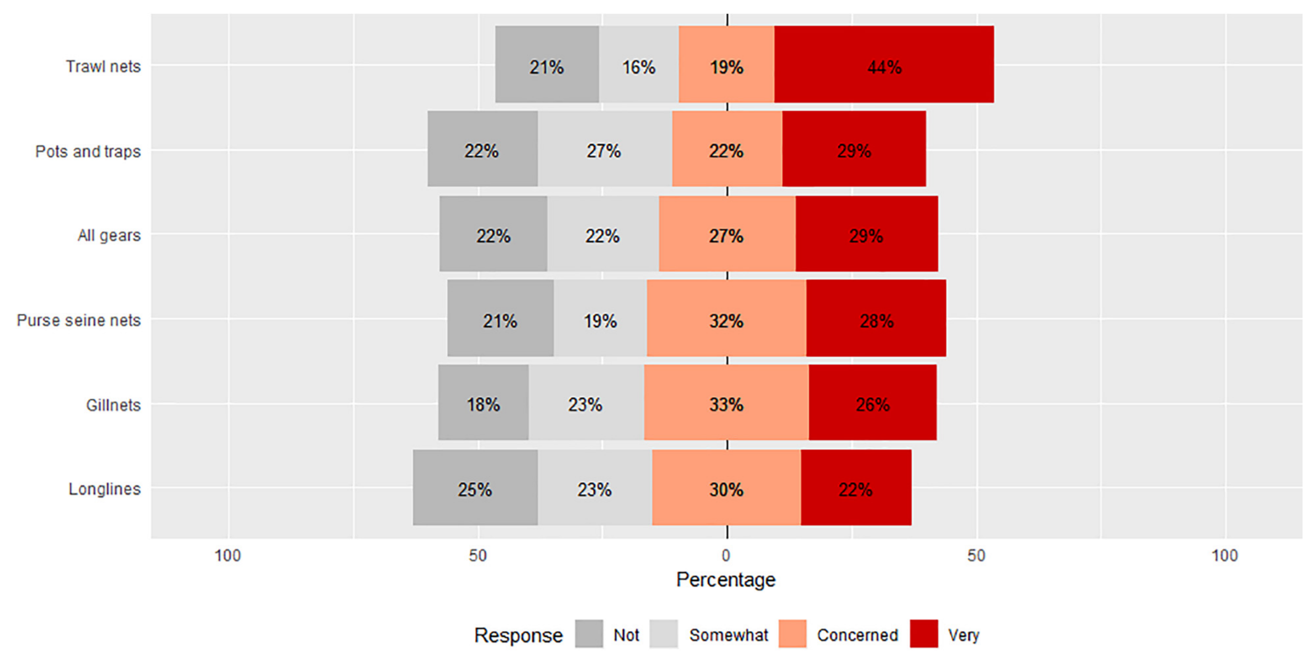

FIGURE 4 | Levels of concern around ALDFG reported by fishers across all gear types and countries, combined; and for specific gear types (gillnets, purse seine nets, trawl nets, longlines, and pots and traps) across all countries. Low levels of concern are presented on the left side of the figure in dark to light grays, leading to higher concern levels as the reader moves right and the colors warm from orange to salmon to red. Reading left to right, levels of concern reported by fishers were ranked as "Not at all concerned," "Concerned," "Somewhat concerned," and "Very concerned." Total percentages are reported for each response and presented over the associated color code.

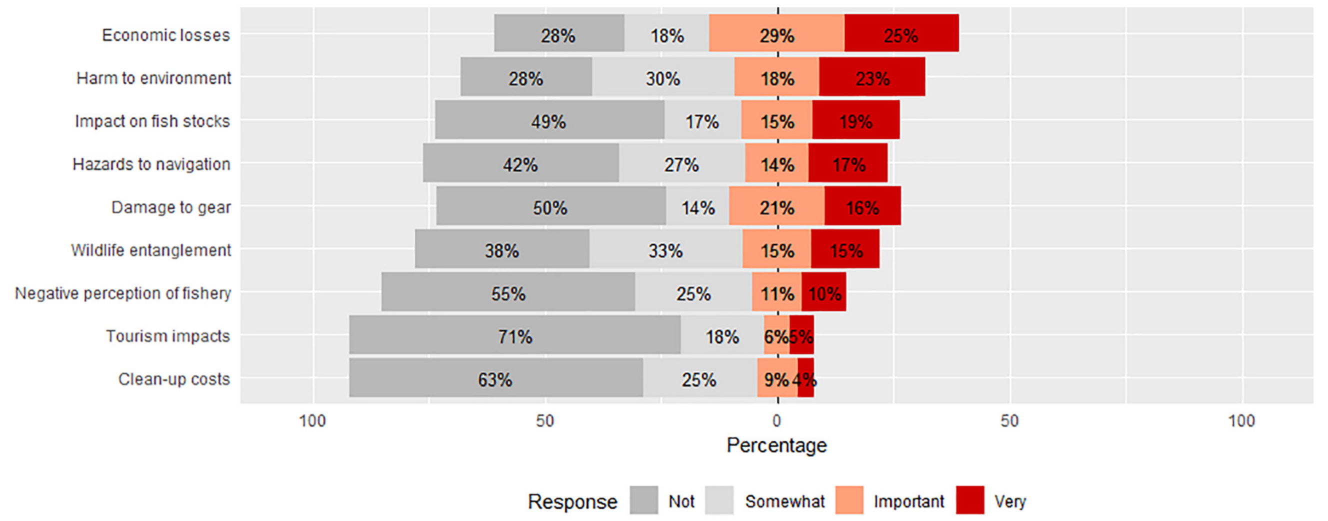

FIGURE 5 | Issues of concern around ALDFG to fishers across all gear types and countries combined. Low levels of concern are presented on the left side of the figure in dark to light grays, leading to higher concern levels as the reader moves right, and the colors warm from orange to salmon to red. Reading left to right, issues reported by fishers were ranked as "Not important," "Somewhat important," "Important," and "Very important." Total percentages are reported for each response and presented over the associated color code.

Drivers of Gear Losses

Gear losses are more prevalent across all gears and countries surveyed with longer trips, as concern around ALDFG increases, for longlines, purse seine nets and trawl nets and for Morocco (**Table 2** and **Supplementary Table 2**).

Significantly lower proportions of gillnet losses occur if no port disposal facilities are available for end of life gear (**Table 2** and **Supplementary Table 3**).

We found significantly higher proportions of purse seine net losses as gear lifetimes increased, with larger purse seine nets, longer set times and longer trips (**Table 2** and **Supplementary Table 4**). We found significantly lower proportions of purse seine net losses with more daily sets and if port disposal facilities for fishing gear were unavailable (**Table 2** and **Supplementary Table 4**).

Our model for drivers of trawl net losses showed significantly higher proportions of trawl net losses if fishers did not attempt to retrieve lost gear, with longer trips and with less fishing experience. We found significantly lower proportions of trawl net losses if trawl net gear does not contact the bottom, if fishers are a member of a fishing organization and for higher levels of fishing experience (**Table 2** and **Supplementary Table 5**).

Longline losses are higher if fishers are a member of a fishing organization, in Morocco (compared to other countries surveyed), with more daily sets and with longer trips. Lower proportions of longline losses occur in Belize (compared to other countries surveyed) and with longer mainlines (**Table 2** and **Supplementary Table 6**).

Our model for drivers of pot and trap losses showed significantly lower proportions of pot and trap losses with longer gear lifetimes, and if the entire crew or the associated corporation that manages the vessel is responsible to pay for gear repairs and replacements (**Table 2** and **Supplementary Table 7**).

DISCUSSION

Causes of Gear Losses

The top causes of gear loss reported by fishers (bad weather, interactions with wildlife, snagging gear on a bottom obstruction and conflicts with other fishers) are consistent with findings from a recent global meta-analysis (Richardson et al., 2019b) and regional case study (Richardson et al., 2018). Practices reported by fishers to prevent these losses include avoiding fishing in bad weather and in areas risky for gear snagging, communicating gear locations with vessels to avoid conflicts, and avoiding fishing in overcrowded areas and areas with high vessel traffic.

Fishers also highlighted that wildlife entanglement was an important concern from ALDFG, especially following active gear interactions with wildlife. Actions that could be undertaken by fishers and management agencies to minimize wildlife interactions with active gears include: time-area and area-gear closures; wildlife deterrent technologies; decreased soak times; gear modifications such as excluder devices and post-entanglement release mechanisms; and backdown procedures by purse seine vessels to release trapped wildlife[3] (Hamilton and Baker, 2019; FAO, 2021).

Drivers of Gear Losses

The higher proportions of longline losses reported from fisher surveys compared to other gears, and for purse seine and trawl nets losses compared to other net gear, is consistent with previous analyses (Richardson et al., 2019b). The positive relationship observed between gear losses and increased concern by fishers around ALDFG likely reflects a greater awareness by

[3]Backdown procedures should be employed with dolphin-safe techniques or rescue methods, and a dolphin safety panel (Medina panel) (FAO, 2021).

TABLE 2 | Summary of drivers of gillnet, purse seine net, trawl net, longline and pot and trap losses across Belize, Iceland, Indonesia, Morocco, New Zealand, Peru and the United States of America.

Gear type	Gear loss driver	Coefficient estimate	Standard error	*P*-value	Higher (↑) or lower (↓) Proportions of gear lost
All gears	**ALDFG Concern level by fishers (Linear)**	0.301	0.127	**0.0176***	↑
	Trip length	0.00420	0.00103	**0.0000475*****	↑
	Morocco	0.652	0.194	**0.000756*****	↑
	Longlines	0.486	0.138	**0.000442*****	↑
	Purse seine nets	1.06	0.282	**0.000183*****	↑
	Trawl nets	0.564	0.172	**0.00101****	↑
Gillnets	**No port disposal facilities for end of life gear**	−0.578	0.217	**0.00772****	↓
Purse seine nets	**Gear lifetime**	0.106	0.0109	**<2e-16*****	↑
	Net size	0.00000415	0.00000148	**0.00489****	↑
	Time per set	0.0248	0.00726	**0.00063*****	↑
	Trip length	0.0146	0.00460	**0.00152****	↑
	No port disposal facilities for end of life gear	−1.31	0.634	**0.0403***	↓
	Number of sets per day	−0.137	0.0260	**0.000000100*****	↓
Trawl nets	**No attempts for gear retrieval**	0.924	0.233	**0.0000713*****	↑
	Trip length	0.0473	0.0127	**0.000200*****	↑
	Years of fishing experience, Quadratic	−0.503	0.234	**0.0314***	↓
	Years of fishing experience, Cubic	1.18	0.284	**0.0000301*****	↑
	Years of fishing experience, Quartic	0.947	0.281	**0.000732*****	↑
	Years of fishing experience, Quintic	−0.762	0.236	**0.00122****	↓
	Gear does not contact the bottom	−1.27	0.324	**0.0000890*****	↓
	Fishing organization member	−1.20	0.198	**0.00000000142*****	↓
Longlines	**Fishing organization member**	0.447	0.171	**0.00905****	↑
	Morocco	0.897	0.395	**0.0231***	↑
	Number of sets per day	0.157	0.032	**0.000000700*****	↑
	Trip length	0.00669	0.00164	**0.0000447*****	↑
	Vessel fishes at night	0.853	0.273	**0.00177****	↑
	Belize	−1.25	0.531	**0.0189***	↓
	Mainline length	−0.0150	0.00523	**0.00411****	↓
Pots/Traps	**Corporation pays to replace end of life gear**	−0.979	0.327	**0.00278****	↓
	Entire crew pays to replace end of life gear	−0.725	0.308	**0.0186***	↓
	Gear lifetime	−0.0444	0.0146	**0.00233****	↓

*Drivers were significant within 95% confidence intervals. The models use treatment contrasts, and thus one level for each categorical variable is included in the intercept terms as a reference level. Coefficients for categorical variables are differences with respect to the reference levels. Reference levels are: Captain is responsible to pay to replace end of life gear (pots and traps), fishers attempt to retrieve lost gear (trawl nets), Fishers do not belong to a fishing organization or management group (trawl nets, longlines), gear contacts the bottom (trawl nets), gillnets (for the gear types, all gears), Iceland (for the country types, all gears), port disposal facilities are available for end of life gear (gillnets and purse seine nets), and vessel only fishes during the day (longlines). Values are rounded to three significant figures. *Indicates a P-value < 0.05, ** indicates a P-value < 0.01, and *** indicates a P-value < 0.001. ↑ indicates an increase in proportion of gear losses with the driver, and ↓ indicates a decrease in proportion of gear loss with the driver. Significant p-values < 0.05 are bolded.*

fishers of gear losses when they occur more frequently, and thus, more concern around associated impacts. For example, trawl fishers reported the highest levels of concern around ALDFG and had some of the highest levels of gear losses compared to other gears.

By contrast, however, while longline fishers reported the least amount of concern around ALDFG, they also reported the highest levels of deliberate gear discard to the ocean. Illegal and deliberate gear discard can be a serious cause of gear loss for some fisheries, which is often under-reported, in the rare cases that it is reported at all (National Research Council, 2009; Richardson et al., 2018). Interestingly, longline losses were higher for fishers who were members of a fishing organization. While counterintuitive, this relationship might arise from licensing requirements for longline fishers to be organization members, and, as such, presents an opportunity for such organizations to engage their fishers in ALDFG best practices. Establishing programs to engage longline and other fishers with gear loss prevention and stewardship programs could help to raise awareness around and increase environmental responsibility for ALDFG. For example, a voluntary litter clean-up program by fishers in the United Kingdom showed that fishers involved in the program increased their responsibility and engaged in less environmentally harmful waste management behaviors compared to fishers not involved in the program (Wyles et al., 2019). The reduced trawl net losses when fishers are members of a fishing organization could reflect the impact of community engagement on gear stewardship. The European Union's recent directive on the reduction of the impact of certain plastic products (including fishing gear) on the environment further supports ALDFG awareness raising measures regionally, through its direction to Member States to raise awareness for consumers (including fishing gear users) around the availability of reusable materials, systems and waste management options for fishing gears containing plastics; best practices in waste management; and the impacts that arise from inappropriate waste disposal and littering activities, including from fishing gears (Official Journal of the European Union, 2019b).

Economic losses from ALDFG was the most important issue of concern reported by fishers, likely because of the negative economic consequences of losing gear. The potential for middle income countries undergoing rapid economic growth to experience large amounts of marine plastic pollution has been previously examined (Jambeck et al., 2015). Furthermore, dwindling global fish stocks and increased market pressures are driving fishers to increase risk-taking behaviors in search of fish catch (Richardson et al., 2018; Rousseau et al., 2019; FAO, 2020). Of the seven countries surveyed, Morocco has the lowest income[4] and Moroccan fishers earn the least per fishing trip. They also reported the highest gear losses. Targeting ALDFG interventions and fisheries improvement measures in middle and low-income countries with significant fisheries sectors where gear losses might be more likely can help to combat this. Examples of such efforts in countries represented within this study include overall improvements in the sustainability of the Indonesian and Moroccan fishing sectors and efforts to combat illegal, unreported and unregulated fishing activities (UNEP/MAP, 2015; Richardson et al., 2018); and more direct measures such as fishing gear marking, tracking, and ALDFG recovery and recycling initiatives in Indonesia and Peru (FAO, 2018b; GGGI, 2018, 2020; WWF, 2020) and ALDFG surveys, workshops and awareness raising in Belize (GGGI, 2020).

Gear characteristics significantly affected losses. The higher proportions of trawl net losses when nets contact the seafloor is consistent with previous analyses (Richardson et al., 2019b) and supports the findings from this study that gear snagging on bottom obstructions is a major cause of gear losses. The positive relationship observed between purse seine net sizes and losses might be explained by larger nets typically hauling larger catches, resulting in greater strains and pressures to the gears and thus greater risk for damage and loss. Larger gears may also be more difficult to recover in bad weather and more prone to fouling and damage. For longlines, the negative relationship observed between mainline size and losses could reflect a generally higher quality and durability of larger, more technologically advanced mainlines, as well as better gear stewardship for these more expensive gears through gear marking, tracking and maintenance.

Gear maintenance also appears to influence the lifetime of gears and associated losses. The relationship observed between pot and trap lifetimes and losses not only reflects the importance of maintenance, but also of using higher quality, more durable materials for these otherwise relatively inexpensive gears, noting possible trade-offs between longer lasting materials and associated impacts should these gears become lost. The relationship between purse seine net losses and net lifetimes suggests the need for more frequent net replacement, likely arising from the major loads and strains incurred on these nets from large volumes of catch. The lower proportions of pot and trap losses reported when the crew and/or a corporation is responsible to pay for repairs and replacements suggests that increased effort to extend the gear's lifetime is non-negligible if there is a direct financial link.

Efforts to retrieve lost gears can also reduce losses, which is exemplified by the lower incidences of trawl net losses when fishers attempted to retrieve lost nets. Gear marking, tracking and reporting of gear losses can assist with ALDFG identification and retrieval efforts (FAO, 2019). The variation in trawl net losses with fishing experience additionally highlights the importance that greater levels of fishing experience has on preventing gear losses. Efforts to ensure crew members are trained in tools, technologies and best practices for gear stewardship and local fishing conditions can further assist in gear loss prevention where experience is otherwise lacking (Richardson et al., 2018).

In contrast to findings reported elsewhere (Macfadyen et al., 2009; National Research Council, 2009; Gilman, 2015), we found reduced gillnet and purse seine net losses when no port disposal facilities were available. This might reflect the deployment of waste bins at ports where more gear losses and damages occur, in response to a higher need by vessels for these waste facilities for large amounts of damaged and end of life gears. It could also reflect a change in practices or experiences of fishers in the countries we surveyed, or the presence of high fees and/or administrative burdens that exist in some ports, which can have the unintended consequence of discouraging fishers from using these facilities (Brodbeck, 2016). Despite all countries surveyed being signatories to the International Convention for the Prevention of Pollution from Ships' MARPOL Annex V (ECOLEX, 2020), which includes requirements for waste reception facilities at ports for ships including fishing vessels, port reception facilities are not always adequate for the wastes received, with adequacy challenging to determine given limited reception facilities specifically for fishing gear, limited reporting by states and private operators oftentimes responsible for ship waste handling (National Research Council, 2009; Mikelis, 2012; Øhlenschlæger et al., 2013; FAO, 2019). Minimizing administrative and financial burdens and incentivizing fishers to dispose of their gear at ports could encourage fishers to use port disposal facilities when available and reduce intentional gear discarding at sea (Brodbeck, 2016). The European Union has shown leadership on this front through recent updates to its directive on port reception facilities for the delivery of waste from ships, which includes noting the value of separate collections

[4]Morocco is a Lower Middle Income (LMI) country; Belize, Indonesia, and Peru are Upper Middle Income (UMI) countries and Iceland, New Zealand and the United States of America are High Income (HI) countries (World Bank, 2020).

for ship wastes (including derelict fishing gear) that facilitate reuse or recycling, consideration of indirect fees that support cost recovery of waste delivery to ports without direct charges, and alternative financing for initiatives that incentivize collection and recovery of fishing gear wastes (Official Journal of the European Union, 2019a).

Vessel and operational characteristics also influenced gear losses. The higher amounts of gear losses observed with longer fishing trips, across all gears and especially for purse seine nets, trawl nets and longlines, likely reflects increased chances of gear losses with more time spent at sea fishing and typically more gear used. This is similarly reflected in the positive relationship observed between longline losses and number of daily sets. The time of day that fishing occurs is also important. Longline fishing at night may result in increased gear loss because it is harder to find and see gear, making the lines more vulnerable to damage, snagging and other accidents. While we were unable to explore the relationships between active versus passive gears and losses, and gear attendance and losses due to imbalanced data, in their global gear loss meta-analysis Richardson et al. (2019b) observed negative relationships between active and attended gears and losses. The relationships observed between purse seine net losses and both the number of daily sets and set times likely arises from purse seine nets both being an active gear type, and greater gear attendance as more gear is actively set and recovered throughout the day.

CONCLUSION

Interviews with fishers around the world highlighted the importance of weather and interactions with wildlife in terms of causes of fishing gear losses. Snagging gear on a bottom obstruction was a top cause of loss for gears that contact the seafloor, along with conflicts with other fishers for gillnet and pot and trap fishers. Gear, operational and behavioral characteristics, such as gear type, trip length, time of day that fishing occurs, and the party responsible to pay for gear repairs and replacements all influenced specific gear losses.

Gear maintenance was the most important gear loss prevention mechanism reported by fishers. This has important implications for reducing gear loss rates; and can be used to develop a roadmap to reduce ALDFG across fisheries, geographies, and gear types. We also suggest structures that reduce burdens at port disposal facilities to encourage fishers to dispose of their gear appropriately, coupled with targeted awareness raising programs to increase educational awareness of ALDFG impacts on coastal and marine ecosystems. This may be particularly useful in low income fisheries and countries where gear losses are likely to be higher.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Tasmania Social Sciences Human Research Ethics Committee. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

KR: conceptualization, methodology, software, formal analysis, investigation, data curation, writing the original draft, reviewing, editing, and visualization. BDH: conceptualization, methodology, resources, writing, reviewing, editing, supervision, and project administration. JV: resources, writing, reviewing, editing, and supervision. CW: conceptualization, methodology, software, formal analysis, resources, writing, reviewing, editing, and supervision. All authors contributed to the article and approved the submitted version.

FUNDING

This work was funded by CSIRO Oceans and Atmosphere and University of Tasmania.

ACKNOWLEDGMENTS

We dedicate this work to the memory of Joanna Toole, for her support and collaboration on this project, and her commitment to decreasing abandoned, lost or discarded fishing gear around the world. We thank CSIRO Oceans and Atmosphere, and the University of Tasmania's School of Social Sciences and Centre for Marine Socioecology for supporting this research.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.690447/full#supplementary-material

REFERENCES

Al-Masroori, H., Al-Oufi, H., and McShane, P. (2009). Causes and mitigations on trap ghost fishing in Oman: scientific approach to local fishers' perception. *J. Fish. Aquatic Sci.* 4, 129–135. doi: 10.3923/jfas.2009.129.135

Antonelis, K. L. (2013). *Derelict Gillnets in the Salish Sea: Causes of Gillnet Loss, Extent of Accumulation and Development of a Predictive Transboundary Model.* Doctoral dissertation. Washington, DC: ResearchWorks Archive.

Ayaz, A., Ünal, V., Acarli, D., and Altinagac, U. (2010). Fishing gear losses in the gökova special environmental protection area (SEPA), eastern mediterranean, Turkey. *J. Appl. Ichthyol.* 26, 416–419. doi: 10.1111/j.1439-0426.2009.01386.x

Bilkovic, D. M., Slacum, H. W., Havens, K. J., Zaveta, D., Jeffrey, C. F., Scheld, A. M., et al. (2016). *Ecological and Economic Effects of Derelict Fishing Gear in the Chesapeake Bay 2015/2016 Final Assessment Report*. Virginia: William & Mary.

Brodbeck, L. (2016). *Mechanisms to Support the Recycling/Reuse of Fishing Gear and the Prevention of Gear Becoming Lost/Abandoned at Sea. Barrier Assessment*. Norway: Norwegian University of Science and Technology.

Brown, J., Macfadyen, G., Huntington, T., Magnus, J., and Tumilty, J. (2005). *Ghost Fishing by Lost Fishing Gear. Final Report to DG Fisheries and Maritime Affairs of the European Commission. Fish/2004/20*. Brussels: Institute for European Environmental Policy.

Bryer, J., and Speerschneider, K. (2016). *likert: Analysis and Visualization Likert Items. R package version 1.3.5*.

Burnham, K. P., and Anderson, D. R. (2003). "Model selection and multimodal inference: a practical information-theoretic approach," in *Prediction and the Power Transformation Family*, eds R. J. Carroll and D. Ruppert (New York, NY: Springer-Verlag), 60–65.

Cribari-Neto, F., and Zeileis, A. (2010). Beta regression in R. *J. Stat. Softw.* 34, 1–24. doi: 10.18637/jss.v034.i02

Dagtekin, M., Ozyurt, C. E., Misir, D. S., Altuntas, C., Cankaya, A., Misir, G. B., et al. (2019). Rate and causes of lost gillnets and entangling nets in the black sea coasts of Turkey. *Turk. J. Fish. Aquat. Sci.* 19, 699–705. doi: 10.4194/1303-2712-v19_8_08

Deshpande, P. C., and Aspen, D. M. (2018). "A framework to conceptualize sustainable development goals for fishing gear resource management," in *MaransHandbook of Sustainability Science and Research*, eds W. L. Filho and R. W. Callewaert (Cham: Springer), 727–744. doi: 10.1007/978-3-319-63007-6_45

Drinkwin, J. (2017). *Methods to Locate Derelict Fishing Gear in Marine Waters. a Guidance Document of the Global Ghost Gear Initiative Catalyze and Replicate Solutions Working Group. August 31, 2017*. Seoul: Global Ghost Gear Initiative. doi: 10.31230/osf.io/f3sq5

Du Preez, C., Swan, K. D., and Curtis, J. M. (2020). Cold-water corals and other vulnerable biological structures on a North Pacific seamount after half a century of fishing. *Front. Mar. Sci.* 7:17. doi: 10.3389/fmars.2020.00017

ECOLEX (2020). International Convention for the Prevention of Pollution from Ships (MARPOL) – Annex V (Optional); Garbage (Nov. 2, 1973). The Gateway to Environmental Law. Available Online at: https://www.ecolex.org/details/international-convention-for-the-prevention-of-pollution-from-ships-marpol-annex-v-optional-garbage-tre-000989/participants/ (accessed January 10, 2021).

FAO (2018a). *FAO Yearbook. Fishery and Aquaculture Statistics 2016/FAO Annuaire. Statistiques des pêches et de L'aquaculture 2016/FAO Anuario. Estadísticas de Pesca y Acuicultura 2016*. Roma: FAO.

FAO (2018b). *Project Summary of: Case Study for Gear Marking in Indonesian Small-scale Gillnet Fisheries. Technical Consultation on the Marking of Fishing Gear*. Rome: FAO.

FAO (2019). *Voluntary Guidelines on the Marking of Fishing Gear. Directives Volontaires sur le Marquage des Engins de peche. Directrices Voluntarias Sobre el Marcado de las Artes de Pesca*. Rome: FAO.

FAO (2020). *The State of World Fisheries and Aquaculture 2020. Sustainability in Action*. Rome: FAO.

FAO (2021). *Fishing Operations. Guidelines to Prevent and Reduce Bycatch of Marine Mammals in Capture Fisheries*. Rome: FAO.

GGGI (2018). *GGGI Project: Gear Marking in Indonesian Small Scale Fisheries*. Seoul: GGGI.

GGGI (2020). *GGGI 2020 Annual Report*. Seoul: GGGI.

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

Gunarathna, K. T. N. P., Hallinnage, D. R., and Manikarachchi, I. U. (2019). "Assessment of the status of abandoned, lost or otherwise discarded fishing gear (ALDFG) in Southern Coastal waters of Sri Lanka: fisher's perspectives," in *Proceedings of the National Aquatic Resources Research and Development Agency*, Colombo.

Gunn, R., Hardesty, B. D., and Butler, J. (2010). Tackling 'ghost nets': local solutions to a global issue in northern Australia. *Ecol. Manag. Restoration* 11, 88–98. doi: 10.1111/j.1442-8903.2010.00525.x

Hamilton, S., and Baker, G. B. (2019). Technical mitigation to reduce marine mammal bycatch and entanglement in commercial fishing gear: lessons learnt and future directions. *Rev. Fish Biol. Fish.* 29, 223–247. doi: 10.1007/s11160-019-09550-6

He, P., and Suuronen, P. (2018). Technologies for the marking of fishing gear to identify gear components entangled on marine animals and to reduce abandoned, lost or otherwise discarded fishing gear. *Mar. Pollut. Bull.* 129, 253–261. doi: 10.1016/j.marpolbul.2018.02.033

Hong, S., Lee, J., and Lim, S. (2017). Navigational threats by derelict fishing gear to navy ships in the Korean seas. *Mar. Pollut. Bull.* 119, 100–105. doi: 10.1016/j.marpolbul.2017.04.006

Huntington, T. (2017). *Development of a Best Practice Framework for the Management of Fishing Gear. Part 2: Best Practice Framework for the Management of Fishing Gear*. Hampshire: Global Ghost Gear Initiative.

IMO (2018). *International Convention for the Prevention of Pollution from Ships (MARPOL)*. Available Online at: www.imo.org/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx. (accessed April 1, 2020).

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., et al. (2015). Plastic waste inputs from land into the ocean. *Science* 347, 768–771. doi: 10.1126/science.1260352

Joshi, A., Kale, S., Chandel, S., and Pal, D. K. (2015). Likert scale: explored and explained. *Curr. J. Appl. Sci. Technol.* 7, 396–403. doi: 10.9734/BJAST/2015/14975

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., et al. (2018). Evidence that the Great Pacific Garbage patch is rapidly accumulating plastic. *Sci. Rep.* 8:4666. doi: 10.1038/s41598-018-22939-w

Macfadyen, G., Huntington, T., and Cappel, R. (2009). *Abandoned, Lost or Otherwise Discarded Fishing Gear*. UNEP Regional Seas Reports and Studies No. 185. Rome: FAO. .

Macmullen, P., Hareide, N., Furevik, D. M., Larsson, P., Tschernij, V., Dunlin, G., et al. (2004). *A Study to Identify, Quantify and Ameliorate the Impacts of Static Gear Lost at Sea.* Available online at: https://www.seafish.org/document/?id=55615b7b-bfee-40f5-8f64-29529b12bfb6

Marcou, M., Marn, N., Muñoz, M. S., Macías, F. P., Kalachani, F., Parenzan, T., et al. (2016). *Med-Zero-Litter Action Plan-Targeting the Marine Litter of the Tourism Industry in the Mediterranean Sea. Massive Open Online Course on Marine Litter Netherlands Open Universiteit*. Available online at: https://bib.irb.hr/datoteka/815695.MOOC_MED.pdf (accessed January 10, 2021).

Masompour, Y., Gorgin, S., Pighambari, S. Y., Karimzadeh, G., Babanejad, M., and Eighani, M. (2018). The impact of ghost fishing on catch rate and composition in the southern Caspian Sea. *Mar. Pollut. Bull.* 135, 534–539. doi: 10.1016/j.marpolbul.2018.07.065

Matthews, T. R., and Glazer, R. A. (2010). "Assessing opinions on abandoned, lost, or discarded fishing gear in the Caribbean," in *Proceedings of the Gulf and Caribbean Fisheries Institute*. (Florida: University of Miami).

Mikelis, N. (2012). "MARPOL requirements for port reception facilities," in *Proceedings of the III Hemisphere Conference on Environmental Port Management*, Panama.

Miralles, L., Gomez-Agenjo, M., Rayon-Viña, F., Gyraitë, G., and Garcia-Vazquez, E. (2018). Alert calling in port areas: marine litter as possible secondary dispersal vector for hitchhiking invasive species. *J. Nat. Conserv.* 42, 12–18. doi: 10.1016/j.jnc.2018.01.005

National Oceanic and Atmospheric Administration Marine Debris and Program (2015). *Report on the Impacts of "Ghost Fishing" via Derelict Fishing Gear*. Silver Spring, MD: National Oceanic and Atmospheric Administration Marine Debris Program.

National Oceanic and Atmospheric Administration Marine Debris and Program (2016). *Report on Marine Debris Impacts on Coastal and Benthic Habitats*. Silver Spring, MD: National Oceanic and Atmospheric Administration Marine Debris Program.

National Research Council (2009). *Tackling Marine Debris in the 21st Century*. Washington, DC: The National Academies Press.

Nemoto, T., and Beglar, D. (2014). "Likert-scale questionnaires," in *Proceedings of the JALT 2013 Conference*. (Tokyo: JALT).

Nitta, E. T., and Henderson, J. R. (1993). A review of interactions between hawaii's fisheries and protected species. *Mar. Fish. Rev.* 55, 83–92.

Official Journal of the European Union (2019a). *Directive (EU) 2019/883 of the European Parliament and of the Council of 17 April 2019 on port Reception Facilities for the Delivery of Waste From Ships, Amending Directive 2010/65/EU and Repealing Directive 2000/59/EC*. Belgium: European Union.

Official Journal of the European Union (2019b). *Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the Reduction of the Impact of Certain Plastic Products on the Environment*. Belgium: European Union.

Øhlenschlæger, J. P., Newman, S., and Farmer, A. (2013). *Reducing Ship Generated Marine Litter—Recommendations to Improve the EU Port Reception Facilities Directive-Report Produced for Seas at Risk*. London: Institute for European Environmental Policy.

Pham, C. K., Ramirez-Llodra, E., Alt, C. H. S., Amaro, T., and Bergmann, M. (2014). Marine litter distribution and density in european seas, from the shelves to deep basins. *PLoS One* 9:e95839. doi: 10.1371/journal.pone.0095839

R Core Team (2019). *R: a Language and Environment For Statistical Computing*. Vienna: R Foundation for Statistical Computing.

Rech, S., Salmina, S., Pichs, Y. J. B., and García-Vazquez, E. (2018). Dispersal of alien invasive species on anthropogenic litter from European mariculture areas. *Mar. Pollut. Bull.* 131, 10–16. doi: 10.1016/j.marpolbul.2018.03.038

Richardson, K., Asmutis-Silvia, R., Drinkwin, J., Gilardi, K. V., Giskes, I., Jones, G., et al. (2019a). Building evidence around ghost gear: global trends and analysis for sustainable solutions at scale. *Mar. Pollut. Bull.* 138, 222–229. doi: 10.1016/j.marpolbul.2018.11.031

Richardson, K., Gunn, R., Wilcox, C., and Hardesty, B. D. (2018). Understanding causes of gear loss provides a sound basis for fisheries management. *Mar. Policy* 96, 278–284. doi: 10.1016/j.marpol.2018.02.021

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

Rousseau, Y., Watson, R. A., Blanchard, J. L., and Fulton, E. A. (2019). Evolution of global marine fishing fleets and the response of fished resources. *Proc. Natl. Acad. Sci. U. S. A.* 116, 12238–12243. doi: 10.1073/pnas.1820344116

Santos, M. N., Saldanha, H., Gaspar, M. B., and Monteiro, C. C. (2003). Causes and rates of net loss off the Algarve (southern Portugal). *Fish. Res.* 64, 115–118. doi: 10.1016/S0165-7836(03)00210-8

Stelfox, M., Hudgins, J., and Sweet, M. (2016). A review of ghost gear entanglement amongst marine mammals, reptiles and elasmobranchs. *Mar. Pollut. Bull.* 111, 6–17. doi: 10.1016/j.marpolbul.2016.06.034

Stelfox, M., Lett, C., Reid, G., Souch, G., and Sweet, M. (2020). Minimum drift times infer trajectories of ghost nets found in the Maldives. *Mar. Pollut. Bull.* 154:111037. doi: 10.1016/j.marpolbul.2020.111037

Uhrin, A. V. (2016). Tropical cyclones, derelict traps, and the future of the Florida keys commercial spiny lobster fishery. *Mar. Policy* 69, 84–91. doi: 10.1016/j.marpol.2016.04.009

UNEP/MAP (2015). *Regional Survey on Abandoned, Lost or Discarded Fishing Gear & Ghost Nets in the Mediterranean Sea - a Contribution to the Implementation of the UNEP/ MAP Regional Plan on Marine Litter Management in the Mediterranean*. Athens: UNEP/MAP.

Wilcox, C., and Hardesty, B. D. (2016). Biodegradable nets are not a panacea, but can contribute to addressing the ghost fishing problem. *Anim. Conserv.* 19, 322–323. doi: 10.1111/acv.12300

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

World Bank (2020). *World Bank Open Data*. Washington, DC: World Bank.

WWF (2020). *Stop Ghost Gear The Most Deadly form of Plastic Debris*. Switzerland: WWF.

Wyles, K. J., Pahl, S., Carroll, L., and Thompson, R. C. (2019). An evaluation of the Fishing for litter (FFL) scheme in the UK in terms of attitudes, behavior, barriers and opportunities. *Mar. Pollut. Bull.* 144, 48–60. doi: 10.1016/j.marpolbul.2019.04.035

Yıldız, T., and Karakulak, F. S. (2016). Types and extent of fishing gear losses and their causes in the artisanal fisheries of Istanbul. Turkey. *J. Appl. Ichthyol.* 32, 432–438. doi: 10.1111/jai.13046

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.