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METHODS, TOOLS, AND SOFTWARE

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A model for the intensity of fishing gear

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Abstract

Industrial fishing, instrumental in feeding the world's population while providing a livelihood to many people, also presents a variety of hazards to the health of the ocean, including the accumulation of derelict fishing gear. Although direct evidence of harm from derelict gear is abundant, efforts to quantify and assess the threats posed by it are confounded in part by the tremendous diversity of fishing gear and techniques. In this paper, we advance a novel analytic framework for describing the use of fishing gear that can be applied to evaluate the environmental impacts that arise from fishing activity. We model fishing as a unit process comprising three successive characterizations, each of which can be observed and validated independently: the intensity of fishing effort, the material intensity of gear, and the intensity of the environmental effect. We present the method as an open-source computation system with a library of gear models that can be reviewed and extended by the research community. We apply the program to estimate the generation of derelict gear for several different gear types and discuss how it can be expanded to advance the understanding of the impacts of industrial fishing at the global scale. This article met the requirements for a Gold–Gold *JIE* data openness badge described at http://jie.click/badges.

KEYWORDS
abandoned, lost, or otherwise discarded fishing gear (ALDFG), fishing effort, fishing gear, industrial ecology, marine plastic debris, unit process model

1 | INTRODUCTION

1.1 | Plastic debris from fishing gear

Fishing provides sustenance and economic well-being to a tremendous number of people. However, fishing gear also generates environmental impacts during the course of its normal use. Derelict fishing gear, also known as abandoned, lost, or otherwise discarded fishing gear (ALDFG) (Jambeck et al., 2015; Li et al., 2016; Macfadyen et al., 2009), is a prominent source of marine debris. Although ALDFG has attracted significant attention from both research and governance perspectives (FAO, 2019; Gilman, 2015; Scheld et al., 2016; UN General Assembly, 2015), little is known about the actual quantity of gear lost during fishing activities.

Of all the types of debris entering the oceans, ALDFG is particularly harmful as it can potentially capture and trap both target and incidental marine organisms for decades once it is released (Macfadyen et al., 2009). This phenomenon is known as ghost fishing and it makes ALDFG one of the most threatening waste fraction for marine life (Wilcox et al., 2016). Lost fishing gear has the potential to entangle in seabeds, harming coral reef, seagrass beds, macroalgae forest, and mangrooves, which are critical nursery areas for many species (NOAA, 2016). It also impacts fisheries given that ALDFG damages in-use fishing gear and contributes to more gear loss, affects the sustainability of principal market species, and also poses danger to navigation and safety at sea (Gilman, 2015; Macfadyen et al., 2009; Scheld et al., 2016). After plastic has degraded, micro-particles can accumulate through food webs and ecosystems (Rochman et al., 2015) with unknown consequences on long-term health and sustainability.

Because of the expansion of the quality of fishing effort as well as the geospatial and vertical footprint of fisheries in the last decade, in combination with the transition to synthetic and more durable materials (e.g. nylon) used for fishing gear, the quantity, distribution and effects of ALDFG are thought to have increased significantly (Derraik, 2002; FAO, 2019; Gilman, 2015; Halpern et al., 2008). Gear may be lost accidentally or abandoned or discarded deliberately. Accidental losses can occur due to mechanical failure or wear, weather-related phenomena, entanglement with other vessels or gears, disputes between fishers, or through carelessness or neglect. Deliberate discard of gear is illegal (Lethbridge, 1991), but can occur when gear has failed or is worn out and cannot easily be returned to shore or repaired, when gear use can implicate the fisher in illegal activity, or because of insufficient storage space on a vessel (Huntington, 2017; Macfadyen et al., 2009).

Much research effort has been directed to characterizing gear losses in specific fisheries, fleets, or regions, but no study has yet attempted a bottom-up estimation of overall global gear loss per year. Recent work has estimated annual fishing gear loss rates via a meta-analysis of publications from 1975 to 2017 that contain details about ALDFG (Richardson et al., 2019). Overall, the study estimated that 5.7% of all fishing nets, 8.6% of traps, and 29% of all lines were lost globally each year. Deshpande et al. (2020) used material flow analysis (MFA) to model the flow of plastic through Norwegian fishing activities. Based on extensive commercial information from gear suppliers, as well as a large-scale survey of fishermen, they estimated that the Norwegian fleet contributes around 380 t/year mass of plastic from lost fishing gear. Generally, geographic studies of gear loss from the literature conducted decades ago may no longer correctly characterize contemporary gear losses (Breen, 1990; Brown & Macfadyen, 2007; Chopin et al., 1995; MacMullen et al., 2003). Quantifying how much ALDFG is entering the ocean annually could illuminate steps to tackling the issue and reducing the threats to marine life.

1.2 | The challenge of fisheries research

Fisheries research is robustly empirical due to the recognition that the range of fishing techniques, target species, practitioners, and operating conditions is incredibly diverse. The FAO standardized classification of fishing species includes over 12,000 target species, and reports annual landings from over 190 countries. Fishing vessels range from a few meters to hundreds of meters in length, from hand-operated shore gears to 14-MW trawlers. Operational data on fishing activity is scarce and difficult to obtain because of the reluctance of fishermen to share detailed information. For many countries, fishing effort data are patchy, non-existent, or inaccessible (Anticamara et al., 2011). Publicly available fisheries records are vague, especially in locating where fishing occurs (Watson, 2017).

The great variety of techniques and equipment used for fishing poses a modeling challenge for industrial ecology (Avadí & Fréon, 2013). A recent assessment of global marine fisheries discards (Pérez Roda et al., 2019) involved a review of the world's active fisheries, including their classification by gear type, target species, and scale, and allocation by species among each country's fisheries. Based on this study, the global catch by gear type can be estimated (Table 1). Roughly 70% of fishing activity is considered industrial, with the remainder being small-scale, artisanal, or subsistence fishing. Attempts to characterize the environmental impacts of this activity at a global scale must contend with high complexity and uncertainty.

1.3 | Fishing gears

Fishing gear refers to the physical/mechanical implements and devices that are used to capture fish. They are generally divided into two main categories: active and passive. Active gears involve the use of powered vessels to actively gather or chase the target species. Passive gears, including lines, nets, and traps, rely on the target species approaching or entering the gear and becoming trapped or hooked (Cochrane, 2002). Passive gears can be stationary, floating, or towed. The efficiency or effectiveness of gear is typically reported as "Catch per unit effort" (CPUE), but the exact measurement of effort is gear specific (FAO, 2020).

1.3.1 | Active gears

Active gears, where capture is achieved by moving the gear to pursue and capture organisms, at the industrial scale are highly technical, carefully engineered, and have high economic cost. The main types of active gears are trawls and surrounding nets. Trawls are towed either with contact to

TABLE 1 Annual fisheries landings by fisheries sector and gear type for 2018. Additional support for the annual landings data presented in this table can be found in Supporting Information S1

	Annual landing (10^6 tonnes)*			Annual gear
Gear type	**Industrial**	**Non-ind.**	**FAO recommended fishing effort (units)****	**loss (%)*****
Trawl	22.0	2.4	Number of hours fished	12
Purse seine	23.7	4.1	Boat: Hours fishing per day; Beach: number of sets	2.3–6.6
Net	5.1	3.1	Drift: Length of nets and the number of times cleared; Fixed: Length of nets and the number of sets made	5.8
Handline	4.6	0.5	Number of days fished	N/A
Longline	2.4	0.3	Hooks set and hauled	29
Pot	1.1	0.4	Pound Nets: Number of days fished and number of units hauled; Pots and Fyke: Total number of units fished in a given period	8.6
Dredge	0.4	0.9	Number of hours fished	N/A
Miscelanea	0.3	10.5	Varies	N/A
Total	59.6	22.2		
Percentage	72.9	27.1		

Notes: * Based on Perez Roda et al. (2019). Totals represent 95.9% of reported FAO ocean-based capture fisheries. Details in Supporting Information.
** FAO (2020), Capture Fisheries Statistics, Annex N "Selected combinations of gear and effort."
*** Richardson et al. (2019). N/A – Not available.

the seafloor or in mid-water. Surrounding nets, such as purse seines, are large netting walls used for surrounding aggregated fish both from the sides and underneath. After the fish are surrounded, the net is retracted, capturing the fish. Large purse seines can approach 1000 m in length and hundreds of meters in depth.

1.3.2 | Passive gears

Passive gears, where the capture process relies on the movement of organisms into the gear, can be operated at any scale. Key exemplars include gillnets, lines, and traps. Gillnets are large grids of fine mesh and trap fish of a specific size by encircling them around their bodies and catching their gills. They can be stationary (set gillnets), one end attached to vessels or drifting (drifting or pelagic gillnets). They can be positioned at the sea surface, within the water column, or at the sea floor. Longline fishing is a scaled-up version of traditional fishing, in which hundreds or thousands hooks are attached to a mainline that can stretch for kilometers. Pots and traps are general terms for a wide variety of containers and structures that fish can enter but not easily escape. Most passive gears are left to operate for hours or days at a time before the catch is retrieved.

1.4 | Proxy modeling of fishing activity

Industrial ecology is based on two mutually supporting perspectives: that industrial activities can be represented as process models that are continuous, linear, and homogeneous; and that well-characterized process models in one setting can be used meaningfully as proxies for similar activities that are poorly characterized.

We describe a modeling framework that can be used to characterize fishing activity in terms of a series of distinct transformations or "stages" that can each be independently observed. By collecting many such observations, they can be combined combinatorially to illustrate the system and delineate the bounds of the question. Confidence in the model can be arbitrarily improved, especially for specific scopes of interest, by collecting more observations, which themselves provide further information for bounding the extrapolated results.

We provide an implementation of a gear library, which we populate with a small selection of models gathered from the literature. We use stochastic simulation to compare alternative models and to estimate the potential plastic leakage from individual vessels, fisheries, and sectors of fishing activity. The library can be extended by introducing additional observations. If results based on observations from different sources are seen to be consistent with one another, that will validate the methodology. The library of unit gears is published online as an open-source software package written in Python, such that gear models may be contributed by the community (see Code and Data Availability).

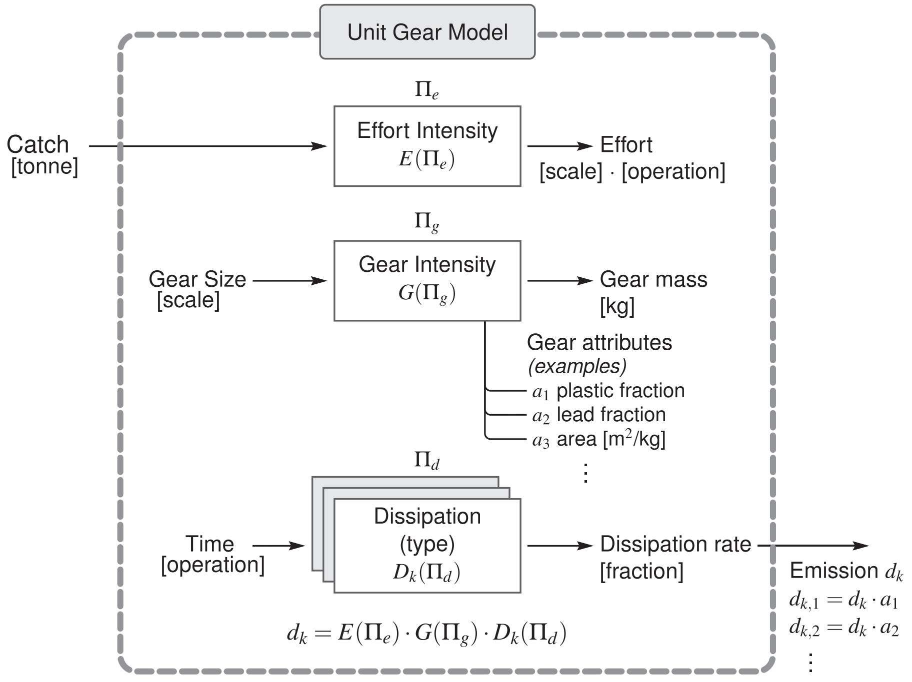

FIGURE 1 Schematic diagram of the unit gear model as three distinct stages that each transform an input variable to an output variable. The dimensions of each variable are reported in square brackets

2 | METHODS

2.1 | Guiding assumption: Linearity of fishing gear effort

We begin with a set of assumptions about how fishing gear operates. To begin, we assume that fishing gear can be grouped into categories, and different gears within the same category are broadly similar. Then we introduce the central assumption that the gear operates in a linear fashion, specifically:

- The amount of fish caught by a specific gear is proportional to its time of operation (assuming availability and catchability of fish are constant);
- The rate at which fish are caught by a specific gear is monotonically dependent on its size, and can be approximated as linear with some measure of gear size over some domain;
- The quantity of gear lost or dissipated into the ocean is also proportional to the time of operation.

Under these assumptions, we devise a modeling framework that allows us to represent the operation of fishing gear on a linearized basis and to accumulate information about different types of gear.

2.2 | A unit gear model

We conceptualize the fishing gear material flow and its interaction with the ocean as having three adjacent stages, each of which we regard as directly observable and independent from one another. These are: the deployment of the gear for catching fish, which we refer to as "effort intensity"; the relationship between gear or vessel size and gear mass, or "gear intensity"; and the rate at which the gear is lost into the environment, the "dissipation rate." The three stages are shown in Figure 1.

Although "fishing effort" is widely studied by fisheries scientists, its exact meaning is highly dependent on the context in which it is used (McCluskey & Lewison, 2008). We define fishing effort as the product of operating time and some explicit gear scaling dimension. This definition is analogous to the measure of freight, the product of mass and distance, used commonly in life cycle assessment (LCA) as "tonne-kilometers." Likewise with freight, in our model the fishing effort obtained by a particular vessel is directly proportional to both the operating time and the gear scale, and can be used to linearize the relationship between catch and either of these two parameters.

$$\text{Fishing effort} = \text{Gear dimension} \cdot \text{Operating time}. \quad (1)$$

To define a model of a particular type of gear, we first must define the two characteristic quantities of gear scale and operating time. A "unit gear" is a gear whose scaling dimension has a value of 1. We use the term "effort intensity" to express the amount of fishing effort required to capture a unit mass of fish. This can be interpreted as the operation time for a unit gear, or the scale of gear over a unit operation time. The inverse of effort intensity is termed the "capture rate" for the gear.[1]

Next, the "gear intensity" of the gear model describes the mass per characteristic unit gear, as well as other attributes that are proportional to mass.

$$\text{Mass of gear} = \text{Gear dimension} \cdot \text{Gear intensity}. \tag{2}$$

Finally, we characterize the rate at which the gear is lost into the environment, known as a "dissipation rate." The dissipation rate reports the fraction of the gear's total mass that is lost to the sea over a given operating time. There may be several distinct forms of environmental dissipation, including principally gear abandonment, loss, and discard.

$$\text{Dissipation of gear} = \text{Mass of gear} \cdot \text{Dissipation rate} \cdot \text{Operating time}. \tag{3}$$

Combining these equations together gives us a formula for estimating gear dissipation per unit of catch.

$$\text{Dissipation of gear} = \text{Catch} \cdot \text{Effort intensity} \cdot \text{Gear intensity} \cdot \text{Dissipation rate}. \tag{4}$$

2.3 | A library of gears

An important objective of this work is to support the synthesis and discovery of new knowledge (about the flow of plastics into the ocean) through the application of existing knowledge (about different fisheries and gear types). The quantitative relationships in each of the three stages above are topics of extensive research by fisheries scientists and practitioners; our approach to this study is to schematize these three relationships, and then to accumulate reported observations of the various relationships in the hopes of discerning a pattern. For this to be successful, data sources must be identified in which both the input and the output to one stage are reported together. However, the validity of a result obtained by combining models from disparate sources to generate an estimate as in Figure 1 and Equation (4) is not clear.

Thus, we introduce two new assumptions:

- The effort intensity, gear intensity, and dissipation rates for a given gear type are independent of one another.
- Vessel size can be used as a proxy for gear size in certain situations; in other words, fishing vessels are generally equipped with an amount of gear that is optimal for the vessel size, and larger vessels carry and operate more or larger gears.

We consider model parameters to be continuous random variables, while selection among different possible models can be thought of as discrete random variables. Stochastic simulation over both continuous and discrete inputs can be used to explore the space of possible model outcomes.

Under these assumptions, we can begin to record observations of each of these parameters separately, without concern for whether all three parameters were observed in a given situation. This introduces the possibility of creating a library of widely heterogeneous models of fishing operation from a variety of sources, and allowing them to be re-combined with one another. The library supports stochastic simulations with both discrete (i.e., selection of models) and continuous (i.e., variation of parameters) variables (see Mendoza Beltran et al. (2015) for the use of a similar approach).

2.4 | Application of the framework

2.4.1 | Defining the operation unit

A unit of operation is always a measure of time, and for most reports of fishing activity, the unit of operation is synonymous with the measurement of effort. CPUE is often described as a mass of target species per hour or day of fishing, or per "set" or gear deployment.

In the case of passive gears like traps and gillnets, the time dimension of gear effectiveness is often reported in terms of a specified "soak" period, typically a number of hours. Fisheries studies also commonly report typical or average numbers of fishing days per season or per year for

[1] We elected to coin a new term, rather than to use an existing term such as "fishing power" (Kirkley & Squires, 1999) or CPUE (for catch per unit effort), because of the explicit proportionality of capture to both gear size and operating time. Observations of CPUE, fishing power, or other efficiency or effectiveness of fishing can be put in terms of capture or effort intensity by defining the two dimensions of the effort measurement.

different vessels. This is convenient because conversion between different units of time is straightforward. For a given study, any stated equivalencies between the reference operational quantities were noted in the effort models.

2.4.2 | Defining the scaling parameter

The most challenging parameter to define for any gear type was the scaling quantity. The natural approach, to define a scaling quantity in terms of a physical dimension of a gear, could be applied successfully for passive gears such as gillnets and traps. In these cases, it was not uncommon to find articles that reported meaningful dimensions of catch and gear scale. Passive line-based methods also lend themselves well to direct technical measurement.

Active gears, however, account for a far larger portion of fishing activity, and it was much more challenging to find characterizations of both effort intensity and gear intensity in the literature. Thus, gear intensity models are best developed by experts in the gear. In this paper, one extensive meta-analysis of trawl gears is implemented based on a recent publication (Sala et al., 2019) as a model approach for characterizing complex gears.

2.4.3 | Life-cycle inventories

When a LCA study of fishing activity includes the production and maintenance of fishing gear in their inventory analysis, the practitioner has already internalized a model of effort and gear intensity. If the functional unit is a measure of catch, then the life cycle model itself is effectively the "unit gear model," and the information reported about the gear in the life-cycle inventory directly reflects the gear intensity of the fishing method. In this case we introduce a "trivial" measure of effort intensity, which is simply the "effort required for one functional unit of catch." Its value equals study's functional unit per metric tonne.

Moreover, because of the assumption of homogeneity inherent in LCA, the gear intensity inventory value represents the portion of fishing gear that is allocated to the functional unit, regardless of operating time. In other words, the life-cycle model also must internalize the gear's lifetime. This means that the conversion rate between the trivial effort intensity and the dissipation rate is *always unity*. The portion of net that was allocated to the catch can be thought of as "entirely used up" by that functional unit of catch, never again to be allocated to any other catch, regardless of the net's life time. Any portion of the net that is lost to the sea will be lost "during" the harvest of that functional unit.

As an illustrative example, consider a purse seine that weighs 1500 kg and catches 25 tonnes of catch per deployment. In an LCA study, the practitioner determines that the net is used 120 times per year and has a life of 3 years. Thus, over its life the gear catches 9000 tonnes of fish, and the life-cycle inventory result reports 0.167 kg of net per tonne of catch.

Now, if we assume that net fragments totaling 1% of the mass of the seine are lost to the sea for each year of operation, this equates to 45 kg of net losses over the life of the gear. Allocating this amount to the total catch on a life-cycle basis, we would expect the life-cycle inventory to report 5 g of net losses per tonne of catch, or 1.67 g of net losses per tonne of catch per year. But this amount is exactly 1% of our gear intensity determined above. This tells us that we can apply dissipation rates to life-cycle estimates of gear intensity directly, regardless of the unit of operating time inherent in the dissipation model.

3 | RESULTS

A variety of model components were constructed from different data sources, enabling the simulation of dissipative losses from several types of fishing gear. Depending on the source, a few different scaling and operation quantities could be extracted and used to build valid models. Each model constructed is shown in Table 2, listed in terms of the publications used to characterize the effort and gear intensity models. The stochastic simulation results are shown in Figure 2. In general, because results for each gear type are based on only one or two studies, often with widely inconsistent methodologies, the results reported here cannot be used to draw any but the most coarse inferences about fishing gear use. Instead, the results only illustrate the operation of the proposed method.

Although the specific units of effort vary by model, the product of catch intensity and effort intensity is the mass of gear in kg per ton of catch, amortized over a year of operation. Each combination of effort and gear models was applied to two different dissipation models. One was based on a recent prioritization study of ALDFG generation (Gilman et al., 2021); the other based on the results of a survey study in Norway (Deshpande et al., 2020). These are distinguished by G and D, respectively, and each reports the estimated fraction of gear that enters the ocean over a year of operation. The product of all three columns forms the result, in kg of gear lost per ton of catch. A complete listing of each unit gear model, including the units of correspondence between adjacent stages and mean characterizations for each stage, is documented in the electronic supplementary materials and in the source code.

TABLE 2 Performance of unit gear models constructed for the study. The reported values correspond to the 20% and 80% confidence intervals ($n = 1000$ simulations)

Model		Effort-20-80	Gear-20-80	Dissipation-20-80		Result-20-80
Effort-gear	Gear type	[scale]·year·t^{-1}	kg·[scale]$^{-1}$	G/D	Percent·year^{-1}	kg·t^{-1}
Soldo 2019-Pravin 2016	Seiners	0.135–1.97	15–173	G	2.46–14.2	0.507–3.66
				D	0.454–1.94	0.0884–0.496
Soldo 2019-Laissane 2011	Seiners	0.108–0.177	11–16.2	G	2.46–14	0.0414–0.281
				D	0.454–1.95	0.00788–0.0371
LCI Model-Laso 2017	Seiners	1–1	9.54–13	G	2.46–14	0.269–1.61
				D	0.453–1.96	0.0505–0.216
LCI Model-Avadi 2014	Seiners	1–1	0.0711–0.536	G	2.44–13.9	0.00518–0.0428
				D	0.446–1.93	0.000928–0.006
Watanabe 2016-Sala 2019	Trawlers	0.39–5.59	0.323–3.22	G	3.3–19.3	0.0447–0.32
				D	2.35–3.8	0.0239–0.0848
Watanabe 2016	Trawlers	0.356–0.456	548–654	G	3.36–19.6	7.96–47.1
				D	2.37–3.83	5.72–9.48
Grimaldo 2019	Passive	1.45–8.38	0.00938–0.0106	G	8.01–8.82	0.0012–0.0068
				D	0.822–1.18	0.000152–0.000789
Gabr 2012	Passive	6.87–48.1	0.194–0.414	G	2.11–5.5	0.0552–0.533
				D	3.85–4.91	0.0802–0.612
Akyol 2012	Passive	0.0811–0.102	26.2–47.1	G	2.94–3.25	0.0717–0.132
				D	0.811–1.2	0.0238–0.0446

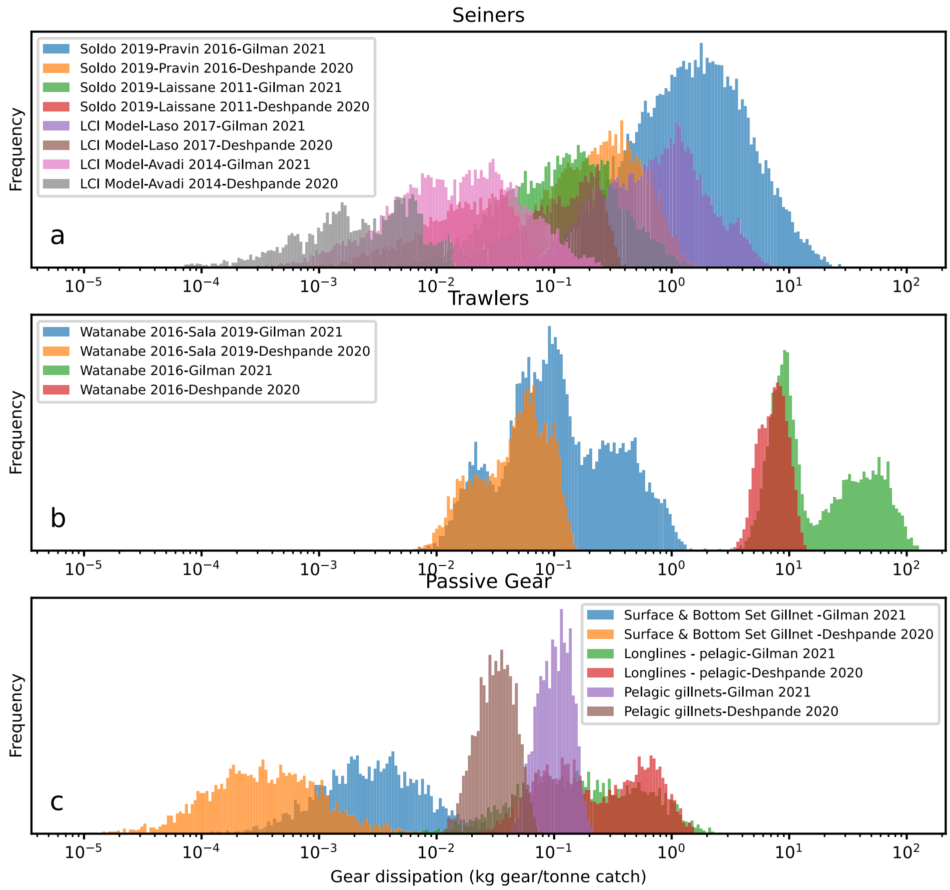

FIGURE 2 Gear dissipation stochastic simulation results. Underlying data used to create this figure can be found in Supporting Information S2

The model results show that gear use estimations, as well as estimations of the loss of gear to the ocean, vary over several orders of magnitude, depending on the gear type and the individual study. In general, estimated differences in effort and gear intensity match or exceed differences in the dissipation rate. Below, each category of gears is discussed briefly to support the interpretation of the model structure.

3.1 | Purse seiners

The purse seine models are drawn from one direct report of effort intensity (Soldo et al., 2019), two direct reports of gear intensity (Laissane, 2011; Pravin & Meenakumari, 2016), and two life-cycle studies of purse seine fisheries (Avadí et al., 2014; Laso et al., 2017). As discussed, in the life-cycle studies the gear intensity of the functional unit is applied directly, and no conversion factors are required to apply the dissipation rate. The life-cycle studies thus provide the highest confidence that their results are meaningful and consistent, because no conversions between models are required.

Among the direct (non-life-cycle) studies, Soldo et al. (2019) reports variations of catch per set with all measures of vessel size but does not report on gear intensity. Both Pravin & Meenakumari (2016) and Laissane (2011) report on gear intensity but not effort intensity. The models find correspondence on either vessel length or vessel weight; however, there is no evidence that the gear intensity of vessel sizes in India (Pravin) or Mozambique (Laissane) are informative for anchovy fishing in the Adriatic (Soldo). Therefore the representativeness of each model would depend on it being properly paired with an effort model. Nevertheless, we observe the life-cycle and non-life-cycle results to be of the same order of magnitude (although the direct studies are generally higher).

3.2 | Trawlers

It was difficult to locate reports of effort intensity for industrial trawl operations. Only one study, of small-scale trawling in the Bay of Sendai, Japan, was modeled (Watanabe & Tahara, 2016). This was a life-cycle study, but it also reported effort intensity and gear intensity separately. We elected to model the study as two non-life-cycle stages in order to improve the usefulness of the model. However, the model reflected unusually high gear intensity of 1667 kg of net per 0.3 vessels. We remain highly skeptical of this value but included it in the model for illustrative purposes. The two peaks in the bimodal green distribution correspond to dissipation estimates for mid-water (lower) and bottom trawls (higher).

Alongside that was an extensive study of trawl gear intensity in the Mediterranean Sea (Sala et al., 2019), which reported the culmination of a 10-year data gathering and meta-analysis process. The study used self-organizing maps to identify four clusters of vessel-gear characteristics, and we coded each as a separate model. The effort intensity measurements of Watanabe were combined with the gear intensity measurements of Sala to generate the blue and gold distributions shown in Figure 2b. The four clusters are evident in the blue histogram.

3.3 | Passive gears

For passive gears it was usually straightforward to identify the scaling and operational dimensions of effort intensity. In fact, most studies of CPUE in passive gear fisheries report it directly in terms of these two dimensions. We modeled one study for each of three gear types: set gillnets (Grimaldo et al. (2019); cod; Norway); pelagic or drifting gillnets (Akyol and Ceyhan (2012); albacore; Turkey); and pelagic longlines (Gabr and El-Haweet (2012); albacore; Egypt). For all three studies, physical dimensions of the gear were provided, along with either statistical summaries or direct reports of catch per gear over a period of operation.

A very light weight is characteristic of all three gear types, because polymer-based lines and nets are extremely material efficient. Thus the gear intensity and dissipation rates of all three gears were relatively low, with the highest-intensity case (pelagic longlines) coincided with the mid-range estimates for trawlers and seiners. All three passive gear cases have low catch efficiency, but this is especially true for the pelagic gears. Gabr reported 7–22 fish per 1000 longline hooks per day, while Akyol reported 13 ± 1.6 fish per 1000 m of driftnet per day. Undoubtedly, the actual characteristics of passive gears differ far more widely than the case study results displayed here; further empirical studies can be conducted and contributed to the library.

4 | DISCUSSION

The results demonstrate a framework for estimating the material flow of derelict fishing gear into the seas a result of fishing activity. By characterizing the industrial system as a series of independent components (fishing effort, gear utilization, and environmental impact) the framework provides a means for generating a priori computational results that can later be validated through direct observation. The implementation of a gear library as an open-source software project supports the ascendant goals of reproducibility and methodological consistency in industrial ecology (Pauliuk, 2019).

4.1 | Assumptions and limitations

The assumption at the core of the framework is that fishing effort can be described as bilinear (linear with respect to both gear size and operating time) and homogeneous when considered over a sufficiently large scope. The effort intensity model assumes that if a given fishing gear having scale *s* collects *X* tonnes of fish while operating for a set period of time *h*, then the same vessel operation for $2 \cdot h$ time will result in catching $2 \cdot X$ tonnes of fish, as will two identical vessels each operating for *h* time, or a vessel operating a gear set with scale $2 \cdot s$. It is unknown whether this is necessarily true for a single vessel or day, but it is assumed to be valid on average over the scope. A similar assumption is at work throughout industrial ecology, but the high variability of fishing activity renders it unusually important for modeling fishing gears. As a consequence, the key limitation to the framework in the empirical information used to estimate model parameters. For the present study, a small number of indicative studies were used to create initial estimates for a set of gears; before the results can be generalized, that empirical basis must be broadened to incorporate a set of observations that begins to span the entire scope of commercial fishing.

The gear dissipation models used in this study are the result of intensive efforts over one geography on the one hand (Deshpande et al., 2020), and a long-running meta-analysis of small-scale studies on the other (Gilman et al., 2021; Richardson et al., 2019). The latter model uses a posterior estimation as the high estimate, suggesting at the upper bound that half of all purse seining gear is lost, which is not consistent with reported gear life cycles on the order of years (e.g., Avadí et al., 2014; Laso et al., 2017) and observer reports.

An important caveat about all gears in the current methodology is that they discount bycatch in estimating gear intensity. Bycatch can reach or exceed 1:1 ratio with target catch in some fisheries (Gray & Kennelly, 2018), and so it is recommended to account for bycatch when applying the models, that is, by interpreting the functional unit as one tonne of all captured biomass, rather than only target catch.

4.2 | Opportunities and challenges

In the dissipation phase, the question of how fishing gear becomes derelict is long standing and challenging (Gilman, 2015; Macfadyen et al., 2009). It is quite possible that the principal routes by which some gears are lost to the ocean are not through dissipative losses but through deliberate mismanagement by fishermen, for instance by discarding end of life gear overboard. An example of this is the prevalent practice of abandoning drifting fish-aggregating devices (FADs) by tuna purse seine vessels (Banks & Zaharia, 2020; Griffiths et al., 2018). These practices are irretrievably cultural and fishery dependent, and so any generic characterization of dissipative losses should be considered with skepticism. Survey-based approaches that focus on measurable parameters, such as the rate at which fishing vessel managers procure new gear and dispose of old gear (Deshpande et al., 2019) may be locally effective, but questions remain about their applicability to general results.

There are fundamental challenges to expanding the library at each stage of the model. To begin with, there is a tremendous diversity in the world's fishing gears and fisheries. While all industrial ecologists are to some extent generalists, collaboration with domain experts is crucial to ensuring the validity of fishing gear models. In the effort intensity stage, without high spatial–temporal contrast in the data, catch–effort relationships of different gears and fisheries is sometimes difficult to parameterize. Systematic and/or emerging methods at estimating fishing effort, such as the observation of fishing vessels by satellite (Kroodsma et al., 2018; Natale et al., 2015), could hold promise to improve the availability of catch–effort data. In the gear intensity stage, details about gears can be highly technical and often proprietary. The comprehensive trawls database presented by Sala et al. (2019), a culmination of a decade of research, is a testament to the degree of effort required to understand the gear intensity relationship; however, according to the publication, the data are not available for use. Publication of data summaries in a digestible form can help support the incorporation of models into the library.

5 | CONCLUSION

We have presented an estimation strategy for evaluating the impacts that arise from the operation of fishing gear, and shown how it can be used to generate evaluations of environmental impact. Although in this case we characterized dissipative loss, the same framework can be used to compute other indicators extensive of fishing effort, for instance measures based on the length of line deployed, swept area of netting, or surface area impacted while fishing. Other aspects, such as the biodegradability of gear materials, could also be described. Through further work, we hope to apply these characterizations to estimate impacts at the level of individual fisheries and at the global scale.

The unit gear framework offers a structure and data model for systematic harmonization and knowledge synthesis of observations and technical information about fishing gears in the context of industrial ecology. If it were developed into a sufficiently complete and accessible resource, the gear library could be used by fishery managers locally to evaluate gear management against published benchmarks and otherwise inform the development of mitigation strategies.

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CODE AND DATA AVAILABILITY

The unit gears software system, including the library of gear model components and their documentation, is available for use under the BSD License and can be found in our GitHub reposiotory, https://github.com/bkuczenski/unit_gears. The version used to produce the tables and results figure in the paper can be found at https://github.com/bkuczenski/unit_gears/releases/tag/v1.0.1 and DOI: 10.5281/zenodo.4648562. More information is available in Supporting Information S1 and in the repository itself. Support in using the software is available from the corresponding author. Reviews, submissions of gear models, and the identification of problems and/or potential improvements in code and documentation are appreciated.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

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