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Ghost fishing gear and their effect on ecosystem services – Identification and knowledge gaps

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ABSTRACT

Abandoned, lost, and discarded fishing gear (ALDFG) is claimed to be a global problem with impacts on marine animals and ecosystems, posing considerable ecological and socioeconomic challenges. Nonetheless, insufficient understanding regarding how marine ecosystem services are affected by ALDFG creates a knowledge gap that challenges a holistic estimation of the long-term economic impacts of using non-degradable fishing gear. In this study, a systematic review and meta-analysis of the existing literature on ALDFG and ghost fishing is conducted, with the aim to assess findings in the literature and identify knowledge gaps. 90 published works were included in the systematic review, of which 67 were examined further in the meta-analysis. We identified a limited number of economic studies, as well as research from developing countries. Focus is largely on ghost fished commercial species, while other species, and non-use values are largely ignored. Though provisioning, supporting and cultural services are represented in the studies, regulating services impacted for instance by the marine plastic pollution of ALDFG, received no attention. Expanding research to include more of these currently lacking elements may be vital for efficient management in relation to ALDFG.

1. Introduction

Abandoned, lost, and discarded fishing gear (ALDFG), also called derelict fishing gear, has been a growing problem with substantial quantities identified in oceans, posing challenges for marine conservation and management [14,15]. Many types of fishing gear continue fishing after they are abandoned, lost or discarded, and this is the case for both passive and active fishing gear, thereby causing so called ghost fishing [40,41]. The variety in exposure time and catch efficiency of different fishing gear types (e.g., net, line, trap, pot) challenges the impact evaluation of ALDFG. Furthermore, not all ALDFG continue to catch fish, and other detrimental impacts may be non-negligible [28]. Among different drivers of ALDFG, gear characteristics have significant effect on the loss probability of fishing gear, but so does poor weather, interactions with wildlife, faulty/damaged gear, discards or operator error [41]. Following technological advancement in fishing gear, the expansion of fishing grounds, and the transition of conventional gears to synthetic materials with more resilience, lower cost, higher breaking strength, and better durability, ALDFG in the oceans has significantly increased over time in terms of its quantity, impacts, and distribution [14,28]. The presence of ALDFG may cause heavy plastic pollution in the marine trophic chain, negative effects on marine animal welfare and marine ecosystems, and detrimental influences on socioeconomic status [14].

The harmful impacts of ALDFG ghost fishing on target and non-target species results in both environmental and economic damage, which consequently affects the sustainability of fisheries and human wellbeing in terms of food security and livelihoods. It is reported that ALDFG alone represents 46% of the 79,000 tons of plastic within the surveyed area of 1.6 million km^2 in the North Pacific Ocean [25]. Before either sinking or accumulating, ALDFG may be dragged by sea currents for long distances from shorelines [6,28]. This possibility to travel contributes a major threat to the biodiversity of marine ecosystems which provide services to humans, i.e., food provision, recreational opportunities, and spiritual enhancement [26,54]. ALDFG may cause massive damage to benthic habitats, both commercial species of fish and crustaceans as well as non-commercial species of birds, marine mammals, and turtles [5]. Given the significant role played by marine ecosystem services for food security, livelihoods, income, and health [30], the loss of these services may cause substantial impacts on the wellbeing of humans. To date, attempts to synthesize available data to provide the scope and the magnitude of the effects of ghost gears on marine ecosystem services is

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far from complete [38,41]. We carry out systematic literature review to identify ecosystem services impacted by ALDFG.

Globally, Macfadyen et al. [28] estimated that 640,000 tons of fishing gear, a significant contribution to global marine debris, is lost, abandoned or discarded annually in different geographical fishing regions. The majority of ALDFG are not degradable in the ocean, and persist for a long time, continuing to unintentionally catch target and non-target fish. This phenomenon is widely known as ghost fishing [28], which causes increased fish mortality and economic loss, as well as adverse effects on benthic habitats [43]. It is estimated that ghost fishing not only results in losses of up to 30% of commercial species catches [14], but also substantially threatens non-target species [12,16,45,52]. Despite the fact that the avoidance of ALDFG may be efficient for individual fishers (i.e., secure fish stock abundance, and avoid economic loss), the commons aspect of ALDFG implies that tackling lost fishing gear and its consequences, especially ghost fishing, requires substantial management efforts. There exist studies identifying drivers of ALDFG [40,41], but a broad understanding of the factors of actual ghost fishing catch rates is lacking. We therefore carry out the first meta-analysis of experimental studies of ghost fishing, thereby contributing to identifying what drives catch rates of ghost gear.

In the United Nations 2030 Agenda for Sustainable Development, goal 14.1, reductions in marine pollution by 2025 call for actions towards marine debris, including ALDFG [49]. Although there has been increasing attention, ALDFG has not raised much concern, and efforts to change the situation are deemed insufficient [38]. Some countries have specific ALDFG legislation, i.e., United States, Norway, and Canada, while management of ALDFG or marine debris is largely absent in the rest of the world [53].

To contribute to management of ALDFG and ghost fishing, this paper reviews and integrates previous studies which investigate the impacts of ghost fishing gears on marine ecosystem services to produce insights about the severity of the problem, suggest management implications, and assess possible knowledge gaps. We collect available peer-reviewed literature to address two main questions: (1) How are marine ecosystem services affected by ALDFG? (2) What are the factors affecting the catch rate of ghost gear? This study is expected to contribute an overview of the evidence about the impacts of ghost fishing gear on marine ecosystem services and provide information for well-managed fishing activities to promote marine sustainability.

Our key findings from this study are as follows. First, largely the natural science sample of ALDFG and ghost fishing publications have been increasing in recent years, providing evidence of the detrimental impacts on provisioning, supporting, and cultural services. Out of 90 papers focusing on commercial species, only 14 studies estimate the economic loss caused by ghost fishing. Second, a significant causal relationship between catch rate of ghost gear and its determinants, especially exposure time in the water, is found in meta-analysis of extracted data from literature reviewed.

The rest of the paper will be structured as follows. The second section presents the method for and data from systematic review and meta-analysis. Results will be discussed in the third section. In conclusion, key findings will be summarized, and policy implications will be suggested.

2. Method and data collection

2.1. Systematic review

This paper synthesizes published works about ecosystem, social and economic effects of ALDFG by utilizing a systematic review and meta-analysis, thus combining a qualitative assessment and a statistical summary of results. Among a variety of existing approaches, Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) which is based on a comprehensive framework and procedure for meta-analysis is employed for this study [20].

2.2. Literature search

A literature search was carried out using the search engines Scopus, Web of Science, and JSTOR for peer-reviewed articles to consider the consequences of lost fishing gear. Search terms in groups (e.g., exposure, biological and socioeconomic impacts) were designed and combined to source relevant studies. The full list of search terms is presented in Supplementary Table S1. No geographical boundaries and time constraints were indicated in the inclusion criteria. The eligibility criteria for selected papers in the systematic review are presented in Supplementary Table S2, which contains information included in the review, such as on subject, exposure, outcomes, and study designs.

2.3. Data collection and extraction

A common procedure of data collection and extraction incudes four stages; identification, screening, eligibility and exclusion, and overview of included studies. Utilizing search strings in advanced search engines in terms of titles, abstracts, and keywords, 864 records were retrieved in the initial search, namely 444 papers from Web of Science, 273 papers from Scopus, and 147 papers from JSTOR. Due to the scarcity of academic studies on the economic impacts of lost gear and ghost fishing, the identified papers consist of peer-reviewed academic journal articles, and grey literature from credible sources. Of these, 226 publications were duplicates and eliminated before screening for relevance (i.e., see Table S2), language (i.e., English), and form (i.e., original research studies).

Articles were assessed for further eligibility if their titles and abstracts mentioned relevant information to the research questions. Priority was given to research that studies the relationship between lost gear and detrimental impacts on marine environments and benthic communities. Among the 109 papers assessed at full-text level in the stage of eligibility assessment, 19 were removed either because the issue of lost fishing gear was not a main subject or object of the study, or was mentioned only one time.

Finally, excluded papers from the systematic review and meta-analysis are those discussing assessment or viewpoints regarding the ghost gear situation or relevant regulations. Qualitative findings relating to ghost gear regulations are noted for discussion in the fourth section. A shortlist of 90 records was produced for review. The process and number of articles filtered at each assessment stage is detailed in Fig. 1, and the final list of reviewed articles is supplied in the Supplementary information.

Data extracted from the systematic review representing the impacts of ALDFG on ecological subjects, i.e., numbers of caught species, habitats, is presented in a standardized format. Instead of performing an ecological assessment, we focus on other aspects of the ghost gear situation. Different groups of findings are observed based on the specific impacts of gear types; (1) Net (gillnet/Trammel nets/Surrounding net/Trawl net/Cast net/Miscellaneous net), (2) Trap and pots, (3) Line, and (4) unspecific ALDFG; duration of catch/exposure time; experimental period; water depth; location name; region; country ISO code; type of study; regulations (yes/no). The existence of regulations relating to gear loss and gear retrieval in reviewed papers shows some institutional action to manage gear loss and address ghost fishing issues. Essential data used for meta-analysis are extracted from the finalized list of studies that carried out ghost fishing experiments, providing both ALDFG quantity and amount of caught species.

2.4. Translation to ecosystem services impact

The assessment of the ecological impact is performed to determine the effects of ALDFG on ecosystem services. The review aims to provide evidence for the impacts ghost gear have on ecosystem services in terms of the target of impact (subject) and impacted process (status). The methodology of Papathanasopoulou et al. [32], along with the

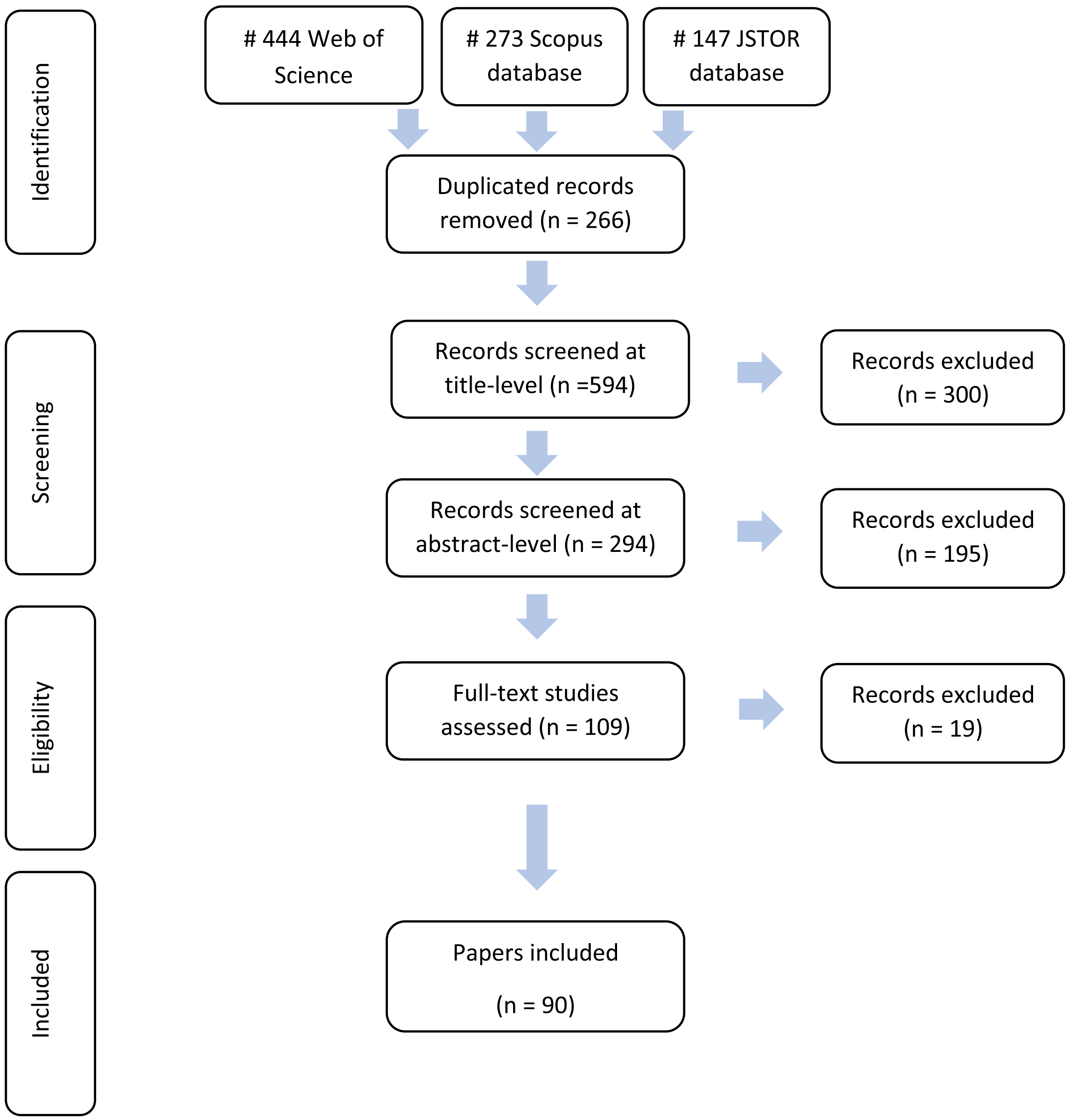

Fig. 1. Study screening and selection. This flow diagram was constructed following Moher et al. [29]. Note: *n* is number of publications.

Economics of Ecosystems and Biodiversity (TEEB) and the CICES ecosystem services classification (CICES) version 4.3 [18], are employed to translate the impacts on the ecological subjects into those on ecosystem services.

The classification of "negative", "positive", and "uncertain" status of the impact of ghost gears on ecosystem services is based on the findings and implications from the reviewed literature. Specifically, negative status is ascribed to papers which report detrimental impacts of ghost fishing gear on benthic communities, i.e., entangled or dead marine species. Alternatively, the status is recorded as positive for papers which come up with the finding that lost gear somehow generates a beneficial impact on the marine habitat, e.g., lost traps may become shelters to protect lobsters and other species from predators [17]. The last category of uncertain is ascribed to studies which report both negative and positive impacts of lost gear, which makes an overall evaluation uncertain.

2.5. Meta-analysis

The meta-analysis in this study is aimed to investigate whether there are factors that affect ghost fishing. Data representing catchability of ghost fishing gear types reported in individual experimental studies was extracted in a standardized format.

Based on the literature reviewed, we develop meta-analysis regression models to examine catch rate of ghost fishing gears, as follows:

$$lncatch_{ij} = \alpha + \beta_1 E_{ij} + \beta_2 E_{ij}^2 + \varphi W_{ij} + \vartheta Q_{ij} + \gamma T_{ij} + \delta C_{ij} + \theta S_{ij} + \varepsilon_{ij} \quad (1)$$

where i is an index for the observed value in study j; α is a constant term; $\beta_{k=1,2}$, φ, ϑ, γ, δ and θ are vectors of the coefficients to be estimated for the moderator variables, namely exposure time (E) and its square term (E^2), water depth (W), gear quantity (Q), gear types (T), study site characteristics (C) and species (S), respectively, and η is the usual error term.

In the finalized data, catch of each species is recorded as an observation which means one study can provide more than one observation. From the quantity of catch and quantity of lost gear collected from the reviewed experimental literature, the catch rate is calculated by dividing the catch by the number of lost gears (individual/gear), with the dependent variable given as the natural logarithm in the regression model (1), labelled *lncatch*.

Additionally, exposure time, denoted *E*, which is the time period that ghost gear continues to soak in the water and provide unintentional catch, is collected to capture the impact of soak time. As this information is not always provided in the literature, the exposure time is assumed to be equal to the number of observed/experimental days for cases where the exposure time of the lost gear is not available. Moreover, the depth of water at the studied sites and the quantity of gear are also collected from the original literature. The majority of studies that carry out experiments on gears report detailed descriptions of the location sites, e.g., geographical map and sea bottom.

Other groups of moderator variables in the model are gear type (e.g., traps/pots and nets), study site (e.g., open sea), and caught species (e.g., fish and crustaceans). These variables are expressed as dummy variables. A summary statistic of the regressor and regressands in the model are presented in Table 1.

As is widely recommended for meta-analysis [31], a random-effects panel data approach with robust standard errors is employed to estimate the model in Eq. (1) to capture both within-study potential correlation among observations [27,37] and between-study autocorrelation [37].

3. Results

3.1. Systematic review

The geographic distribution of countries with ALDFG research, and the location of the studies are shown in Fig. 2. Among the 90 papers included, 3 studies investigate the impact of ALDFG at a global scale while 6 studies examine the issue at a multinational scale. The most significant clusters are North America, including the US, Canada, and the Gulf of Mexico (32 references), Europe (28 references), and Australia (6 references). Among developing countries, the studies spread across Asia (7 references) and South America (5 references), with notably no African studies.

The last twenty years has seen an increase in the number of publications about marine ecosystem services affected by lost fishing gear (see Fig. 3). There was insignificant change in the number of annual publications from 2008 to 2013, but the trend has turned upward since 2014. A possible explanation for this surge in research on ALDFG impacts is the introduction of SDG 14, in combination with increased focus on marine plastics. The number of studies published in 2019 and 2021 dominate with 10 papers, accounting for 20% of the total number of papers in the list of reviewed literature. Number of publications in 2022 was last updated in February which was the time that data collection was carried out, hence explaining the low number of studies that year.

Table 1
Descriptive statistics of the variables.

Variables	Mean	Std. Dev.	Minimum	Maximum
Dependent variable				
Catch rate, total catch over the number of lost gears (individual/unit of specific gear*)	7.1	17.02	0.01	92.02
Moderator variables				
Exposure time, the period that ghost gears continue to soak in the water (days)	359.8	613.8	12	3650
Water depth, the depth of water conducting experiment (meter)	27.8	48.9	2	325
Gear quantity, the number of gears (unit of specific gear)	293.6	832.8	3	5748
Moderator variables: Gear type characteristics				
Trap (= 1 if traps/pots)	0.477	0.502	0	1
Nets (= 1 if any kind of nets)	0.465	0.502	0	1
Moderator variables: Species characteristics				
Fish (= 1 if caught fish species)	0.302	0.462	0	1
Crustaceans (= 1 if caught crustacean species)	0.360	0.483	0	1
Moderator variables: Study site characteristic				
Open sea (= 1 if studies conducted in open sea)	0.744	0.439	0	1

Note: $N = 86$
(*) individuals per trap/pot, or per meter net

Among the 90 studies in the reviewed list, 83% are in natural science and only 15 are in social science, with 14 studies including estimation of economic loss triggered by ALDFG and ghost fishing. Out of 73 papers included in the field of natural science, 55 papers are recorded as experimental. The social science studies, on the other hand, seem to face the challenge of data unavailability which creates a barrier in relation to quantifying the economic or social impact of ALDFG and ghost fishing.

The majority of the reviewed studies discuss the impacts of ALDFG on the ecosystems of open sea/ocean (68%), followed by coral reefs (15%), coastal systems (10%), and rivers and lakes (7%) (see Fig. 4). Most studies do not mention specific ecosystems but rather assess fisheries, with the exception of less than 20 studies that focus on benthic habitats or coral reefs. These results are relatively unsurprising, given that the coastal systems mainly relate to very nearshore environments with limited fisheries. Regarding the ALDFG type, traps/pots and nets constitute equal parts of almost 80% of the studies.

A diversity of affected subjects is recorded in the studies included, something that poses challenges in integrating the subjects for meta-analysis. Fig. 5, therefore, presents the statistics of 5 clusters of subjects including solely fish (21%), solely crustaceans (29%), a combination of sea animals, largely fish and crustaceans (31%), coral reefs, sea grass, and other refugia (8%), and biodiversity protection (11%). The grouping of five different subjects in Fig. 5 is based on the studied species found in the reviewed literature. As some studies include numerous species of interest, the separation of fish or crustaceans from the combination is not feasible. The domination of fish and crustaceans together is followed by the papers focusing on crustaceans or fish alone.

The results presented in Fig. 6 show that the presence of ALDFG and ghost fishing have impacts on Provisioning services, Supporting services and Cultural services. Regulating services which cover the transformation of biochemical or physical inputs to ecosystems and regulation of physical, chemical, and biological conditions [47] has been examined widely in papers about marine litter [2]. The absence of regulating services in the papers reviewed raises questions about a research gap needing to be filled regarding how ALDFG and ghost fishing contribute to marine plastic pollution and environmental degradation.

The recorded impacts of ALDFG on ecosystem services are consistently found to be negative. Multiple damages cause negative impacts to benthic habitats by smothering or colliding with habitat elements, reducing above-ground biomass, disrupting below-ground components, and breaking or denuding habitat-forming foundation species [48]. Our analysis shows that more than 70% of the publications examine commercial species. When ghost fishing causes fish and crustacean mortality, not only landings in the commercial and recreational fisheries decline, but also the ecological role of these marine animals is negatively influenced [8]. We also find an animal welfare issue, where trapped fish and crustaceans die of starvation, cannibalism, and due to the presence of predators [13,35]. Additionally, ALDFG are shown to cause harm to non-commercial animals. Coral mortality increases with increasing amounts of entangled fishing lines, and ghost fishing has negative impacts on shallow reef ecosystems, directly affecting branching corals and important coral-fish interactions [3]. ALDFG may also attract turtles [44], with evidence that longer nets caught more turtles [52].

Some studies in the sample are inconclusive regarding detrimental impacts of ALDFG. Parrish and Kazama [33] and Kim et al. [23] carry out experiments to test the catch rate only, and do not assess effects of

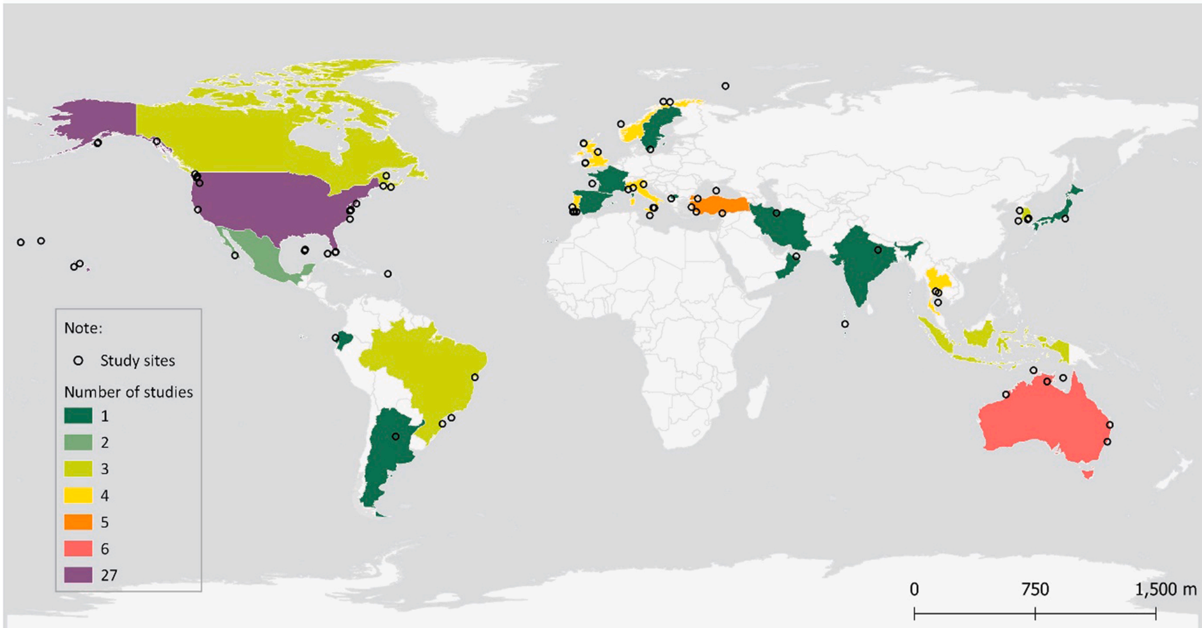

Fig. 2. Map showing study sites and number of ALDFG studies by countries.

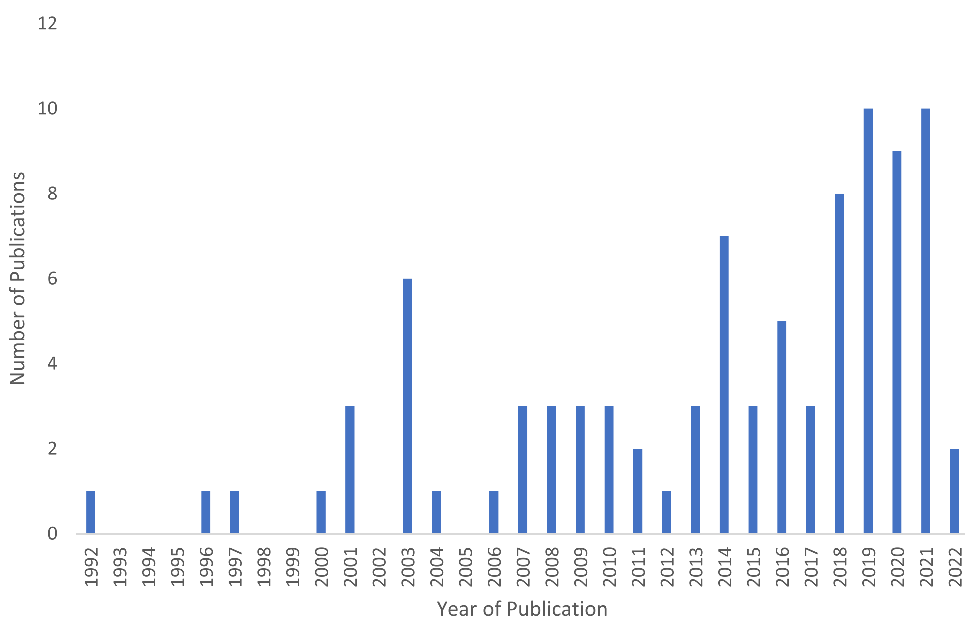

Fig. 3. Number of ALDFG papers per year.

ALDFG and ghost fishing. Humborstad et al. [21] report that 98% of crabs caught by abandoned pots were alive, vital, and active. Only a few crabs were found dead and rapidly got preyed on by larger crabs, implying that dead crabs became a source of nutrition for the entangled ones [21]. ALDFG can become habitat for marine organisms where natural shelter is less prevalent [16], thereby providing an artificial reef type characteristic. However, the vast majority of the papers underlined detrimental effects of ALDFG.

3.2. Meta analysis

Descriptive statistics of data extracted and results from meta-analysis show a variety of findings for the assessment of insights regarding ALDFG in the experimental literature (see Table 1). Efforts to examine the effects of ghost fishing and test alternative eco-friendly fishing gear mostly focuses on commercial species that are harvested by passive fishing gear such as gillnet, traps or pots, and longlines. In our sample experimental studies involving traps/pots and nets, accounted for over 48% and 47%, respectively, while the remainder covered line fishing gear. The average catch rate of ghost traps/pots was nearly 8 individuals per unit of gear, while that of nets was about 7 individuals per meter. Although a variety of species are caught by ghost fishing gear, experiments largely focused on fish or crustacean species, or a combination of different species (also crustaceans and fish).

Among 86 observations from experimental studies (67 papers), there are 64 observations conducted in open sea/ocean. The water depth in the experiments range from 2 to 325 m, averaging at around 28 m. Among various types of ALDFG in the literature, commercial nets and

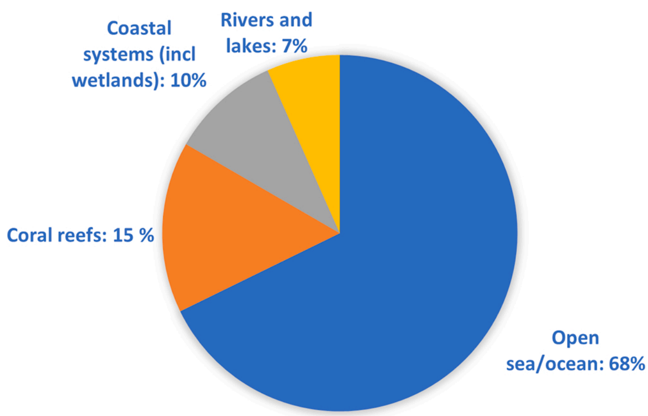

Fig. 4. Biomes in the literature reviewed.

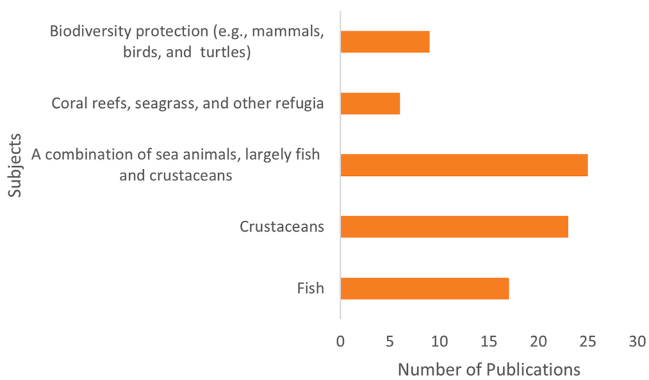

Fig. 5. Subjects studied in the literature.

traps/pots are the most used gears in the experiments. The length of net designed for the experimental setting is in the range between 3 and 5748 m while the number of traps/pots varies from 2 to 325. The number of days that the experimental ghost gear soak in the water varies from 12 to 3650 days.

Results of different meta-regressions are provided in Tables 2 and 3, where two models are applied, in order to carry out a robustness check. To control for the difference in catch rate regarding fishing gears, the dummy variables of traps/pots and nets are included in the models. In all models, the natural logarithm of the catch rate is specified as the dependent variable. The vectors of species and study site characteristics are included in both models, and exposure time is included in a quadratic form to test the non-linear relationship between exposure time and catch rate, in Model 2. The test for the presence of exposure time impacts on the number of individuals caught is indicated in the last row of the table for Model 2. The test result shows that exposure time is found to have a statistically significant impact on the catch rate of ghost gears. In particular, the negative sign of exposure time indicates that the more days following gear deployment, the lower catch-per-unit-gear. This finding is consistent with previous works which provided evidence for decreasing efficiency of ghost gears (e.g., [7,22,34]).

In addition, meta-regression models, using the same variables as in Table 2, are also estimated in sub-samples of traps/pots and nets in Table 3, to more deeply control for specific characteristics of gear types. Deeper water is found to give higher catch-per-unit-effort for pots/traps only. This is consistent with the specific characteristics of such fishing gears, operating mainly on the sea floor, while not necessarily the case

Table 2
Estimates of the meta-regression function using full sample size.

Variable	*The natural logarithm of catch rate*			
	Model 1		Model 2	
	Coefficient	Robust Std. Err.	Coefficient	Robust Std. Err.
Constant	-0.252	1.732	0.057	1.757
Exposure time (days)	-0.0008***	0.0002	-0.002**	0.001
Exposure time^2			2.62e-07	2.33e-07
Water depth (meter)	0.001	0.004	0.0005	0.004
Gear quantity (unit)	-0.0003**	0.0001	-0.0003	0.0001
Gear type characteristics				
Trap (= 1 if traps/pots)	-0.013	1.773	-0.123	1.779
Net (= 1 if any kind of nets)	-1.791	1.831	-1.891	1.833
Species characteristics				
Fish (= 1 if caught fish species)	2.545***	0.553	2.541***	0.561
Crustacean (= 1 if caught crustacean species)	2.284***	0.550	2.315***	0.553
Study site characteristic				
Open sea (= 1 if studies conducted in open sea)	0.208	0.701	0.152	0.678
Hypothesis testing				
No effect of exposure time			34.44***	
Obs.	86		86	

Note: *** , **, and * refer to statistical significance at 1%, 5%, and 10% levels, respectively.

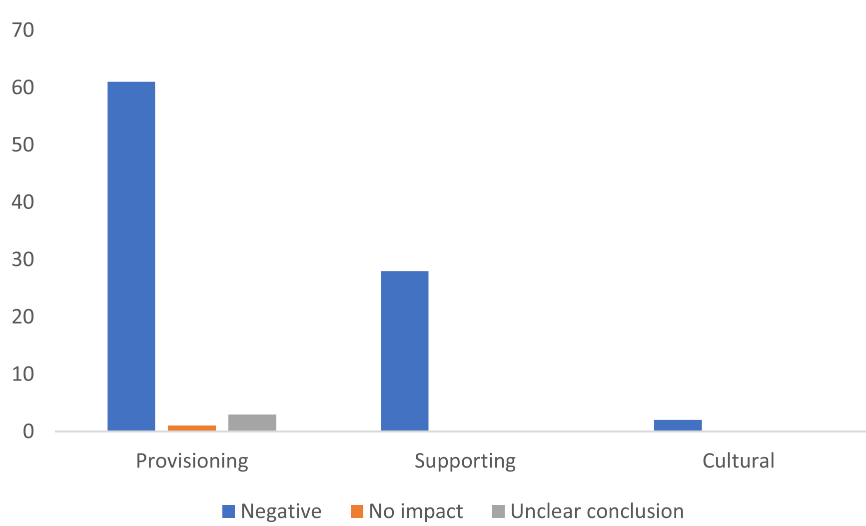

Fig. 6. Summary of results by ecosystem service group.

Table 3
Estimates of the meta-regression function using the sample of traps/pots and nets.

Variable	*The natural logarithm of catch rate*			
	Traps/Pots		Nets	
	Model 1 Coefficient	Model 2 Coefficient	Model 1 Coefficient	Model 2 Coefficient
Constant	-1.096	-0.963	-0.852	-2.148
	(0.817)	(0.884)	(1.626)	(1.976)
Exposure time (days)	-0.0006***	-0.001	-0.002***	0.007
	(0.0001)	(0.001)	(0.0005)	(0.008)
Exposure time^2		1.20e-07		-3.4e-06
		(2.51e-07)		(2.98e-06)
Water depth (meter)	0.005*	0.004*	-0.020**	-0.016
	(0.003)	(0.002)	(0.010)	(0.014)
Gear quantity (unit)	-0.0001	-0.0002	-0.0005***	-0.001*
	(0.0002)	(0.0002)	(0.0002)	(0.001)
Species characteristics				
Fish (= 1 if caught fish species)	2.011***	1.972***	3.900***	3.965***
	(0.732)	(0.762)	(0.339)	(0.348)
Crustacean (= 1 if caught crustacean species)	2.072**	2.117**	2.643***	2.714***
	(1.027)	(1.047)	(0.471)	(0.453)
Study site characteristic				
Open sea (= 1 if studies conducted in open sea)	1.093	1.046	-0.724	-0.957
	(0.764)	(0.786)	(0.910)	(0.765)
Hypothesis testing				
No effect of exposure time		22.85***		29.65***
Obs.	41		40	

Note: *** , **, and * refer to statistical significance at 1%, 5%, and 10% levels, respectively. Robust standard errors in parenthesis.

for nets. The gear quantity is found to have no impact on catch rate in the subsample of traps and pots, while negative signs are found for the subsample of nets, implying that larger number of nets lost would decrease the catch rate. The fact that more nets is shown to reduce catches is an unexpected result. However, it is important to remember that these results are found in the context of experiments.

Exposure time appears to have a significant negative effect on the catch rate in Model 1 in Table 3 for the traps and pots, while it is found to have a U-shaped relationship in Model 2 with a negative sign on the first exposure term and a positive sign on the squared term. Although the individual coefficients of exposure time in Model 2 are not statistically significant, the null hypothesis of no effect of exposure time is rejected, at the significance level of 1%. The impact of the number of days after net deployment on catch rate is similar to the results for the traps/pots subsample in Model 1. However, an inverted U-shaped relationship between exposure time and catch rate of ghost nets is found with a positive sign on the first and a negative sign on the square term, though none statistically significant. Again, the null hypothesis of no effect of exposure time is however rejected, at the significance level of 1%.

Fig. 7 shows the relationship between predicted catch rate of ghost fishing traps/pots and nets and exposure time from Model 2. The predicted average catch rate per year is 2.77 individuals per ghost trap/pot and 2.72 individuals per meter ghost net. As catch rate is calculated using the natural logarithm of individuals per unit of gear, a negative marginal impact of soak time in the sea is observed on the catch rates of ghost traps/pots, i.e., low catch rate for longer exposure time. For nets, however, an increasing number of individuals are caught up to approximately 1200 days. Further soak time in the water will lead to a considerable reduction in catch rate which implies nets and traps/pots have different characteristics regarding ghost fishing. Note however the large variance in these results, pointing to the importance of further studies.

In Tables 2 and 3, fish and crustaceans are assessed relative to the reference group that involves a combination of different species and have positive effects in all models and subsamples. The larger magnitude of the coefficients is explained by the dominance of fish and crustacean species in the sample.

4. Discussion

4.1. *Insight from the systematic review*

We find that ghost fishing has so far mainly been studied with a focus on commercial species which far from covers all ecosystem effects, for instance on benthic communities, or issues related to animal welfare and other non-use values. Furthermore, besides ghost fishing, ALDFG drifting with wind and wave action may cause damage to benthic habitats. Aquatic animals are lured into or attracted by ALDFG, and spread, potentially invasively, increasing their abundance and range [2]. A broader evaluation should cover the subjects that reflect both non-use and non-market costs of ALDFG.

Findings of the systematic review demonstrate that there are detrimental impacts of ALDFG on provisioning, supporting, and cultural ecosystem services. However, the lack of studies reporting effects on regulating services points to a gap in the research, given that ALDFG are part of marine litter causing plastic/microplastic pollution. Beaumont et al. [2] identify that a number of regulating services are significantly impacted by plastic pollution, spanning climate regulation, pest/disease control, life cycle maintenance, and mediation of wastes. How ALDFG contribute to different types of plastic pollution is a knowledge gap that

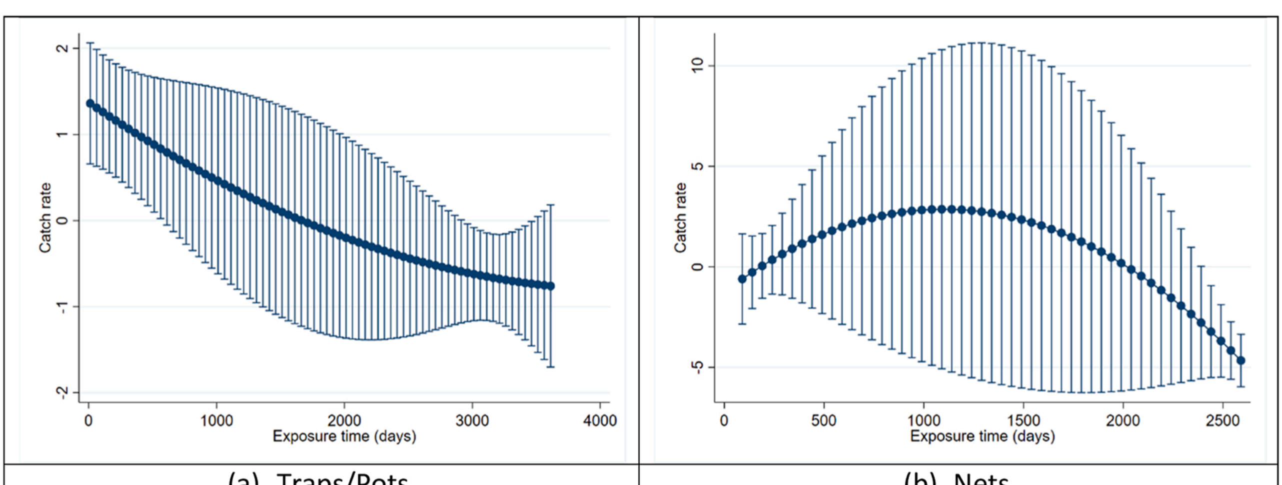

Fig. 7. Catch rate (natural logarithm of individuals per unit of gear) over experimental exposure time for ghost fishing traps/pots (a) and nets (b).

requires filling in order to provide a more complete assessment of ALDFG effects in excess of ghost fishing.

Most studied locations are distributed amongst developed countries where fishery management has been evolving for decades. In North America, Canada has implemented various regulations for governance in relation to fishing gear loss and recovery as well as at-sea disposal prohibition. Relevant legislation includes The Fisheries Act, Environmental Protection Act, and Vessel Pollution and Dangerous Chemicals Regulations [17]. In the US, the implementation of ALDFG related regulations, e.g., Trap Retrieval Programs and Crab pot clean-out programs, have been imposed since the 1970 s [4,50]. Australian Fisheries Management Authorities conduct data collection which includes location, date, type of fishing gear and the catch composition to not only detect and respond to marine threats but also to ensure ghost net tracking and retrieval [57]. In Europe, Norway has conducted fishing gear retrieval surveys regularly since 1983 [24] while in the Mediterranean regulations have recently been put in place restricting the fishing period, during which the practice of ALDFG is banned [10,11]. Fishing activities in most developing countries are, however, open access and regulation is largely absent. In addition, effective implementation of fishery regulations is a significant challenge in these countries. Some Asian countries, e.g., Indonesia, Turkey, and South Korea have national regulations for fishing activities, but not directly involving ALDFG interventions [39,51,55]. This has raised concern about the transboundary effects in common waters, e.g., in the Arafura Sea [9,39]. Due to the absence of African studies in the literature reviewed, and relatively few South American and Asian studies, there may well be more ALDFG regulations than mentioned here, and a broader identification would be beneficial.

Beyond the impacts on ecosystem services as reported, ALDFG and ghost fishing have been estimated to generate significant economic losses [1,17,19,43,46]. Market price method basically uses the market price of caught species at the studied point of time and assumes a fixed catch rate per period, usually a year [4,17,36]. The cost of loss caused by ghost fishing includes the first-hand values of caught species and the cost for gear removal, however, the complete estimation of cost is far more complicated. Costs in relation to ALDFG removals vary upon location and conditions, method, potential disposal, and potential recycling costs [42]. Collection and removal of ALDFG has been considered a method to incentivize fishers to report gear losses, given the possibility of retrieving their lost gear. Nevertheless, mitigation alone may be insufficient, and retrieval involves costly vessel-time. A combination of both retrieval and policies of prevention may be expected to be more effective.

4.2. Insight from the meta-analysis

The meta-analysis conducted is based on published experimental papers to provide the first causal estimates of factors affecting the catch rates of ghost fishing, especially focusing on nets and traps/pots. Our analyses indicate that the number of ALDFG has a negative impact on their catch rate, while there are different effects of water depth on catch rate regarding nets and traps/pots. Moreover, catch rates of ALDFG for fish and crustacean species are higher than those for other species, or combinations of species. More importantly, the results show that the impacts of exposure time of ALDFG on catch-per-unit-gear are negative in subsamples of both nets and traps/pots. Moreover, an inverted U-shaped relationship cannot be rejected in case of ghost nets. Particularly, the pattern of the impact of soak time on the catch rate is increasing as long as net are deployed less than 1200 days but decreases when exposure time exceeds this. The variance is however substantial.

From the meta-regression results, the predicted average catch rate per year is about 2.77 individuals per ghost trap/pot and 2.72 individuals per meter ghost net. Though these numbers do not seem prohibitively large, the effect depends on the number of lost gear, and the size and health of the stocks in question. However, experimental versus empirical analysis of the impacts of ALDFG and ghost fishing is challenging. Experiments may not always reflect the actual ghost fishing situation. Additionally, the effects of ALDFG on micro plastic pollution and non-use values, both regarding environmental degradation and animal welfare, is insufficiently examined.

Various options for fisheries management to reduce the future occurrence of ALDFG could include both preventative strategies and mitigating measures. Even though retrieval programs have been implemented in an effort to mitigate the detrimental impacts of ALDFG, the expense of such programs raise concern about cost effectiveness. From the perspective of top-down policy, national legislation and fishing rules should beneficially be perceived as legitimate and include fisher involvement, thereby assuring greater compliance [56]. Providing guidance and requirements for lost gear reporting, and online platforms to publicly update real time ALDFG data, can help to avoid gear conflicts and reduce negative impacts of ALDFG. In addition, education and awareness raising among fishers regarding gear maintenance can improve the level of ALDFG regulation compliance, as gear malfunction is a potential driver of gear loss [41]. Though technical innovations may continually be in progress producing more environmentally-friendly fishing gears, such gears may not necessarily be adopted by the fishing industry voluntarily. Economic incentives to promote biodegradable fishing gear, such as taxes or subsidies, could be introduced to motivate the actual switch from conventional fishing gear, given that market imperfections lead to less than societally optimal uptake of such gear. It is worth noting that the geographical diversity in fisheries and fishery management systems leads to a need for localized strategies of legislative design covering effective monitoring, evaluation, and enforcement, in both the short and long-term.

4.3. Possible limitations

Regarding the systematic review, some limitations must be taken into account. First, this study only points out the direction of the impacts on ecosystem services which are either negative or inconclusive and does not identify the magnitude of these effects. Second, long term and wider impacts of marine pollution resulting from ALDFG, must be investigated separately from the shorter-term impacts of solely ghost fishing.

The meta-analysis includes a small number of papers, and the results suffer from limited degrees of freedom which leads to low statistical power in the meta-regression models. A second limitation is sample selection bias arising from the literature selection process, which may be a concern for meta-data. Following standard practice in systematic review methodology, this sample selection process includes only the most relevant studies which might not guarantee randomization. Therefore, the results of the meta-regression may not be a true reflection of the full set of ALDFG-related studies. Third, due to potential further continuation of ghost fishing in excess of the experimental exposure time, the catch rate calculation might be misleading. Fourth, ALDFG may cause additional fishing mortality in excess of target species which requires additional reporting about the catch and soak time.

4.4. Recommendations for further studies

There are multiple potential directions for further studies. First, increased diversity of studied locations will provide better insights for ALDFG impacts as specific characteristics of each location, e.g., geography, weather conditions, and habitat types, will result in varying probabilities and consequences of gear loss. Currently, ALDFG experiments have been conducted at a limited number of locations, mostly in developed countries where funding is more plentiful. However, it can be argued that ALDFG may be a more serious challenge in developing countries. This since fisheries in developing countries are largely open access, leading to larger fishing effort, increasing potential crowding and collisions, and thereby gear loss. Furthermore, open access leads to greater pressure on fish stocks, making additional ghost fishing a larger threat. In parts of the world where fisheries are mostly subsistence, and fishing is an occupation of last resort, these challenges may be far more damaging from a societal perspective, than what is the case where economic alternatives are more prevalent. Second, investigation into regulating services and estimation of non-use values affected by ALDFG may impact on optimal fisheries management. Third, data availability regarding ghost fishing is limited, which again hinders bioeconomic analysis i.e., the stock effects of ghost fishing are largely ignored in the literature, and assessment of management options is therefore hampered.

5. Conclusion

This systematic review and meta-study are motivated by concern about the detrimental impacts of ALDFG and ghost fishing, and the potential ecological, social, and economic consequences worldwide.

Key findings include the identification of a limited, but largely natural science sample of publications on ALDFG and ghost fishing. Though most papers focused on ghost fishing of commercial species, of 90 papers reviewed, only 14 provided estimations of economic loss caused by ghost fishing. Additionally, ALDFG impacts on regulating services are lacking in the reviewed literature while the evidence of affected provisioning, supporting and cultural services are recorded. Significant causal relationships between catch rate of ghost gear and exposure time in the water is found in the meta-analysis of extracted data.

Current research on ALDFG and ghost fishing far from covers the complete impacts on marine ecosystems, animal welfare and other non-use values. Furthermore, the connection between ALDFG and micro-plastic pollution requires more study.

The spatial penetration of existing studies in developed countries, such as USA and Australia, reflects the systematic progress of fishery management. Developing countries where open access is common, face various challenges in managing ALDFG due to the absence of solid regulations. And even in the presence of well-designed ALDFG management, a system of monitoring, evaluating, and enforcing ALDFG legislation, thereby securing the compliance of fishers is a prerequisite for effectiveness. This is clearly challenging for any country, whether developing or developed, and there is a need to assess fisher incentives in relation to societally optimal behavior. Here market instruments such as taxes or subsidies may be relevant.

Assessment of economic loss including non-use and non-market costs of ALDFG is largely lacking. Market price methods usually only provide first-hand values of caught species, while the cost of gear retrieval will vary depending on reporting, location, and weather conditions, as well as method applied. ALDFG retrieval programs have been implemented to incentivize fishers to report gear losses, in order to potentially retrieve them. However, such mitigating measures are resource intensive. Preventive options such as introduction of biodegradable fishing gear are expected to be more effective, pending technological development. Therefore, a wide variety of policies could be considered for fisheries management, including both command and control as well as market-based instruments.

We recommend casting a wider geographic net for research on ALDFG, expanding the studies to non-commercial species, services that are not necessarily found in markets, and non-use values. This broader perspective is a requirement for a more holistic assessment of the effects of ALDFG and ghost fishing, providing more knowledge-based input for the shaping of management.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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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.2023.105528.

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