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Matching fishery-specific drivers of abandoned, lost and discarded fishing gear to relevant interventions

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ABSTRACT

There has been increasing recognition of the need to address adverse ecological and socioeconomic effects of abandoned, lost and discarded fishing gear (ALDFG). This component of marine debris has been progressively problematic over recent decades with the rapid expansion of global fisheries' footprint and effort, and the transition to synthetic and more durable materials for gear components. ALDFG drivers and consequences vary substantially by gear type, region, scale and individual fishery within these and other broad categories, including by the robustness of the fisheries management framework and influence of market-based incentives. Therefore, relevant interventions to avoid, minimize and remediate ALDFG depend on the fishery-specific context. This study compiled comprehensive, cross-referenced databases of causes of ALDFG production, and mitigation methods and enabling conditions for effective ALDFG management. Management interventions were categorized within a sequential mitigation hierarchy, where approaches to avoid and minimize ALDFG production and adverse consequences are considered before potentially less effective and more costly interventions for remediation and offsets. The linked databases enable discovery of the most promising ALDFG mitigation methods and priority fisheries management improvements so that a broader range of ALDFG policy interventions can be tapped. Illustrative case studies of ALDFG drivers and interventions were explored for gillnet, pelagic longline, trap and anchored fish aggregating device fisheries. By enabling stakeholders to identify the subset of alternative interventions that are relevant to fishery-specific ALDFG drivers and enabling conditions, the cross-referenced databases guide the allocation of resources to mitigate this especially problematic component of global marine litter.

1. Introduction

Over the past decade there has been increasing recognition of the need to address adverse ecological and socioeconomic effects of abandoned, lost and discarded fishing gear (ALDFG), also called derelict fishing gear [57,69,74,106,120,191]. There is extremely limited understanding of the life cycle and end-of-life management of fishing gear, trends in the magnitude of ALDFG entering oceans, and the effectiveness of interventions to avoid, minimize and remediate the production and adverse effects of derelict gear [85,117,164].

Unlike other forms of marine debris, derelict fishing gear is designed to catch marine life. Under certain conditions, derelict gear can continue to catch and kill organisms for years or decades, a phenomenon known as 'ghost fishing' [78,88,111]. This ghost fishing affects vulnerable species across taxonomic groups of cartilaginous and bony fishes, seabirds, marine mammals, reptiles and invertebrates, as well as principal market species [8,174,90]. While ghost fishing is the most studied and politicized adverse consequence of derelict gear, it causes other serious problems. This includes distributing and transferring toxins and microplastics into marine food webs; transporting invasive alien species; distributing microalgae that may cause harmful algal blooms; altering and damaging coastal and marine habitats; obstructing vessel

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navigation; damaging in-use fishing gear and submarine cables; and reducing the socioeconomic value of coastal and nearshore areas [12,51,52,85,103,120].

Marine macro-, micro- and nano-plastic pollution, including from ALDFG, is a major concern due to its direct adverse impacts on coastal and marine biota and habitats, indirect ecotoxicological impacts across manifestations of marine biodiversity, and risks to humans from seafood contamination [12,63,70,71,85,166]. Annually, about 74% of industrial fisheries lose an estimated 48.4 kt of plastic gear to the global oceans, not including plastic in abandoned and discarded gear [117]. In marine environments below the photic zone, especially on the deep seabed, plastics break down extremely slowly and are predicted to persist for extensive periods, from centuries to millennia and possibly longer [7,12,116].

ALDFG's adverse effects have been increasingly problematic over recent decades with the rapid expansion of the effort and the footprint (area affected and depth fished) of global fisheries, as well as the transition to synthetic, lighter but more durable materials used for fishing gear components [96,147,169,187,194]. ALDFG and other marine debris are produced by the world's ca. 39 million fishers participating in marine capture fisheries with 4.6 million fishing vessels [59].

There are numerous intentional and unintentional causes for gear from marine capture fisheries to be abandoned, lost or discarded, and these causes vary substantially by gear type, region, small- vs. large-scale and individual fishery within these and other broad categories [74,76,78,89,120]. Variability between fisheries in the robustness of their domestic and regional governance frameworks and in market-based incentives for environmental performance is likewise substantial [86,134,151,152,167]. As a result, different interventions to mitigate derelict fishing gear are appropriate for different fisheries. However, there is currently no resource available to identify ALDFG management interventions that are relevant for addressing specific drivers of ALDFG production, similar to a tool developed by the Conservation Evidence initiative, which enables conservation practitioners to link relevant management interventions to specific threats to a species group or habitat [180].

This study develops the foundation to fill this gap for ALDFG. The study enables stakeholders to identify ALDFG mitigation approaches that match their local context, so that interventions address the fishery-specific causes of abandonment, loss and discarding of gear and are viable within the context of the local fisheries' governance and socio-economic enabling conditions [101,160]. Previous studies identified causes of derelict gear generation [76,121,155,161,162,176,179] and identified and trialed derelict gear mitigation methods [35,74,78,99,120,143]. This study builds on this accumulated body of knowledge by integrating underlying drivers for the production of ALDFG and interventions relevant to specific causes. ALDFG mitigation methods and enabling conditions were categorized within a sequential mitigation hierarchy, allowing stakeholders to identify potentially more effective preventative approaches before considering approaches for remediation and offsets. The study also accounts for requirements for compliance monitoring, commercial viability costs (i.e., economic, practicality and safety costs), and the required degree of incentives from government and market-based rewards and penalties to achieve compliance with the use of alternative ALDFG mitigation methods. The resulting cross-referenced databases guide the allocation of resources for ALDFG management interventions to prevent and reduce this especially problematic component of global marine litter.

2. Methods

The study conducted a targeted, unstructured literature review to compile a comprehensive database of direct drivers (causes) for ALDFG production and interventions to mitigate the abandonment, loss and discarding of gear from marine capture fisheries. We searched the Bycatch Management Information System database of references and regulations, filtered for ALDFG management (https://www.bmis-bycatch.org/), and reviewed reference lists of relevant compiled publications and grey literature. For each intervention, we identified which drivers for the production of derelict gear that it has the capacity to address. We also identified whether the intervention is implemented specifically to manage derelict gear or otherwise is implemented for broad fisheries management purposes but contributes to managing derelict gear.

ALDFG mitigation enabling measures, which are interventions or conditions that incentivize the implementation of ALDFG mitigation measures, were compiled. Enabling conditions that incentivize implementation of practices that mitigate ALDFG are necessary preconditions for effective ALDFG management [101,160]. Enabling measures can be market-based, such as from private fisheries assessment and certification programs, and governance enabling measures, including from command-and-control frameworks of large-scale industrial fisheries and community-based self-governance and co-management frameworks of small-scale fisheries. The governance enabling conditions include robust components of fisheries management frameworks of monitoring, control, surveillance, enforcement and outcomes of enforcement actions, including a broad range of combinations of penalties and rewards that are sufficient to deter noncompliance [21,100,146,177].

ALDFG mitigation measures were categorized within three tiers of an adapted ALDFG sequential mitigation hierarchy. Avoidance methods completely prevent a cause of derelict gear generation within the scope of the intervention. Minimization measures can reduce rates of generating ALDFG or reduce fishing effort, which reduces the magnitude of derelict gear created. Minimization methods can also reduce the adverse effects caused by ALDFG. Remediation methods halt one or more adverse effect of ALDFG. The study scope did not include mitigation methods that involve offsetting residual impacts from ALDFG that were not avoided, minimized and remediated. Supplemental Material Section S1 reviews potential approaches to offset ALDFG, and Section S3 contains a glossary of acronyms and technical terms, including definitions of the tiers of a sequential ALDFG mitigation hierarchy.

For each mitigation method, the study identified monitoring and surveillance approaches that enable compliance monitoring. Fisheries monitoring methods that can be used for compliance monitoring of one or more ALDFG mitigation method include: at-sea human observers, electronic monitoring, electronic tracking of gear position, and detection of derelict gear that was sighted or recovered when grounded or at sea, including through crowd-sourcing [56,107,139]. Fisheries surveillance approaches relevant to one or more ALDFG mitigation method include: Automatic Identification System (AIS), satellite-based Vessel Monitoring System (VMS), satellite imagery for vessel detection and some gear types, aerial surveillance, dockside inspections, and patrol vessel at-sea boarding and inspection [56,107,184].

The study presents illustrative case studies of causes and alternative interventions for mitigation of ALDFG, some from small-scale fisheries of developing countries, others from large-scale fisheries of developed countries. Case studies are included for: (1) India's gillnet and trammel net fisheries, (2) terminal tackle bite-offs in global hook-and-line fisheries, (3) California's commercial Dungeness crab fishery, and (4) Indonesia's and the Maldives' tuna fisheries using anchored fish aggregating devices (aFADs).

The study scope is on derelict gear generated by marine capture fishing vessels. The scope excluded marine debris from aquaculture and ranching facilities, and pathways for derelict fishing gear to enter the sea other than directly from fishing vessels at sea, such as from fishing harbors and seaports. The scope also excluded non-gear marine debris from fishing vessels, including intentionally-discarded types of garbage that are specific to fishing vessels, such as plastic bags containing salt used to make brine and plastic-lined boxes and plastic packing straps used for frozen bait [47,118]. Furthermore, the study excluded solid and liquid waste that is produced across types of marine vessels, including oil, sewage, cargo nets, anti-fouling paint particles, bilge water and ballast water [53,163,66].

3. Results - Linked databases of ALDFG drivers and solutions

Table 1 identifies direct drivers of ALDFG production, categorized as resulting in the abandonment, loss or discarding of fishing gear. Of 36 drivers in Table 1, some, such as inclement environmental conditions and sinking of vessels, may occur across all gear types of vessel-based fisheries. Other drivers, however, are applicable to either static or mobile gear types, such as severed buoy lines and abrasion and loss of strands of dolly ropes, respectively. And, some apply only to untended passive gear, such as gear moving position, theft and vandalism.

Drivers vary by fishery, region and gear type and we therefore did not rank drivers according to their relative importance in ALDFG production. However, across fisheries, some drivers, such as the sinking of fishing vessels, are likely to be infrequent and small contributions to ALDFG production. Others, including loss during inclement weather, snagging on submerged features and debris by bottom fisheries, gear conflicts, conflicts with marine vessels, practices by inexperienced new entrants, and the unavailability of affordable and convenient port reception facilities may be relatively important global causes of ALDFG production [120,121,161,162].

Table 2 identifies methods for mitigating derelict fishing gear and enabling measures that provide incentives to implement ALDFG mitigation methods. Table S1 provides illustrative examples for each ALDFG mitigation method, and for some records includes details on the definition of the method. For each mitigation method, the causes for producing derelict gear that it has the capacity to address are identified, hence Tables 1 and 2 are cross-referenced or linked. By using the unique ID of each ALDFG driver, each driver can be related to relevant ALDFG mitigation interventions, and each intervention can be related to relevant drivers.

The subset of methods in Table 2 that would be used specifically to mitigate derelict gear are identified. Other approaches may be employed for multiple applications (e.g., gear designs that reduce ghost fishing rates may also be used to reduce bycatch rates of vulnerable and unwanted species by in-use gear). Approaches that enable effective compliance monitoring are identified for each method.

Some ALDFG mitigation methods are mutually exclusive. For example, using more durable gear components conflicts with less durable gear. However, the gear components involved may differ, where, for instance, less durable, thinner net twine diameter could reduce gillnet ghost fishing efficiency while more durable floatlines could reduce gear loss (Table S1). And, for example gear marking to increase the visibility of passive gear may conflict with some approaches to reduce gear theft and vandalism, including using submerged buoys and floatlines. For cases where interventions are mutually exclusive, the fishery-specific drivers and predicted mitigation efficacy of the conflicting approaches could guide the selection between them.

There are four enabling measures included in Table 2: A broad measure on robust components of an ALDFG management framework, positive and negative incentives for compliance with ALDFG control measures, and fleetwide and vessel-based ALDFG quotas. The 32 mitigation interventions in Table 2 are categorized within a sequential mitigation hierarchy. Illustrative examples of measures within each mitigation hierarchy tier include:

- **Avoid ALDFG production**

  - o Area-based management tools, ranging from static and permanent no-take marine protected areas to temporally- and spatially-dynamic (mobile) closures, might enable complete avoidance of derelict gear production, such as by avoiding gear conflicts by temporally or spatially separating passive and mobile gear sectors [20].
  - o Input controls, such as buyback programs which reduce fishing capacity by purchasing and retiring fishing vessels and permits, and

Table 1
Direct drivers of the production and adverse consequences of ALDFG[a] categorized as resulting in abandoned (A), lost (L) or discarded (D) fishing gear.

No.	ALDFG causes	ALDFG component
1	Lack of incentives to implement ALDFG mitigation methods due to deficits with control, surveillance, or enforcement systems; inadequate penalties resulting from enforcement actions for identified infractions; and inadequate rewards for compliance with ALDFG management measures	A, L, D
2	Limited awareness or low concern over adverse consequences of ALDFG	A, L, D
3	No program in place to retrieve or disable gear reported as ALD; legal framework prohibits retrieving and disabling others' gear	A, L, D
4	Economic instruments (e.g., subsidies for new gear, insurance for lost gear, fishers are not responsible for covering costs for new gear) make it inexpensive for fishers to replace gear. This reduces the incentive for fishers to repair and maintain gear and vessel equipment, to not abandon and discard unwanted gear, to avoid risks of gear loss, and to attempt to retrieve temporarily lost and abandoned gear	A, L, D
5	Bad weather, strong currents or sea ice sever, move or submerge surface marker buoys or float lines; move the gear so that it cannot be relocated or cause the gear to snag on bottom features; break moorings; and sweep improperly stored gear overboard	A, L
6	Impractical, including insufficient time, or economically inefficient to retrieve gear or to attempt to locate and retrieve temporarily lost or abandoned gear	A, L
7	Static gear (gillnets, pots) is set too deep, increasing risk of loss and impracticality for retrieval, and reducing the likelihood of recovery if temporarily lost	A, L
8	Risk of detection of illegal fishing or illegal gear (e.g., crew spot a patrol vessel while illegally fishing in a closed area, and flee, abandoning their gear, in order to attempt to avoid detection)	A, D
9	Use of biodegradable gear creates a disincentive for fishers to responsibly dispose of end-of-life gear	A, D
10	Worn/damaged gear components, including ash from onboard incineration of unwanted fishing gear, are perceived to be most convenient to discard or abandon at sea	A, D
11	Insufficient storage room onboard for all gear that was set (e.g., when the space used to store gear when starting a trip is subsequently used as the fish hold)	A, D
12	Malfunction of vessel equipment other than gear tracking system (e.g., hauler)	A
13	Unsafe to retrieve gear (e.g., snagged on submerged feature, inclement weather)	A
14	Untended gear drifts out of fishing grounds into areas where the fishing vessel/gear is prohibited (e.g., dFAD drifts into an EEZ where the vessel is not authorized to fish)	A
15	When repairing and making up new gear onboard vessels at sea, used and new gear components (crimps, chafing gear, net clippings, fragments of line, strands of dolly rope, etc.) may be inadvertently swept or intentionally discarded overboard	L, D
16	Catch escapes with gear remaining attached (e.g., hook biteoffs of terminal tackle of hook-and-line gear, baleen whale entanglement in floatlines and groundlines of active, in-use pots and gillnets)	L
17	During use of the gear, due to regular wear and from the use of bottom gear that contacts the seabed, fragments of gear components can detach, such as small pieces of foam	L

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Table 1 (*continued*)

No.	ALDFG causes	ALDFG component
	from floats and buoys, and strands or pieces of strands from dolly ropes	
18	Fishing vessel sinks with gear onboard or set	L
19	Gear conflicts, both between (e.g., passive gear is accidentally or intentionally towed away or marker buoy and buoy lines are cut by mobile fishing gears such as trawlers and dredgers) and within gear types (e.g., in congested fishing grounds, gear is set on top of each other).	L
20	Improper gear designs and materials increase loss rates (e.g., improperly designed mooring for an anchored FAD)	L
21	Inadequate maintenance/replacement of worn gear components, including components used to track gear position, result in loss	L
22	Malfunction of tracking systems of passive gear	L
23	Marine organism moves gear (e.g., baleen whale entangles in float or groundline of fixed gear, and drags the gear away)	L
24	Marine traffic - commercial ships and recreational vessels anchor on static gear, pull up and cause the loss of the gear	L
25	Marine traffic - passing vessel runs over the gear, towing away gear, cutting marker buoys and buoy lines, etc.	L
26	New gear may contain loose fragments that can be lost at sea when first used	L
27	Operator error, including by new entrants/inexperienced fishers (e.g., fish at grounds with high risk of gear loss, use fishing gear designs or materials that result in loss, gear is set too deep for buoy line)[b]	L
28	Snag on wrecks, other debris, infrastructure (cables, oil and gas pipelines and wellheads), and natural submerged features	L
29	Surface marker buoy lines and float lines sever due to wear, causing loss of the main portion of the gear, including the sinking of dFADs	L
30	Theft of passive gear, including removing a satellite buoy from a dFAD	L
31	Untended passive gear is misplaced (e.g., untended gear with no tracking system drifts away and is lost)	L
32	Untended passive, static gear is left in place in between fishing seasons in order to retain possession of fishing grounds, increasing risk of loss	L
33	Vandalism, including cutting buoy lines, removing marker buoys, intentionally running over the gear (e.g., due to conflicts within and between gear types, due to gear located in shipping channel)	L
34	Crew release live catch or discard dead catch with gear remaining attached (e.g., following prescribed handling and release practices for deeply hooked ETP species)	D
35	Discarded offal and bait may contain terminal tackle (e.g., bait with hook)	D
36	Insufficient storage space onboard for worn/damaged gear components that were replaced during the trip	D

[a] [6,20,26,109,120,121,172,133,74,195,19,89,126,143,168,181,186,54,69,76,78,85,132,161,162,179]
[b] May be more appropriately categorized as an underlying, indirect driver of ALDFG production

output controls, such as a fleetwide catch limit that when reached triggers a temporary fishery closure. There is complete avoidance of ALDFG production by vessels that are retired through the buyback program, and during a temporary fishery closure.

- **Minimize ALDFG production and adverse consequences**

Table 2
ALDFG mitigation and enabling interventions and drivers of derelict gear production that each mitigation method has the capacity to address. Methods are categorized within a sequential mitigation hierarchy. Methods with an asterisk are approaches that would be used specifically to mitigate derelict gear, while other approaches may be employed for additional applications. Approaches that enable compliance monitoring for each ALDFG mitigation method are identified. Key to drivers is in Table 1. See Table S1 for examples of each ALDFG mitigation and enabling method, definitions and citations.

Mitigation hierarchy[a]	Mitigation and enabling methods	Drivers addressed	Compliance monitoring[b]
A	Area-based management tools - static and dynamic time-area restrictions	5, 6, 7, 13, 14, 18, 19, 24, 25, 27, 28, 33	Aerial, AIS, electronic gear tracking, EM, observers, satellite imagery, VMS
A	*Communication within and between fishing fleets on the location of their gear	19, 33	NA (voluntary industry approach)
A	*Limit amount of gear allowed onboard	11, 36	Aerial, board/inspect, dockside, EM, observers
A, M	*Controls on at-sea disposal of debris and infrastructure installation and decommissioning practices	13, 28	NA
A, M	Incinerators and compactors	11, 36	Board/inspect, dockside, EM, observers
A, M	Input and output controls	11, 18, 32	Variable depending on the measure, from none (buyback, limited entry) to combinations of: aerial, AIS, board/inspect, dockside, electronic gear tracking, EM, observers, satellite imagery, VMS
A, M	Periodic or continual attendance of passive gear	5, 6, 14, 19, 24, 25, 30, 31, 32, 33	Aerial, board/inspect, electronic gear tracking, EM, observers
M	Change in gear type	Depends on the old and replacement gear types	Aerial, board/inspect, dockside, EM, observers, satellite imagery
M	Continuous maintenance of gear and vessel equipment to replace and repair worn gear components and damaged equipment	4, 5, 12, 16, 18, 21, 22, 29	Board/inspect, dockside, observers
M	Deterrence of illegal fishing	8, 19	Aerial, AIS, board/inspect, dockside, electronic gear tracking, EM, observers, satellite imagery, sight/recover, VMS
M	*Gear designs and materials that reduce gear loss	5, 7, 16, 17, 20, 23, 25, 30, 33	Board/inspect, dockside, EM, observers, sight/recover
M		2, 8, 30	

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Table 2 (*continued*)

Mitigation hierarchy[a]	Mitigation and enabling methods	Drivers addressed	Compliance monitoring[b]
	Gear marking to enable supply chain traceability		Board/inspect, dockside, EM, observers
M	Gear marking to identify ownership	2, 8, 30	Aerial, board/inspect, dockside, electronic gear tracking, EM, observers, sight/recover
M	Gear marking to increase passive gear visibility	5, 19, 23, 24, 25, 31	Aerial, board/inspect, dockside, EM, observers, sight/recover
M	Gear repair systems	4, 10, 21, 29	Dockside
M	Gear supply chain traceability system and Extended Producer Responsibility schemes for fishing gear	2, 8, 30	Dockside
M	Gear technology that increases ghost fishing selectivity of ALDFG from passive gear	16, 35	Board/inspect, dockside, EM, observers, sight/recover
M	*Management of waste produced when: (1) repairing and making up new gear onboard vessels at sea; (2) preparing gear for storage; and (3) processing offal, spent bait and discards prior to discarding overboard	10, 15, 26, 34, 35	Board/inspect, EM, observers
M	More durable gear components	5, 16, 17, 19, 20, 25, 29, 32	Board/inspect, dockside, EM, observers, sight/recover
M	Prohibitions on the use of hazardous materials (e.g., lead, copper coating and other antifouling agents) in fishing gear components	NA[c]	Board/inspect, dockside, EM, observers, sight/recover
M	Secure stowing of gear onboard	5, 18, 27	Board/inspect, dockside, EM, observers
M	Technology to reduce unwanted gear contact with the seabed	28	Board/inspect, dockside, EM, observers
M	Technology to track gear position	5, 19, 23, 25, 30, 31, 32, 33	Aerial, board/inspect, dockside, electronic gear tracking, EM, observers, sight/recover
M	Training, outreach and education for new entrants and periodic refreshers	2, 9, 20, 27	Dockside
M, R	Degradable and less durable gear	NA[c]	Board/inspect, dockside, EM, observers, sight/recover
M, R	*Disablement of ghost fishing efficiency of reported/detected ALDFG	3	NA
M, R	*Port reception and recycling facilities for ALDFG, convenient and affordable	10	Dockside
R	Materials for gear components that are recyclable	4, 9	Board/inspect, dockside, EM, observers, sight/recover
R	*Removement of reported/detected ALDFG	3, 6	NA
R	*Requirement for fisher reporting of gear that they lost, abandoned or discarded (such as required under MARPOL Annex V[d])	1, 9, 30	Dockside, electronic gear tracking, EM, observers, sight/recover
R	*Requirements for fishers to: (1) possess equipment to retrieve ALDFG, (2) obtain training on how to retrieve ALDFG, and (3) attempt to retrieve ALDFG that they produced or that they encounter at sea, when safe	3, 6	Board/inspect, dockside, EM, observers
R	*Technology to detect temporarily lost and abandoned gear	5, 6, 30, 31, 32	Board/inspect, dockside, electronic gear tracking, EM, observers
E	*ALDFG rate or magnitude limit, fleet- or vessel-based, where the latter could be individual transferable ALDFG quotas	2, 4, 6, 9, 10, 11, 21	Electronic gear tracking, EM, observers
E	*Negative incentives - penalties	1, 4, 9	NA
E	*Positive incentives - rewards	1, 4, 9	NA
E	*Robust ALDFG management framework of control, surveillance, enforcement and outcomes of enforcement actions, including implementation of MARPOL Annex V ban on abandonment and discarding of fishing gear[e]	1, 4, 8, 9, 19, 20, 24, 25, 32, 35	NA

[a] A = ALDFG avoidance; M = ALDFG minimization; R = ALDFG remediation; E = enabling precondition for ALDFG management.

[b] Aerial=manned and autonomous aerial surveillance; AIS=Automatic Identification System used to track vessel position; board/inspect=at-sea boarding and manned and autonomous inspection; dockside=dockside inspection; electronic gear tracking=electronic tracking of gear position, including satellite buoys and AIS beacons; EM=fisheries electronic monitoring system; observers=conventional at-sea human observer program; satellite imagery=satellite technology systems used for vessel detection and detection of some gear types; sight/recover=detection of derelict gear sighted or recovered when grounded or at sea; VMS=satellite-based Vessel Monitoring System.

[c] Use of biodegradable and non-toxic materials and less durable gear components can reduce adverse consequences of ALDFG such as those caused by

drivers 16, 34 and 35 in Table 1, but do not address a driver of production of ALDFG.

[d] Under the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex V, fishing vessel operators are required to record discarded and lost fishing gear in a garbage record book or ship's log, and to report to relevant authorities when it, "poses a significant threat to the marine environment and navigation," as determined by member States. The *2017 Guidelines for the Implementation of MARPOL Annex V* [105] clarify that Party's governments should determine if accidentally lost and discarded fishing gear is required to be reported under Annex V Regulation 10.6 by considering factors including: (i) the amount of lost and discarded gear; (ii) the conditions of the marine environment where it was lost or discarded; (iii) the characteristics of the lost gear, including types, weight and/or length, quantity, material, and buoyancy; and (iv) the vulnerability of habitat and protected species to gear interactions in the location where the gear was lost/discarded. The IMO guidelines use the example of "whole or nearly whole large fishing gear or other large portions of gear" as derelict fishing gear that could be considered to meet the Annex V Regulation 10.6 definition of posing "a significant threat to the marine environment and navigation" [105].

[e] MARPOL Annex V generally prohibits the discharge of all garbage into the sea. Regulation 3 prohibits the disposal of all plastics, including fishing gear, into the sea in all locations [104,105]. Regulation 7 defines exceptions to the prohibitions during emergency and non-routine situations, and additional exceptions are provided in regulations 4, 5, and 6 of the Annex, which are related to food waste, cargo residues, cleaning agents and additives and animal carcasses. The MARPOL Annex V implementation guidelines (Section 1.7.8 in [105]) clarify that, "Fishing gear that is released into the water with the intention of later retrieval, such as fish aggregating devices (FADs), traps and static nets, should not be considered garbage or accidental loss." This clause is likely intended to apply to all untended in-use fishing gear, but not untended gear that fishers set but do not retrieve either due to accidental loss or intentional abandonment, and that fishers intentionally discard at sea.

o Using robust anchored fish aggregating device (FAD) designs and materials (Section 4.4, [1,175]) reduces gear loss rates.
o Securely stowing gear onboard and managing waste produced when repairing and making up new gear reduces the risk of gear being swept or discarded overboard [126].
o When combined with a robust fisheries management framework, gear marking to identify the owner or last user of ALDFG can reduce ALDFG production. Gear marking can disincentivize deliberate abandonment and discarding, incentivize the retrieval of temporarily lost gear, may make it more difficult to steal gear, and may create an incentive to report when gear is lost or abandoned. It may also deter illegal fishing, which can be a driver for ALDFG production [57,99].
o Gear marking can also enable supply chain traceability, facilitating Extended Producer Responsibility schemes for fishing gear, incentivizing gear manufacturers, assemblers, suppliers and other companies in the supply chain to contribute to actions that mitigate ALDFG [143].
o Methods that reduce the duration of ghost fishing or reduce the ghost fishing efficiency of ALDFG can minimize ghost fishing mortalities. For instance, using less-durable and biodegradable materials for fishing gear components, and incorporating escape panels and cords, can reduce ghost fishing duration [24,75,141,183].
o Gear designs that increase the selectivity of in-use (not derelict) passive gear can reduce ghost fishing rates of certain species and sizes of catch in ALDFG. For instance, reducing anchored gillnet profile and eliminating or increasing the length of tiedowns reduces marine turtle catch risk in both in-use and derelict gear [78,83].
o Using biodegradable and non-toxic materials for some gear components would reduce the dispersal and transfer of toxins derived from ALDFG into marine food webs, and risk of ingestion of toxic components of ALDFG [70,71,85,143].

- **Remediate ALDFG production or adverse consequences**

o Programs that detect and remove ALDFG, or that sweep fishing grounds and retrieve derelict gear eliminate continued adverse effects from the derelict gear [49,121,179].
o Sweeping can also disable ALDFG but leave it in place, reducing the derelict gear's ghost fishing efficiency, risk of fouling in-use surface fishing gear and risk of obstructing vessel navigation, but not other adverse effects of ALDFG [85].

In addition to being categorized into tiers of a sequential mitigation hierarchy, at the broadest level, the methods to mitigate ALDFG identified in Tables 2 and S1 can also be categorized as either: (1) input and output controls that eliminate or reduce fishing effort and hence ALDFG production; (2) measures that reduce ALDFG production rates, including methods to locate temporarily lost and abandoned gear; (3) methods that reduce the adverse effects of ALDFG; (4) methods that disable and remove ALDFG; and (5) enabling measures that incentivize the employment of ALDFG mitigation methods. We present a sample of case studies in the following sections in order to demonstrate the high variability among fisheries, region and gear type in drivers of ALDFG production, degree of robustness of the fisheries management framework, and hence appropriate interventions to mitigate drivers.

4. Case studies

4.1. India gillnet and trammel net fisheries

Gillnet and trammel net fisheries compose 67% of India's ca. 194,000 fishing vessels and provide employment for about 860,000 people [125,186]. Artisanal, small-scale gillnet and trammel net fishers use non-motorized canoes and catamarans to target forage fishes and shrimp using small and medium mesh gillnets and trammel nets weighing up to 20 kg, making day trips. Small gillnet vessels with outboard motors target forage fishes, pomfrets and shrimp using small and medium mesh gillnets and trammel nets weighing up to 45 kg, also making day trips. Larger-scale vessels with outboard motors target tunas, billfishes, sharks, other large pelagic fishes and snappers using fleets of gillnets weighing up to 900 kg, with trips lasting up to 5 days. Mechanized vessels with inboard engines target tunas, billfishes, sharks and other large pelagics using fleets of large mesh drift gillnets that are up to 18 km in length and weigh up to 3,000 kg, with trips lasting up to a month [185,186]. Gillnets supply over 37% of India's ca. 200,000 t of annual landings by tuna fisheries [159].

Based on fisher surveys, about 25% of gear is abandoned and lost annually in India's gillnet and trammel net fisheries [186]. Loss and abandonment make up roughly equal proportions of the ALDFG. Discarding gear at sea is relatively uncommon [186]. Once gear becomes unusable for fishing, it is typically repurposed for various land-based activities or sold for recycling.

Inclement weather and snagging on seabed features and submerged debris (e.g., oil rigs, construction material) are primary causes of gear abandonment and loss. For example, the main cause of gear loss in the Andhra Pradesh tuna gillnet fishery, with a relatively high ALDFG production rate of 36%, was due to rough sea conditions during the monsoon season. Entire strings (fleets) may be lost during cyclones. In trammel net fisheries that fish at rocky substrates and coral reefs, there are particularly high rates of abandonment and loss due to gear snagging on the seabed, which was exacerbated when fishers changed from multifilament to monofilament netting [186]. Another cause of gear loss is from trawlers and non-fishing vessels towing away the gear and severing marker buoys. Strings of gillnet panels, which are set at night, are not adequately marked to enable visibility. Entanglement of large marine organisms can also cause the loss of a section or entire string of gear. In ports where gillnets are stored on beaches, the nets can wash out to sea during inclement weather. Less experienced fishers had higher loss and abandonment rates, and longer gillnet lengths had higher loss rates [186].

Improvements in India's federal, state and district fisheries management systems for gillnet and trammel net fisheries are needed to address these drivers of ALDFG creation. This includes filling gaps in monitoring and control, such as capping gillnet effort. Gaps in surveillance and enforcement of existing controls also need to be filled, such as a Kerala State limit on gillnet size, a ban on night fishing by trawlers and a ban on bottom trawling in inshore zones where conflicts with static gear occur [60,61,112,186].

In some small-scale gillnet fisheries, the relatively low value of new netting reduces the incentive for fishers to attempt to repair and not discard old netting, which is exacerbated in some fisheries through government subsidies [45,72]. This is not the case in India, where the cost for new nylon monofilament netting is considered relatively high (personal communication, 17 July 2021, Saly N. Thomas, India Central Institute of Fisheries Technology).

Referring to Tables 2 and S1, potential mitigation approaches to address identified drivers of ALDFG production include:

- Dissemination of accurate weather forecasts and adopting voluntary or mandatory measures restricting fishing during inclement weather;
- Area-based management to avoid fishing in areas with high risk of gear snagging;
- Marking gear to increase visibility, to reduce the risk of vessel strikes and conflicts with mobile gear;
- Area-based management to avoid areal and temporal overlap between gillnet and trammel net fishing grounds and ships and trawlers;
- Communication between gillnet/trammel net vessels and vessels using mobile fishing gear;
- Using gear designs, such as submerged buoys and floatlines, could reduce the risk of loss from vessel strikes;
- More frequent or continual attendance of the gear;
- Employment of technology to detect when gear becomes lost and identify the position of temporarily lost or abandoned gear;
- Training of new entrants;
- Programs for reporting, recovery or disablement of ALDFG;
- Incentives (rewards and penalties) for proper disposal of end-of-life, damaged gear currently with low economic value;
- Improvements to the fisheries management framework to augment ALDFG management; and
- Use of gear designs and fishing methods that reduce the ghost fishing efficiency and duration of ALDFG from gillnets and trammel nets [78,83,200], and restrictions on the use of hazardous materials, such as lead weights on footropes.

4.2. Global pelagic longline bite-offs

Hook-and-line fisheries experience gear losses when catch escape by severing the terminal tackle (e.g., pelagic longline, [4,11,81,136]). Based on estimates of bite-off rates [4,81,197] and global pelagic longline effort [87], ca. tens of millions of terminal tackle components may be lost annually. This estimate does not include the lost gear from bite-offs in numerous other hook-and-line gear types, including recreational hook-and-line shark fisheries which occur in diverse, sensitive coastal and offshore ecosystems [13,67].

Species with sharp teeth, including sharks and some teleosts such as snake mackerel (*Gempylus serpens*), can sever by biting through or abrading monofilament leaders and escape [77]. Species with serrated teeth, like tiger sharks (*Galeocerdo cuvier*), are more likely to be able to bite through monofilament leaders than those with needle-like teeth, like bigeye threshers [197]. Species that tend to thrash violently when hooked, such as longtailed thresher (*Alopias vulpinus*) and blue marlin (*Makaira nigricans*), are more likely to abrade and sever a monofilament leader than those with relatively less energetic reactions to capture, such as black marlin (*Istiompax indica*) [82,197].

The terminal tackle may eventually be expelled if the hook corrodes or is shed [16,153]. The escaped organism may die as a result of the retained gear, especially if hooked internally [2,22,113] or possibly from long trailing line (e.g., [58], however, see [16,137,153]). Or, embedded hooks may be retained for the lifetime of the fish [16,82].

With all of these scenarios, the lost terminal tackle's fate is likely to eventually sink to the seabed in coastal and deep ocean areas, or to strand on coastlines [2,13]. Once on the seabed, derelict hooks and short sections of monofilament line may be buried in soft sediment or incorporated into hard substrate, or may snag on a three-dimensional surface [85]. While posing minimal risk of ghost fishing, the derelict gear, however, risks causing other adverse consequences, include transporting and transferring toxins (e.g., from lead in branchline weights, and chemicals used in light-sticks, [91,142,150,201]) and microplastics into marine food webs; altering and damaging habitat; and reducing the socioeconomic value of coastal and nearshore habitats [85].

There are several approaches to avoid and minimize longline bite-offs. One method is to use more durable materials for leaders, such as wire and multifilament line instead of monofilament nylon – however, this increases shark catch rates [4,197]. In fisheries where shark catch is unwanted (e.g., regulatory restrictions/bans, low or no market value, or avoiding ammonia contamination of more valuable non-shark catch in the hold, [82]), some methods that reduce shark catch risk, other than prescribing monofilament leaders, would also reduce bite-off rates. This includes area-based management tools, such as static and dynamic fishery closures, to avoid temporally and spatially predictable sites with high shark catch rates, or high ratios of shark-to-target species catch rates [98,114]. Using small forage fish species for bait instead of squid species or pieces of incidental catch, adjusting the depth and time-of-day of fishing and using J-shaped instead of circle shaped hooks of the same size are other approaches to reduce shark catchability [79,80]. However, the latter two approaches result in multispecies conflicts, and while reducing shark catch risk, J-shaped hooks increase shark haulback mortality rates relative to circle hooks [80].

'Weak hooks' may also reduce shark catch rates. This entails using a fishing hook with a wire diameter below a threshold, shape, material, and potentially other attributes, in combination with branchlines and leaders of materials and with minimum diameters and concomitant breaking strengths that exceed the pull force required for the hook to bend beyond a threshold angle [15,64]. Weak hooks, theoretically, could enable sharks to bend hooks and escape, while retaining target species. This requires that sharks are able to exert a higher pull force than the target species, and many other caveats, such as the direction of pull and whether tension is maintained on the branchline and mainline during gear retrieval and that crew regularly maintain branchlines and leaders so that they keep the necessary breaking strength.

Using corrodible hooks may reduce ghost fishing mortality rates resulting from bite-offs by reducing the duration that hooks and trailing line remain attached, or, alternatively, using corrodible rings on hooks could reduce the duration of retained trailing line without compromising the hook's strength. However, there may be low risk of sub-lethal and lethal effects of externally hooked sharks [16].

4.3. California's commercial Dungeness crab pot fishery

The California commercial Dungeness crab (*Metacarcinus magister*) fishery is one of California's most valuable, with over 400 active vessels deploying up to 139,000 pots and producing about USD $62 million in ex-vessel value each season [30]. It operates as a derby fishery, with the majority of landings made within the first two months of the season, which varies by year and region [93].

Single pots are fished on the bottom with bait – strings of pots are not used [32,149]. Pots are made with an iron frame, wrapped with strips of rubber, covered with stainless steel wire meshes, and cost approximately USD $200 per trap [30]. There have been no formal studies on the drivers and rates of lost gear production, though PFMC [149] estimated anecdotally that 10% of gear may be lost annually in U.S. west coast

Dungeness crab fisheries, primarily due to rough winter ocean conditions during the highly competitive early weeks of the season. Marine traffic may also contribute to gear loss, as there are important fishing grounds in the vicinity of major shipping ports.

The fishery has long operated with a range of measures to minimize ALDFG and mitigate impacts, such as the use of a "destruct device" escape panel, which uses degradable untreated cotton twine or corrodible metal, to mitigate ghost fishing by lost traps. There have been longstanding voluntary efforts by fishers to remove derelict traps outside of the fishing season, motivated by the high cost of crab traps and potential for gear conflicts with the salmon troll fishing season that operates in overlapping fishing grounds in the spring and summer. Expanding gear accountability and ALDFG remediation became a priority management concern beginning in response to a sudden increase in confirmed whale entanglements in fishing gear off the US west coast beginning in 2014 [171,170]. The increase in entanglements was primarily associated with humpback whales, whose presence off the U.S. west coast peaks in summer months, following the traditional end of the Dungeness crab trap fishery. To further reduce the production and impact of derelict gear and ensure that intact derelict traps do not pose entanglement risk to whales, the fishery has developed and implemented a range of additional measures in recent years [42].

Notably, California commercial Dungeness crab fishers have developed a locally led recovery program for lost fishing gear, with a focus on incentives for industry participation and financial sustainability. Fishing industry leaders in Half Moon Bay, California, partnered with The Nature Conservancy (TNC), an international environmental organization, to pilot and expand an industry-led program in which fishers are compensated for retrieving lost gear with revenue generated by selling recovered traps back to owners [188,189]. TNC created a web and phone application to support the program by allowing fishers to efficiently track and document lost gear from recovery at sea through to final distribution. The multi-year pilot across multiple ports recovered over 1,500 lost traps. In 2019, California formalized a port-based post-season recovery program, bolstering financial incentives by legally requiring gear buyback [32,178]. The lost gear recovery program complements additional provisions for the removal of derelict pots during and after the fishing season without guaranteed compensation, and fishers are also required to report the number of traps lost at the end of each fishing season [32]. In 2020, seven major crab ports reported recovering over 630 lost traps through the port-based program and additional provisions for legal lost-gear recovery [31].

The fishery operates with two cooperative management bodies that advise on overall management measures (Dungeness Crab Task Force) and marine life entanglement specific considerations (Dungeness Crab Fishing Gear Working Group). Many of the regulations that avoid and minimize gear loss and reduce ghost fishing efficiency and duration were developed in consultation with one or both of these bodies [30,32,33,41,149]. These regulations include:

- Limit on the length of surface lines (distance between a main marker surface buoy and final trailer buoy) and limit of two trailer buoys;
- Use of marker surface buoys;
- Use of trailer buoys, which keep vertical lines visible from the surface;
- Traps must be tended (pulled and serviced) at least every four days (weather permitting);
- Input controls - limited entry fishery, limit on the number of pots per permitholder, an up-to 7.5-month long season, dynamic management in response to identification of a high entanglement risk;
- Gear marking - buoy tags contain the permit number; buoys are marked with the operator's commercial fishing license number; trap tags contain the owner's contact information;
- The size of the trap entrance and bait type may contribute to avoiding vulnerable bycatch, including ghost fishing by ALDFG;
- Escape ports (two rigid circular openings $\geq$10.80 cm diameter) allow female and sublegal male crabs to escape, including by ALDFG (only male crabs of a minimize size can be retained);
- Pots contain a degradable "destruct device", described above, which creates a $\geq$ 12.7 cm diameter opening after it corrodes; and
- A "fair start" provision that supports an orderly start to the fishery by prohibiting vessels actively fishing in one area to immediately move into, and overly crowd, a newly opened area that had been subject to temporal closure at the start of the season in certain circumstances.

Additional measures described in Tables 2 and S1 could complement these. Expanded provisions for in-season lost gear reporting and coordinated recovery could mitigate near-term impacts of lost gear and increase the safety and efficiency of recovery operations. Gear that remains in the water for several months can get stuck in sand and muddy substrate and biofouling can partially submerge gear, making it challenging to haul. However, consideration of such measures would require consultation between industry and managers to overcome challenges around distinguishing between in-use and derelict gear during the fishing season and monitoring and enforcement requirements. Technology that enables fishers to monitor gear positions in real time, that is cost-effective (given that one trap per line is used in this fishery) and that is legal (e.g., government rules currently prohibit the use of AIS beacons on fishing gear) could help fishers to locate temporarily lost and abandoned pots [99,179] and report more accurate locations of gear that they are unable to recover. As non-fishing marine traffic conflicts are considered to contribute to gear loss, efforts to communicate and encourage avoidance of active crab fishing grounds would require cross-sector coordination, policies and incentives.

4.4. The Maldives' and Indonesia's anchored FAD tuna fisheries

Some pelagic and neritic species aggregate at natural and artificial floating objects [28,65,95]. Anchored FADs (aFADs) are artificial objects built and deployed by fishers that are designed specifically to aggregate commercial species of pelagic and neritic fishes. Primarily in some developing coastal states in the western Pacific Ocean, but also in the Mediterranean, networks of aFADs support mainly small-scale, artisanal fisheries, including those using pole-and-line, handline, troll, tuna purse seine and ringnet gear [5,18,40,122,176]. The availability of offshore aFADs might divert fishing pressure from heavily exploited, relatively sensitive nearshore ecosystems [3,18].

The ca. 700 vessels of the Maldivian pole-and-line fishery annually land over 100,000 t of mainly skipjack tuna, accounting for over a quarter of the total tuna catch by global pole-and-line fisheries [46,73,127]. About half of the effort and catch is from fishing on a government-owned and -managed network of deep water aFADs [1,108,128]. There are now about 50 aFADs, which cost over USD $15,000 each, located between 19 and 31 km (12 and 20 miles) from the coast, anchored at about 2,000 m depth [1,127].

The fishery achieved a substantial reduction in the aFAD loss rate, from 82% to 20%, by improving aFAD buoy, mooring and anchor designs, and implementing a government incentive program that pays fishers to retrieve aFADs when they break from their moorings [1,175]. In addition to breaking mooring lines, the weight of anchors may have been insufficient to prevent aFADs to counter forces from currents, possibly resulting in aFADs being dragged into deeper water, submerging aFAD surface buoys [175]. From 1993–2009, the average lifespan of an aFAD before becoming lost was about 2.1 years, and an average of 17 aFADs were installed and 14 were lost each year [175].

The more robust aFADs have had a lifespan of about 5–8 years, and only 19 of 50 (38%) aFADs have experienced a mechanical issue that resulted in temporary or permanent loss, of which 9 were subsequently recovered [1]. Fishers are paid US $330 for each recovered aFAD (typically just the buoy is recovered, which costs over USD $2,500 to replace) [1]. At least one pole-and-line vessel typically visits each aFAD location daily, enabling rapid reporting to the government when an aFAD is lost [1]. The Maldivian government's management framework for the aFAD network has achieved the lowest recorded aFAD loss rate [85]. In addition to improved designs that reduce loss rates, since 2004, use of an aFAD design that incorporated repurposed, salvaged netting from the appendages of derelict drifting FADs (dFADs) deployed by tuna purse seine vessels, which can entangle marine wildlife [62], was discontinued. The current surface structure design of aFADs have a raft made of small buoys and a horizontal fine-mesh net to create shade and shelter, attached to a main large buoy. The large buoy is physically marked with a unique identification number and with the name of the owner [1].

Referring to Tables 2 and S1, additional approaches that might further reduce loss rates and adverse effects of aFAD ALDFG include:

- More frequent inspection of accessible components of the aFAD (main buoy, raft, upper mooring line) and maintenance and replacement when worn/damaged to reduce the loss rate;
- Technology to provide a real-time alert when an aFAD moves position and to track the position of lost aFAD surface components that break from their mooring to possibly increase the recovery rate. For example, satellite buoys and devices that transmit positional data over cellular networks were trialed in the Vanuatu aFAD fishery [196];
- Technology to detect aFAD anchors when they move position, which, if a prevalent cause of loss, could be mitigated by using heavier anchors or different anchor designs, and may enable recovery of surface components if intact and not too deep; and
- Using biodegradable and non-toxic materials for the surface raft of small buoys.

Furthermore, more frequent use of the aFADs as a vessel mooring has been identified as a possible cause of a recent decline in aFAD lifespan [1]. If confirmed, this could be managed to further reduce the aFAD loss rate. Instrumenting aFADs with echosounders could increase fishing efficiency, allowing a reduction in the number of deployed aFADs [38].

Relative to the contemporary Maldives' pole-and-line fishery, other tuna fisheries have very high aFAD loss rates [85,119,120,155,176,198]. Indonesian tuna purse seine, handline, troll and pole-and-line vessels fish on tens of thousands of aFADs [155,199]. Indonesia's combined tuna fisheries supply about 13% of global combined principal market tunas and the pole-and-line fishery supplies about a third of the total tuna catch by global pole-and-line fisheries [55,73,130,144].

However, due to low compliance with government requirements to register and report the position of aFADs, accurate estimates of the total number and locations of aFADs are not available, nor are accurate estimates of aFAD ALDFG production rates [155,198]. The low compliance is understood to be due to fishers wanting to prevent competitors from obtaining their aFAD positions [198]. There is also low awareness of and compliance with regulations, including a cap on the number of aFADs that can be owned and deployed, required marking to identify the owner and license number, required attachment of radar reflectors on surface buoys, requirement to space aFADs apart by at least 10 nm, and a ban on deploying aFADs in shipping lanes [43,129,131,155,198]. Regulations require subsurface appendages to be made of non-entangling, biodegradable, natural materials. Palm fronds are typically used as subsurface appendages, but plastic strips are also occasionally used [155].

Most Indonesian deep-water tuna aFADs are privately owned. Some purse seine companies have agreements in place that allow vessels using other gear types to fish on their aFADs, in some cases for a fee or to guard the aFAD from use by other companies [155]. Typical deep-water aFADs have ca. 4 km long, synthetic mooring lines. Surface floats are either a steel cylinder, block of foam encased in car tires or bamboo raft, and the latter may have a bungalow to house a caretaker. Several cement blocks, connected using ropes and tires, anchor the aFAD [155].

The aFADs are understood to be replaced multiple times per year due to loss or wear. In addition to low compliance with government regulations, other causes of aFAD loss include [155,156]:

- Moorings break during inclement weather, in part due to the use of weak materials for aFAD components;
- Storms and strong currents move the location of aFADs with insufficient anchors;
- aFADs degrade over time, lasting a maximum of two years. Components may break resulting, in the loss of the surface structure and mooring line;
- Longline and gillnet fishers may cut aFAD mooring lines in order to avoid the risk of having their gear entangle on the aFAD. Also, fishers that fish on aFADs may vandalize their competitors' aFADs;
- Vandalism also occurs by non-fishing vessels. Cargo and other vessels deliberately cut aFAD mooring lines when they encounter aFADs in shipping lanes. The unavailability to fishing companies of maps identifying the location of shipping lanes is an additional, indirectly related, cause of aFAD loss; and
- Vessels accidentally strike aFADs, causing them to break from their moorings. While most Indonesia aFAD designs use surface floats, one company uses subsurface floats, which is prohibited by government regulations, likely to avoid detection by competitors. The aFADs generally lack navigational aids, such as radar reflectors and lights, but some aFAD rafts have tall objects that provide some visibility.

Referring to Tables 2 and S1, potential additional measures that could mitigate ALDFG from aFADs used by Indonesian tuna fisheries include:

- Augment surveillance and enforcement of aFAD registration and design requirements, possibly through a combination of dockside and at-sea monitoring, including possibly by using cost-effective satellite-based vessel monitoring systems (Midyatmoko et al., 2021). There is recent evidence that the Indonesian government has been conducting at-sea surveillance and removal of illegal aFADs [103,155];
- Incentivize, through a combination of rewards and penalties, compliance with aFAD regulations, required reporting when aFADs are lost, including "no fault" reporting that eliminates penalties for losing aFADs that would present a disincentive for reporting, and a recovery program for temporarily lost aFADs;
- Area-based management to avoid conflicts with gillnet and longline fishers, and to avoid the installation of aFADs in shipping lanes (and, related, provide maps to fishing companies that identify where aFADs can and cannot be installed);
- Improved, cost-effective gear marking (radar reflectors, high-flyer buoys, flags, lights) of aFAD surface structures to increase visibility, reducing the risk of vessel strikes and entanglement with fishing gear;
- If regulations were amended, using aFAD designs with submerged surface structures could reduce the risk of loss from vessel strikes, entanglement with fishing gear, and vandalism;
- More frequent or continual attendance of aFADs;
- More frequent inspection of accessible components of the aFAD and maintenance, repair and replacement of worn/damaged components to reduce the risk of loss;
- If cost-effective technology becomes available for use in small-scale fisheries, employ electronic devices to provide a real-time alert when an aFAD moves position and to track the position of lost aFAD surface components that break from their mooring to enable recovery;
- If cost-effective technology becomes available for use in small-scale fisheries, employ electronic devices to detect aFAD anchors when they move from their original position, which, if a prevalent cause of loss, could be mitigated by using heavier anchors or different anchor

designs, and may enable recovery of surface components if intact and not too deep; and

- Improved aFAD materials and designs to make them more durable, making them less susceptible to loss during strong wind, waves and currents.

5. Discussion

Relevant interventions to avoid, minimize and remediate ALDFG depend on the fishery-specific context. ALDFG drivers and ecological and socioeconomic consequences vary substantially by gear type, region, scale and by individual fishery [85,121,162]. This is partly due to the tremendous range in the robustness of fisheries management frameworks and in the influence of market-based incentives for environmental performance [74,134,151,152,167]. The linked databases developed by this study enable stakeholders to discover ALDFG mitigation approaches that are suitable to the fishery-specific context, and to first consider approaches that avoid and minimize ALDFG production and adverse consequences before potentially less effective and more expensive interventions for remediation and offsets [183]. This enables managers to adopt the most promising ALDFG interventions that address fishery-specific causes of abandonment, loss and discarding of gear and are viable given governance and socioeconomic enabling conditions.

To identify fishery-specific priorities for interventions, as well as to prioritize amongst fisheries, it is important to know the relative importance of each driver of ALDFG production, the magnitude of ALDFG derived from each driver, and driver-specific adverse consequences [85]. Furthermore, for many of the main direct drivers of ALDFG production and adverse consequences identified in Table 1, it is important to understand underlying indirect drivers. For instance, high fuel costs may affect fishers' decisions on the distance they are willing to travel to retrieve versus abandon drifting gear. Government corruption may create a disincentive to report lost gear [193]. A lack of access to weather forecasts, poor economic conditions and a race to fish in derby fisheries may result in a vessel fishing during a storm and losing or being forced to abandon gear, or may result in the vessel sinking [148,161]. Zoning rules or overcapacity and crowding may result in a vessel risking fishing in an area with a high incidence of gear snagging on submerged features [161] or in illegal areas or periods where risk of detection can result in gear abandonment. Government subsidies for new gear may reduce incentives to repair or use worn components to refurbish gear, increasing gear abandonment and discarding and reducing the incentive to locate temporarily lost gear [45,72]. In some small-scale gillnet and trammel net fisheries, the relatively low value of new netting can reduce the incentive for fishers to mitigate ALDFG [45,72]. In addition to direct drivers, managers should identify and account for these indirect drivers for ALDFG production when designing ALDFG management strategies.

Deficits in one or more component of the fisheries management framework can be important indirect drivers of ALDFG production. This is the case across the various forms of fisheries management systems, ranging from government command-and-control frameworks with input and output controls typical of data-rich, large-scale fisheries, to informal community-based self-governance and co-management frameworks with territorial use rights and indicator-based rules typical of data-limited, small-scale fisheries [37,115,154]. ALDFG interventions must be appropriate not only for countering specific drivers but also for the robustness of each fisheries management component, including monitoring, control, surveillance for compliance monitoring, enforcement, and outcomes of identified infractions [17]. Identifying the capabilities and deficits of the fisheries management framework related to managing and mitigating ALDFG enables the selection of viable ALDFG policy. This also identifies needed gradual improvements to address management framework deficits so that a broader range of ALDFG mitigation methods can be tapped in the future.

For example, gear marking is commonly prescribed to curb derelict gear [57]. However, in fisheries with rudimentary management systems, this intervention in isolation is unlikely to control ALDFG production rates, such as aFAD losses in pole-and-line tuna fisheries (Section 4.4). Gear marking also has limited capacity to address the widespread abandonment of dFADs deployed by tuna purse seine fisheries, where wholesale changes in regional dFAD management are overdue to stop the largely accepted practice of abandonment by directing satellite buoy providers to unsubscribe a buoy attached to a dFAD when the gear drifts out of range or into areas where the vessel lacks authorization to fish [76,97]. Conversely, gear marking, including through the use of passive radio frequency identification or RFID tags, has been used effectively for capacity compliance monitoring, as well as to reduce the theft of gear and catch in pot fisheries with individual vessel limits [50,124,140, 158].

Deficits in ALDFG monitoring and control can act as underlying, indirect drivers of ALDFG production and limit the efficacy of some interventions. Half of regional fisheries bodies do not collect ALDFG monitoring data, and over a third have not adopted ALDFG management measures. Furthermore, the bodies with binding ALDFG controls are tapping a small subset of ALDFG mitigation options [74,86]. Similarly, legal and regulatory frameworks at the national level to control ALDFG are limited and most are considered ineffective [25]. Therefore, improvements in ALDFG monitoring and control, including legal and regulatory frameworks, at regional and local levels are needed.

ALDFG mitigation methods vary in the relative necessity for robust fisheries management frameworks to deter noncompliance due to differences in their costs to commercial viability. Commercial viability considerations include economic viability (e.g., direct costs for requisite gear and equipment, effects on catch rates and value), confidentiality of commercially sensitive information such as the location of fishing grounds, practicality and crew safety. For example, required use of biodegradable and less-durable materials for gear components would likely require substantial resources for compliance monitoring if the prescribed gear materials reduce target species catch rates and increase costs and time to replace weaker gear [92]. This would not be an effective intervention in fisheries lacking sufficiently-robust management frameworks. However, in fisheries with rudimentary management systems, win-win interventions, such as introducing affordable technology that enables fishers to locate temporarily lost or abandoned gear, may achieve high compliance without incentives from penalties. Thus, some ALDFG mitigation methods elicit voluntary compliance, others require incentives, and fishery-specific enabling conditions will dictate which methods are likely to be suitable for an individual fishery.

Fisheries sustainability recommendations and standards can catalyze management authorities to adopt binding measures and seafood companies to adopt voluntary policies on ALDFG. In the U.S., European and other markets, major seafood buyers require that seafood be procured from sustainable sources [167]. Ecological and social certification schemes, such as the Marine Stewardship Council, and fisheries assessment and ranking programs, such as Fishery Improvement Projects, are increasingly being employed both to identify sustainable sources of seafood and to achieve gradual improvements in fisheries' environmental performance [27,123]. While market-based mechanisms currently provide minimal incentives for improved ALDFG monitoring, management and outcomes, this could occur, if, for instance, relevant components of the Marine Stewardship Council's fisheries standard were strengthened. For example, the outcomes scope, currently limited to ghost fishing and habitat [135], could be expanded to account for all ALDFG adverse consequences.

Adequate incentives are needed for fishers to prevent and minimize the risk of gear loss, not abandon and discard gear, employ methods that reduce adverse consequences of ALDFG, attempt to retrieve temporarily lost and abandoned gear, and report when gear becomes derelict. To effectively achieve compliance with ALDFG mitigation control measures, outcomes of enforcement actions for identified infractions must be sufficient incentives. This can be accomplished through a broad range of combinations of penalties and rewards through fisheries management frameworks as well as market-based mechanisms [145,167]. Negative economic, market-based and reputational incentives include: a deposit on new gear is not reimbursed if retired gear is not returned; reduced or withheld subsidies including on new gear; a higher tax on new gear if old gear is not returned; levy (tax) assessed per defined ALDFG unit; fine is assessed when an ALDFG production limit (quota) is exceeded; penalty for noncompliance with ALDFG monitoring or mitigation measures; not achieving or losing certification; lower fishery improvement project ranking; and negative market reputation risk. Reward-based measures include the converse of these penalties, such as the provision of a subsidy or increased subsidy such as through discounts on new gear when retired gear is returned, retired gear buyback programs, a fee for retrieving ALDFG encountered at sea, and a reward for participating in voluntary ALDFG research or for implementing optional ALDFG monitoring or mitigation measures [21,100,146,177].

Outreach, education and training can enable more experienced fishers to pass on their knowledge to new entrants on methods that avoid ALDFG production. This includes avoiding areas with a high risk of loss from gear conflicts, collisions by marine traffic, and snagging seabed features, debris and infrastructure; using gear designs and materials, and conducting routine maintenance, that reduce the risk of gear loss; and augmenting familiarity with equipment and methods to recover temporarily lost or abandoned gear. Several ALDFG drivers in Table 1 could fall within the broad umbrella of fisher error in operating vessel equipment or gear. For example, a fisher might misuse the vessel hauler, causing it to malfunction, or might inadvertently set static gear in a navigation channel, accidentally tow bottom gear in an area known to have a high risk of snagging, forget to attach marker buoys to the gear, set surface marker buoy lines that are too short (or set the gear too deep given the length of the buoy lines), or may not securely stow the gear (Table S1). Providing training opportunities for new entrants, refresher training for all fishers, and ongoing outreach can reduce fisher error. Furthermore, improving fishers' awareness of adverse consequences of ALDFG can increase or develop a conservation ethic [165] that, in theory, may then cause a change in behaviors that affect ALDFG production and the adverse consequences of unavoidable ALDFG.

Causes and rates of the generation of ALDFG have been identified using expert surveys [76,132,161,162,172], data from observer and electronic monitoring programs [47,68,163], analyses of data from satellite buoys attached to dFADs [54] and self-reported by fishers, such as in garbage record books as required under MARPOL Annex V (Table 2). Qualitative expert surveys have been the predominant approach, which are at the lowest end of the evidence hierarchy as they have a high risk of bias and error [34,110]. Expert surveys are a rapid and low-cost approach where previously little or no information was available. Information from fisher surveys may be the only source of ALDFG data available for many fisheries. Data from expert surveys and self-reported by fishers, however, are of relatively low certainty, especially where ALDFG is highly sensitive, such as if there are stringent economic or regulatory penalties for identified infractions, but also due to retrospective bias [190]. Furthermore, there is a risk that the data collected from survey respondents are not generalizable and are unrepresentative of the underlying population that was sampled. This is a high risk if a probability sampling design is not employed and results in undercoverage bias (e.g., fishers of large-scale vessels and of vessels from certain seaports are not sampled), nonresponse bias is large and is not explicitly accounted for, there is a low response rate, and the questionnaire design or the way the questionnaire is administered causes biased responses [23,36,48,173].

Data from properly designed fisheries observer and electronic monitoring programs are much higher certainty than data derived from expert surveys. While electronic monitoring systems are not yet able to collect all data fields of conventional human observer programs, electronic monitoring can provide more certain data because it overcomes sources of statistical sampling bias faced by conventional human observer programs (observer effect, observed displacement effect, coercion and corruption) [10,84]. However, in most fisheries, it is challenging for observers and electronic monitoring systems to detect and estimate lost and abandoned gear, and crew may effectively conceal intentional discarding. Furthermore, observational studies, and syntheses of observational studies, can employ flawed designs. For example, a review of records of observations of marine wildlife entangled in fishing gear incorrectly identified some entanglement records as having resulted from ghost fishing interactions with ALDFG that were documented to be due to entanglements with in-use fishing gear or otherwise where the cause of entanglement was unknown [9].

6. Future directions and conclusions

The databases of cross-referenced ALDFG drivers and mitigation methods provides the foundation to develop and maintain an online tool with a searchable relational database. This could be modeled after the Conservation Evidence online tool, which synthesizes available evidence on the efficacy of alternative conservation interventions that could be taken to address a specific threat to a species group or habitat [39,180]. The proposed ALDFG online tool could enable stakeholders to input an ALDFG driver to discover alternative mitigation methods relevant to that driver, and conversely, input a mitigation method to generate a list of drivers that the method has the capacity to address. The tool could be expanded to provide information on additional criteria important for deriving evidence-informed ALDFG policy. In addition to linking drivers and interventions, the ALDFG tool could identify the relative degree of evidence of the efficacy of each ALDFG mitigation method, as included in the Conservation Evidence [39] tool. Independent synthesis of all accumulated scientific information is a fundamental principle for developing transparent, evidence-informed regional conservation management decisions [44,138]. The ALDFG online tool could also categorize mitigation methods within tiers of a sequential mitigation hierarchy, and identify intervention-specific resources required for robust compliance monitoring.

Employment of a robust systematic literature review could identify additional approaches to mitigate ALDFG that were missed by the unstructured literature review employed in this study. Systematic reviews employ an impartial, transparent and thus replicable approach, and reduce the risks of introducing prevailing paradigm, familiarity and publication biases [14,157,182]. Furthermore, there may be drivers and interventions, including industry practices, not documented in the literature. Investment in research approaches, including fisher surveys, that tap the fishing industry's experiences with ALDFG drivers and mitigation practices, could expand the relational database.

The databases produced here enable stakeholders to identify appropriate interventions by: (1) relating ALDFG drivers to relevant mitigation methods, (2) identifying an intervention's tier within a sequential mitigation hierarchy, first attempting to avoid and minimize ALDFG production and adverse consequences before considering remediation and offset approaches, and (3) determining whether resources are available for requisite compliance monitoring. Several additional criteria should also inform the development of an ALDFG management strategy, including: (4) underlying, indirect drivers of ALDFG production; and (5) the relative importance of direct and indirect drivers based on driver-specific ALDFG rates, magnitude, fate and impacts. However, there is extremely limited information available on gear-specific ALDFG production rates and magnitudes, representing a key obstacle to ALDFG management [117,164]. Similarly, knowledge of the short-and long-term fate and ecological and socioeconomic consequences of ALDFG are additional priority information gaps [85]. Assessing (6) the relative degree of evidence of efficacy of each mitigation method is an additional important consideration for ALDFG policy development. Furthermore, the selection of interventions should consider (7) which ALDFG mitigation methods are likely to be effectively employed based on whether efficacy is affected by crew behavior and the likelihood of fishers' voluntary compliance given an intervention's costs to commercial viability (economic viability, practicality, crew safety). For methods where efficacy relies on fisher behavior and voluntary compliance is unlikely, then the evaluation accounts for whether enabling conditions create adequate incentives to deter noncompliance. This includes considering requisite resources for compliance monitoring, covered in item 3, above, and identified in Table 2, but more broadly considers the influence of market-based mechanisms and the robustness of each fisheries management framework component of monitoring, control, surveillance, enforcement, and outcomes of enforcement actions. Improvements to address deficits with ALDFG management frameworks are a priority [74]. The more robust the fisheries management system, the broader the range of alternative ALDFG interventions that can be effectively employed. With the uptake of the most relevant ALDFG management approaches, and improvements in ALDFG information, management and knowledge of outcomes, we can be cautiously optimistic of meeting the United Nations Sustainable Development Goal 14.1 related to ALDFG mitigation [192].

CRediT authorship contribution statement

Eric Gilman: Conceptualization; Methodology; Project administration; Writing original draft, review and editing. **Jenn Humberstone:** Conceptualization, Methodology; Writing original draft, review and editing. **Jono R. Wilson:** Conceptualization; Methodology; Writing review and editing. **Emmanuel Chassot:** Methodology; Writing – review and editing. **Alexis Jackson:** Methodology; Writing review and editing. **Petri Suuronen**: Methodology; Writing review and editing.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2022.105097.

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