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Watson, Audrey; Blount, Craig; McPhee, Daryl Peter; Zhang, Dilys; Lincoln Smith, Marcus; Reeds, Kate; Williamson, Jane

Published in:
Marine Pollution Bulletin

DOI:
10.1016/j.marpolbul.2022.113500

Recommended citation(APA):
Watson, A., Blount, C., McPhee, D. P., Zhang, D., Lincoln Smith, M., Reeds, K., & Williamson, J. (2022). Source, fate and management of recreational fishing marine debris. *Marine Pollution Bulletin*, *178*, [113500]. https://doi.org/10.1016/j.marpolbul.2022.113500

Marine Pollution Bulletin 178 (2022) 113500

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Review

Source, fate and management of recreational fishing marine debris

A.R. Watson [a,*], C. Blount [b], D.P. McPhee [c], D. Zhang [b], M.P. Lincoln Smith [a,b], K. Reeds [b], J.E. Williamson [a]

[a] School of Natural Sciences, Macquarie University, New South Wales 2109, Australia
[b] Cardno (NSW/ACT) Pty Ltd, St Leonards, New South Wales 2065, Australia
[c] Faculty of Society and Design, Bond University, Gold Coast 4226, Queensland, Australia

ARTICLE INFO

Keywords:
Recreational fishing
Sport fishing
Marine debris
Management strategies
Review
Plastic

ABSTRACT

Marine debris, directly and indirectly, threatens marine habitat and biota. Fishing activity is generally recognised as a contributor to marine debris, but the relative input from recreational fishing remains unassessed. Here we provide the first comprehensive literature review of recreational fishing marine debris (RFMD) on a global scale. A systematic literature review identified 70 studies related to RFMD, and plastic and metal respectively were the dominant debris materials found. Nearshore coastal areas and reefs, acted as both sources and sinks of RFMD and a diverse suite of potential impacts such as ghost fishing and entanglement were identified at local scales. Overall, research of RFMD is lacking globally, however, its role in marine debris input is likely underestimated. We recommend more research on the volumes and risks, using a standardised classification approach. Where intervention is required, we suggest cooperative approaches between the sector and authorities.

1. Introduction

One of the greatest challenges of the Anthropocene is managing debris in the marine environment that originates from humans (Thompson et al., 2004). Marine debris, defined as discarded material present in the marine environment from anthropogenic sources (UNEP, 2009), is comprised of a broad range of materials such as plastic, metal, wood and glass (Whiting, 1998). It enters the marine environment directly from land or from boats via dumping, accidental loss or abandonment of fishing gear, or indirectly through storm water or rivers (Katsanevakis, 2008). The marine debris problem is global in scale, intergenerational in impact and results principally from human behaviour (UNEP, 2012). The rate of accumulation of marine debris continues to increase (e.g. Watters et al., 2010), including increasing discard rates, particularly for plastic. It is now estimated that 8300 million metric tons of plastic have been produced by humans since the 1950s and, if this rate continues, 12,000 million metric tons are predicted to be in the natural environment by 2050 (Geyer et al., 2017). Additionally, marine debris has the potential to cause significant global economic impacts given it is expensive to remove, causes declines in fish stocks, inhibits the preservation and recovery of threatened species, can damage or immobilise marine vessels, and can reduce tourism amenity (McIlgorm et al., 2011; Newman et al., 2015). It is thus in the interests of multiple stakeholders to prevent its entry into the marine environment.

Marine debris poses considerable threats to marine organisms through both entanglement and ingestion, as well as facilitating the colonisation of invasive species and the spread of diseases including viruses (Gregory, 2009; Gall and Thompson, 2015; Wilcox et al., 2016; Geoghegan et al., 2018; Lamb et al., 2018). Interactions with debris can cause serious damage to individuals and populations by contributing to reproductive disruption, behavioural alterations, stress, disease and mortality (Jovanović, 2017; Gall and Thompson, 2015). These effects can interact cumulatively with overfishing, human-induced climate change and habitat modification or destruction.

The activity of commercial fishing is considered a significant contributor to marine debris (Jones, 1995). Abandoned, lost or otherwise discarded commercial fishing gear is common, and the size, weight and depth of operation of much commercial gear makes it frequently difficult to remove from the marine environment (Jones, 1995; Richardson et al., 2019). Such gear is a growing concern for sustainable fisheries and healthy ecosystems because of its capture and entanglement of marine organisms, referred to as ghost fishing (Jones, 1995; Wilcox et al., 2016; Azevedo-Santos et al., 2021; Goodman et al., 2021). It also potentially impacts human use of marine systems by creating navigation hazards (Gilman, 2015; Scheld et al., 2016).

The contribution and impacts of marine debris from recreational

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* Corresponding author.
E-mail address: audrey-rose.watson@hdr.mq.edu.au (A.R. Watson).

https://doi.org/10.1016/j.marpolbul.2022.113500
Received 20 September 2021; Received in revised form 21 February 2022; Accepted 24 February 2022

fishing activity is much less understood. Available information suggests that it is an emerging priority (Whiting, 1998; McPhee et al., 2002; Hong et al., 2013). Recreational fishing, defined here as fishing for pleasure, food or sport and not for sale, principally involves angling (use of hook and line), deployment of traps to target crabs and lobsters, and of nets to catch fish and smaller crustaceans, such as prawns. Although other forms of recreational fishing exist, such as spearfishing and gathering by hand, these were not reviewed here because they are less common activities (Henry and Lyle, 2003) and unlikely to substantially contribute to fishing marine debris. Given that recreational fishers in almost all countries and the participants in many countries are numbered in the millions (Aas, 2008; Arlinghaus et al., 2021), recreational fishing marine debris (RFMD) has the potential to significantly contribute to the overall load of marine debris (Campbell et al., 2005). Recreational fishing is common in many countries and can reportedly have a greater ecological footprint than commercial fishing in several instances (McPhee et al., 2002). While there is a consensus that the amount of anthropogenically derived marine debris poses substantial threats to economies and the marine environment, surprisingly little research is available on documenting and quantifying the input from recreational fishing activity. The primary aim of this systematic literature review was to synthesise knowledge about RFMD. A secondary aim was to determine whether sufficient knowledge was available to verify or dismiss the threats from RFMD to the environment. In doing this we needed to understand the types and volumes of RFMD that enter the marine environment and its fate (i.e. its sources, including the source locations, and sinks). We also needed to understand the threats to the environment from each of the various components of RFMD and potential interactions with marine habitats and biota. For context, we also needed to understand the relative contribution of the load of RFMD to the total output of marine debris. We identify where research gaps lie and whether it is possible to determine key target areas for management of RFMD. We examine global and local strategies that have been used to address RFMD and propose options for addressing gaps in knowledge and for managing identified threats.

2. Methods

2.1. Search strategy

Literature was searched in November 2019 using Scopus™, Web of Science™ and ScienceDirect™ to locate scientific publications and grey literature on RFMD since 1965. These databases were searched using the key words [(recreational OR sport OR tournament) AND (fishing OR angling) AND (marine) AND (debris OR pollution OR litter)]. Web of Science™ returned several thousand, mostly irrelevant results hence the search was refined by searching within results using the key words 'recreational' and 'fishing'. Articles that did not examine marine debris in any context were excluded. Marine debris studies with no inclusion of fishing related debris in either quantification or source identification were also excluded. Fishing debris cannot always be definitively categorised as commercial or recreational in origin without analysis of other factors such as region and water depth (GESAMP, 2021). Therefore, only studies that specifically identified recreational or commercial origin were categorised as such for metric analysis, with others categorised as 'fishing (unspecified)' (Fig. 1). Relevant studies were identified and tabulated based on paper type, study type, prominent debris material, prominent source of debris, location and more (Fig. 1 and Supplementary material, Table 1). Other information was also recorded (if given) including the methods used, duration of the study, season of data collection, geomorphology of sample area (i.e. beach, estuary, coral reef etc.) and location usage (i.e. fishing, tourism etc.).

Metrics were then summarised in Microsoft Excel (Version 15.33). Additionally, study locations were mapped using Geolytics, a program allowing the placement of multiple location pins on a global map (GeoLytics, 2003). For context, the results of the systematic search above for RFMD were combined with key information on the general marine debris, such as overall loads and discard behaviours, and recreation fishing sector.

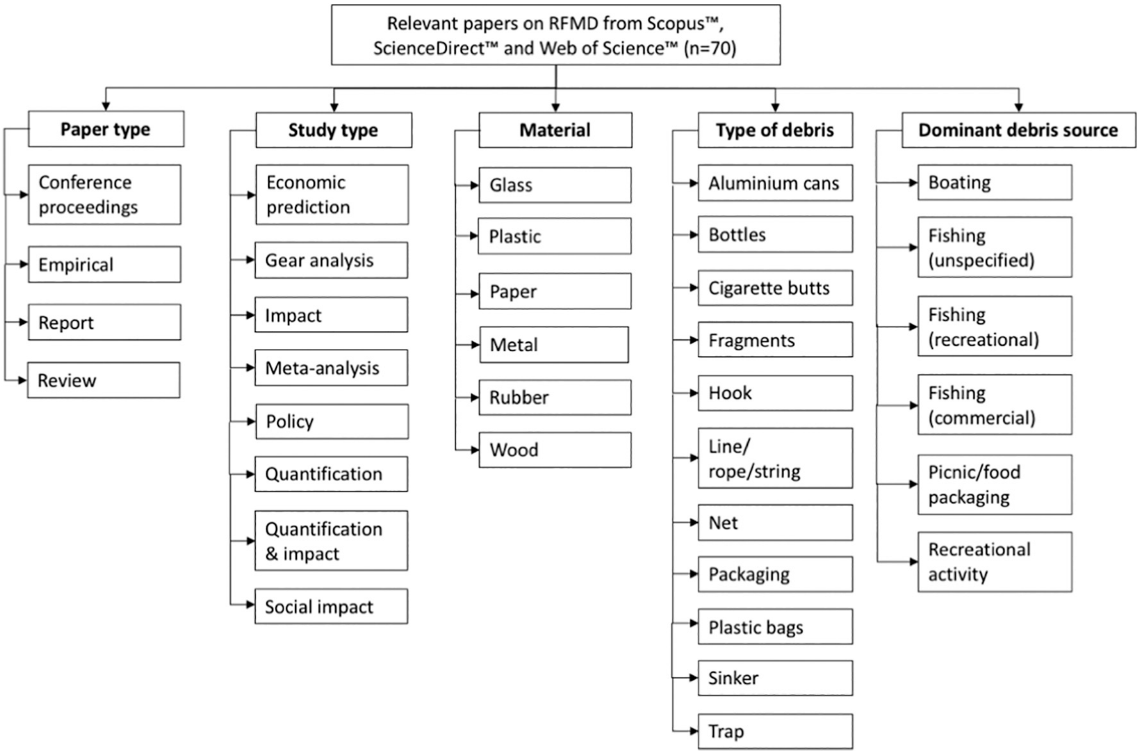

Fig. 1. Classification parameters for assessing available studies on recreational fishing marine debris.

3. Results

3.1. Overall trends in RFMD studies

Seventy relevant studies were identified in the systematic search and were distributed globally, with the largest number of studies in Australia, the Mediterranean and the USA (Fig. 2 and Supplementary material, Table 1). The area covered by the 70 studies was highly variable with some quantitative studies sampling at >100 sites, while others sampled at only a single location. Of the relevant studies identified, 11 were highly specific to RFMD as opposed to general marine debris.

Limited literature on marine debris was available prior to the early 2000s, with output in this field of research increasing around 2008 (Fig. 3). A large proportion of the literature to date are empirical studies (i.e. field studies) (Fig. 3).

Eight study types were identified in the search: economic predictions, gear analysis, meta-analysis, policy, social impact, quantification, impact and quantification/impact (Fig. 4). Thirty-six studies were categorised as quantification studies due to their examination of the abundance, weight and/or density of marine debris in various locations.

3.2. Quantitative studies

Quantitative RFMD studies used a variety of methods (Supplementary material, Table 1). Shore surveys, which included beach clean-ups, shoreline transects and quadrats, were the most common methods used for quantifying marine debris (Fig. 5). Underwater surveys were also frequently used, utilising SCUBA, snorkel and manned submersibles. Several studies used a combination of methods such as SCUBA surveys paired with manned submersible or image mapping to maximise chances of detecting debris present.

Within the 43 quantitative (quantification and quantification/impact) studies reviewed on RFMD, 25 studies identified the main source of debris. Overall, debris associated with fishing prevailed as the main source of debris, however, many studies could not discriminate recreational from commercial fishing debris (Fig. 6). Debris originating from general waste and specific recreational activities, such as tourism and picnics, was also reported in many studies, and in some was the main source of debris (Supplementary material, Table 1).

Plastic was the most abundant material found in those studies that characterised the type of material (Fig. 7). Plastic debris comprised a range of items, including monofilament fishing line, food packaging, cigarette butts and plastic bags.

3.3. Potential sources of RFMD

RFMD may consist of materials specifically related to the act of fishing, such as bait containers, fishing gears and terminal tackle, or ubiquitous materials, such as food wrappers, drinking containers, etc., which can be associated with the act of fishing but may also originate from other activities. The potential for creating RFMD varies based on the fishing activity, target species and the type of coastal habitat in

Fig. 2. Global distribution of studies on marine debris identified in the strategic search where location was given ($n = 55$). Each point represents a single study.

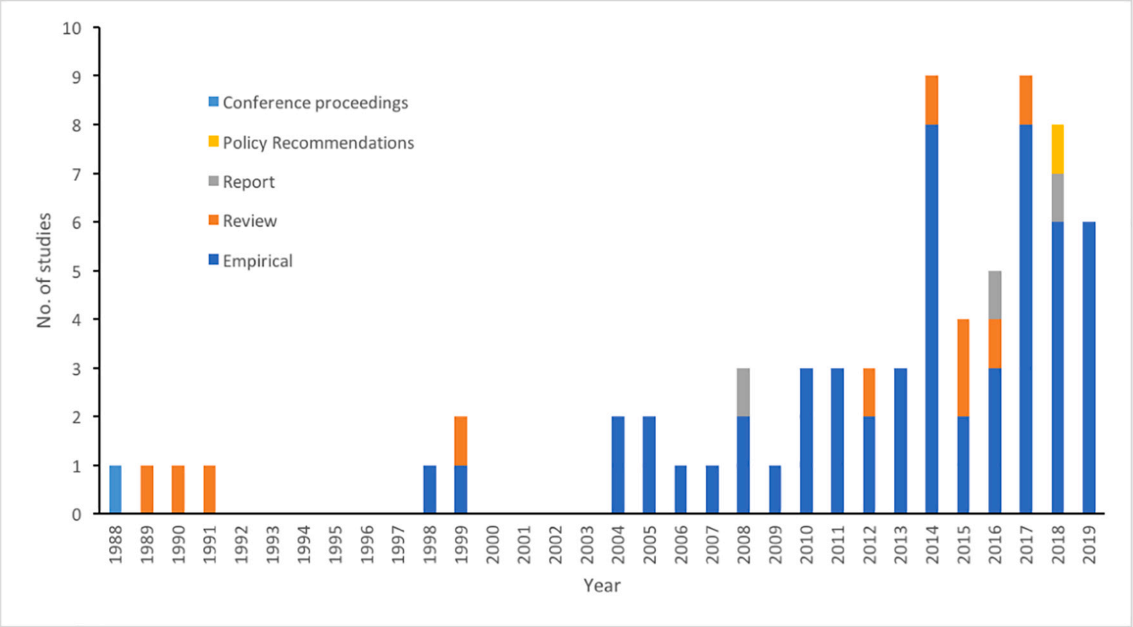

Fig. 3. Proportion of literature types within the number of studies over time, for the studies on marine debris identified in the strategic search ($n = 70$).

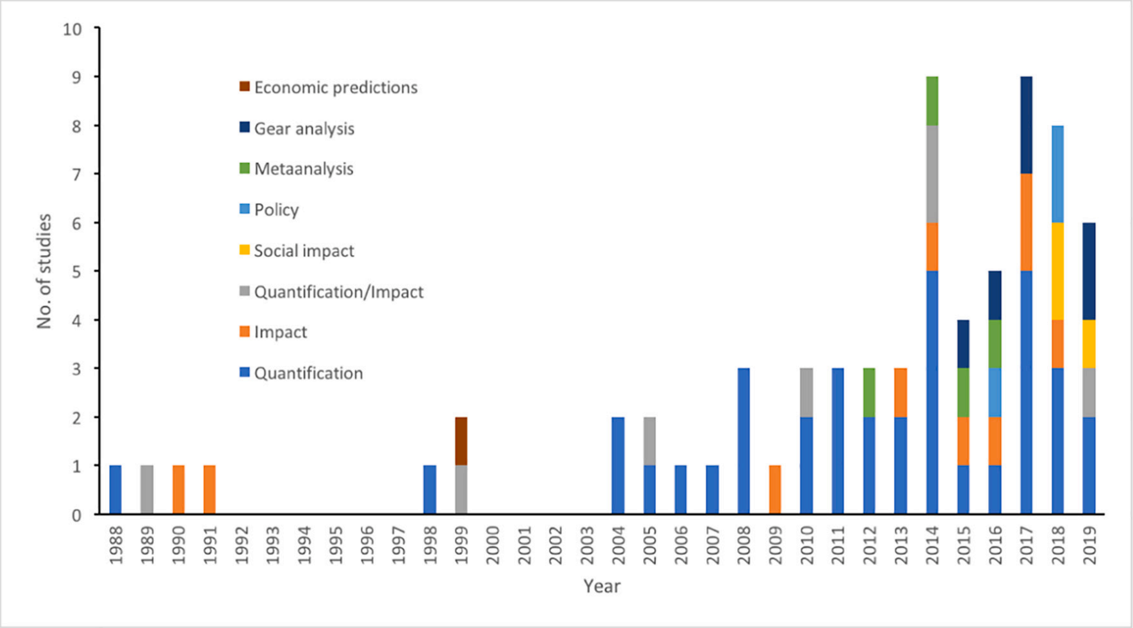

Fig. 4. Proportion of study types within the number of studies over time, for the studies on marine debris identified in the strategic search (n = 70).

which it is undertaken. Although this review focused on RFMD, it is also important to recognise the contribution of general waste on marine debris. Many people undertaking general every-day activities incorrectly or accidentally dispose of general waste. For example, in an Australia-wide study, 23% of people were observed to litter (i.e. to dispose of their rubbish inappropriately), with most littering occurring within five metres of a bin (Williams et al., 1997).

3.3.1. *Fishing gear and effort*

Globally, while participation rates in recreational fishing are falling across developed countries, increasing population sizes are leading to more participants overall (Loomis and Ditton, 1988; Arlinghaus, 2006; Arlinghaus et al., 2015). Factors influencing participation rates include physical and economic constraints, changing demographics and various other social issues (Arlinghaus et al., 2015, 2021). The global increase in the number of participants has implications for the volume of RFMD. While recreational fishing is geographically widespread, fishing effort is generally highly concentrated in locations that are relatively easy to access and that provide appropriate habitat for target species (Caddy and Carocci, 1999; Bucher, 2006; Smallwood et al., 2006; Ochwada-Doyle et al., 2014; Lynch, 2006; Griffin et al., 2021). Most marine recreational fishing occurs in estuaries or coastal areas and embayments that provide protection from prevailing weather. Such areas are more accessible than areas distal from the coast (West et al., 2015). Recreational fishing can also be aggregated around artificial reefs and/or Fish Aggregating Devices (FADs) that aim to increase productivity and

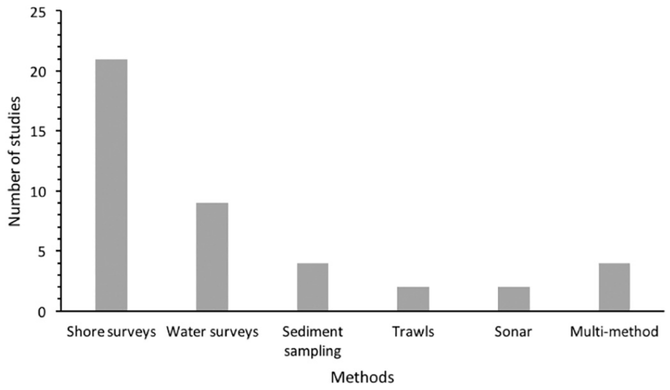

Fig. 5. Number of studies and the general classification of methods used for quantitative studies on marine debris identified in the strategic search ($n = 43$).

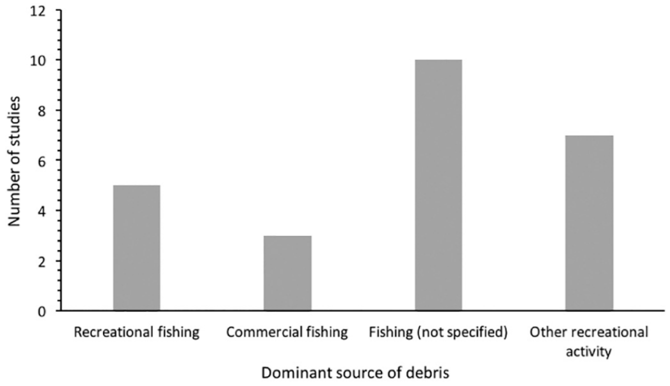

Fig. 6. Number of studies and the main source of debris identified for the quantitative studies that characterised source of debris in studies identified in the strategic search ($n = 25$).

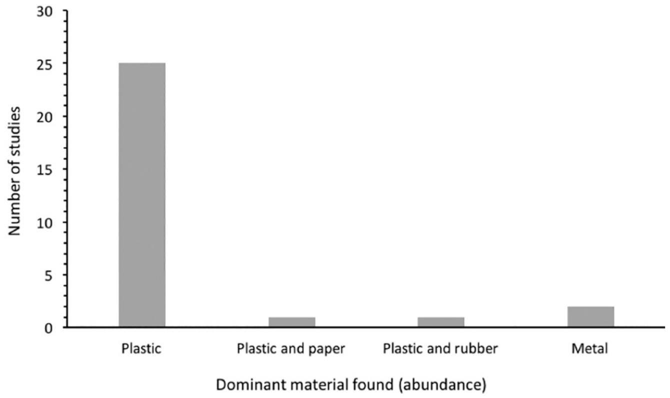

Fig. 7. Number of studies and the dominant material found, by abundance, for the quantitative studies that characterised materials in studies identified in the strategic search ($n = 29$).

aggregate target species (Brickhill et al., 2005; Folpp and Lowry, 2006).

The most common form of recreational fishing is angling, which is done with a rod, reel, line and terminal tackle. In Australia, Henry and Lyle (2003) estimated line fishing methods (bait, lure, jig, fly, setline) accounted for 85% of total fishing activity. The importance of angling as a form of recreational fishing activity is likely to be similar in other parts of the world.

Fishing line consists of two main types: monofilament, which is usually extruded nylon; and braided lines made from multiple strands of ultra-high molecular weight polyethylene (UHMWPE). A variety of different breaking strains of fishing lines are used. Terminal tackle includes sinkers, floats, hooks, swivels and lures. Lures are often used instead of bait and may consist of hard-bodied or soft-bodied structures. The latter consists of a lead jig with a soft plastic body that can be easily damaged/separated by a fish's bite or from snagging. The exact nature of terminal tackle is influenced by the target species and habitat. Recreational fishers also purchase bait or terminal tackle in plastic bags or containers.

Terminal tackle may be cast out over the water where it sinks onto the seabed, cast and retrieved with bait or lure targeting surface fish, or kept close to the surface with the aid of a float, depending on the species targeted. Such tackle can break off the main line when a fish is hooked or when the line becomes entangled (“snagged”) on the seabed or other structures. Some floats (e.g. balloons) are designed specifically to break off the main line when a fish is hooked. These balloons then typically remain on or in the water.

Various types of traps and nets are used by recreational fishers, including those that can be: set in position to enclose or entangle; hauled; cast; or used to scoop up fish or crustaceans. Modern nets are typically constructed from synthetic fibres, such as monofilament nylon or multiple twisted or braided polymer filaments. The top edge of nets is sometimes attached to a rope called the headline, floatline or corkline. Floats of various material (generally polystyrene or cork) are attached to the headline to provide buoyancy. Recreational traps and nets have the potential for ghost fishing – i.e. they continue to catch animals after they have been lost and thus contribute to fisheries mortality (Campbell and Sumpton, 2009; Anderson and Alford, 2014).

3.3.2. *Loss rates of fishing gear*

Studies on loss rates of recreational fishing gear are rare. The only quantitative study that we know of from the systematic search was by Broadhurst and Millar (2017) who investigated breakage rates and twine loss for various configurations of recreational crab hoop nets in Australia. Their study showed that irrespective of configuration, conventional multifilament polyamide twine hoop nets consistently produced marine debris—the extent of which substantially varied according to several biological (i.e. the species targeted) and environmental (i.e. water temperature, salinity and diel deployment) factors. They estimated the total annual twine loss in the state of New South Wales (NSW), Australia, to be ~25,000 m and 400 m when targeting mud crabs (*Scylla serrata*) and blue swimmer crabs (*Portunus pelagicus*), respectively. The difference in twine loss between species was attributed to differences in size and aggression of *S. serrata* relative to *P. pelagicus*. A more recent study by Broadhurst and Millar (2020) found that while all types of hoops lost some twine, twine loss was the greatest with multifilament hoop nets, followed by multi-monofilament and then monofilament. All hoop nets caught the same number of *S. serrata* irrespective of soak time or twine type. The authors suggest that switching from multifilament to monofilament hoop nets while targeting *S. serrata* is a practical method to reduce marine debris without impacting catch.

Commercial fishers also use lines, traps and nets, and studies of abandoned, lost or otherwise discarded commercial fishing gear provide a guide to potential loss rates that could be expected for recreational fishing gear. It is difficult to say whether loss rates for recreational fishing gear would be greater or less than commercial fishing gear. Recreational fishing gear is generally less robust than commercial fishing gear meaning that the frequencies of breakages are potentially greater than for commercial gear. Further, given most recreational fishers would be expected to be less adept (at fishing) than commercial (professional) fishers, this would likely contribute to a greater risk of breakage or subsequent loss of gear (i.e. fishing on unfamiliar ground or with inadequate equipment for the bottom type or range of species that could be hooked). On the other hand, commercial fishers are likely to be more risk averse because their livelihood depends on catch and they generally operate in more extreme conditions than recreational fishers (i.e. in deeper areas with stronger currents) and leave gear unattended for longer periods. Notwithstanding these differences, Richardson et al. (2019) estimated that, worldwide, each year 5.7% of commercial fishing nets, 8.6% of traps, and 29% of lines are lost. Of the lines, predicted losses were 23% for handlines, 65% for pole-lines, 20% for longlines, including 17% loss for hooks from longlines and 22% for trolling lines. Their review also indicated that loss rates were variable and depended on gear characteristics, operational aspects and environmental contexts.

Studies of commercial gear loss discussed in Richardson et al. (2019) indicated that snagging on bottom obstructions was a major cause of gear loss and it is not unreasonable to assume that the same would apply to recreational fishing gear. The reviewers speculated that while line losses were great, these likely comprised of a mix of entire gears and fragments due to breakage. In contrast, while trap and net losses were less, these losses likely comprised of entire gears. Fisher behaviour and effort are also important factors affecting rates of gear loss. Increased fishing effort has the potential to result in gear conflicts arising from overcrowding, increased competition and risk-taking behaviours among fishers, and this can be a factor that drives losses of fishing gear (Macfadyen et al., 2009; Richardson et al., 2019.

3.4. Levels, loads and sinks of RFMD

3.4.1. Incorrect disposal of waste

In this review, incorrectly disposed non-fishing material refers to discarded packaging (e.g. from food, drinks or fishing gear), cigarette butts, etc. Many studies consider this to be generated from land-based activities but in many cases, it is difficult to distinguish between land- and boat-based sources such as commercial or recreational fishing or shipping (Koutsodendris et al., 2008). One study in Greece found that the proportion of anthropogenic debris collected on beaches attributed to fisheries and aquaculture ranged from 4.6% to 10.2% (Prevenios et al., 2018). An Australian study identified a positive correlation between general litter on beaches and the number of recreational boats, most of which were undertaking recreational fishing (Widmer, 2002). In another study of debris loads in coastal areas of eastern Australia, sites that had the highest loads of general marine debris (Nambucca River Estuary and the Pipeline, Port Stephens) were popular shore-based recreational fishing locations (Smith and Edgar, 2014).

Despite these correlations, no studies have successfully differentiated incorrectly disposed non-fishing material (e.g. drink containers, food-wrappings, etc.) from recreational fishing activities to that from general every-day activities. It is plausible that the potential amount of incorrectly disposed non-fishing waste associated with recreational fishing is similar to that of the general public. This is reasonable given that the rates of incorrect disposal of wastes at public waterside areas (i.e. beaches and waterways) are similar to those for roads and residential and industrial areas (Cutter et al., 1991). A study in Cape Town, South Africa quantified the amount of waste that reached the drainage systems and was carried into aquatic environments to be as high as 111 kg ha^{-1} yr^{-1} (Marais et al., 2004). Thus, an important distinction should be made between unintended loss of fishing equipment (e.g. line breakage) and inappropriate disposal of waste by recreational fishers. Notwithstanding this distinction, recreational fishers may be inclined to be more aware of and show greater affinity for the environment with respect to waste disposal because of their direct interaction with the environment (Browne et al., 2012).

Review of the composition of anthropogenic debris in marine regions showed that plastics make up the largest proportion of overall litter pollution (Galgani et al., 2015). This reflects studies of land-based anthropogenic debris in non-marine regions. For example, the majority of incorrectly disposed rubbish collected in a study in New Jersey, USA were cigarette butts (Cutter et al., 1991) of which the filtration material is cellulose acetate, a plastic. This was a trend in most public areas, including beaches and waterways (Cutter et al., 1991). In another study, the proportion of participants who incorrectly disposed of cigarette butts was also the highest of all other types of litter (57%) (Schultz et al., 2013).

3.4.2. Loads of lost or discarded fishing gear

Line, rope, net and plastic fragments are the most common types of fishing-related debris found in the RFMD studies, with much of the monofilament line being derived from recreational fishing (Supplementary material, Table 1).

The first published study that directly reported the contribution and characterisation of RFMD load was by Bauer et al. (2008) who used scuba-based surveys to assess fishing debris within a popular recreational fishing area. They attributed 68% of debris to fishing activity. Despite not differentiating between possible commercial and recreational debris, it is likely that most of the fishing debris originated from recreational fishers as commercial fishing was restricted in the area. This study did not report volume of debris types, rather percentages of total debris and frequencies of debris within sampling areas, making it difficult to determine the gross volume of debris present. Of the 93 items of debris identified, 63 were from fishing gear: 31 fishing line, 10 leaders, one spear gun part and 21 non-descript or other gear items (Bauer et al., 2008). Other studies have also sourced debris from recreational fishing but did not, however, strongly justify their isolation from commercial sources or suggest their relative contributions (Anderson and Alford, 2014; Bo et al., 2014; García-Rivera et al., 2017).

Despite plastic, line and netting appearing as the most abundant material in a large proportion of the literature, other materials such as lead sinkers exceed plastic loads in some areas. Two studies reported that lead sinkers dominated in the proportion of marine debris items found (Lloret et al., 2014; Farias et al., 2018). Over a three-year survey of coastal Spain, lead sinkers constituted 36% of the total number of debris items found, however, line debris was not evaluated for logistical reasons (Lloret et al., 2014). The study reported the total weight of sinkers retrieved per year: 38.46 Kg in 2010, 67.34 Kg in 2011 and 3.9 Kg in 2012 (Lloret et al., 2014). A similar short-term survey in a portion of an estuary in southern Brazil, collected 1752 lead sinkers (83% of total debris) weighing 50 Kg (Farias et al., 2018). In addition, 98% of the total marine debris found was attributed to local recreational and artisanal fishing activities, highlighting the relative importance of recreational fishing to debris load in the area (Farias et al., 2018). Overall, artisanal fishing had by far the greatest contribution to the number of sinkers, however, it was limited to one area of the study region as opposed to those from recreational fishing which were identified in three of the four areas (Farias et al., 2018).

RFMD appears to be accumulating in aquatic systems over time. A 15-year study off coastal California found the volume of marine debris increased over the study period (Watters et al., 2010). While Watters et al. (2010) report debris as ‘density’ (number of items/100 m), making quantities difficult to discern, they documented recreational fishing to be the source of the majority of the marine debris in the 1990s (92%) and 2007 (93%), with the debris being almost entirely monofilament line (Watters et al., 2010). This result is consistent with another study in the same region that found monofilament line from recreational fishing sources to be the predominant type of debris (Love et al., 2010). In contrast, a study in New Jersey, USA, identified crab traps from recreational fishing origin as the primary recreational fishing debris, constituting 7% of marine debris over a four-year period (Sullivan et al., 2019).

Debris load and items recorded may be influenced by the methods used to quantify such debris. As opposed to the above studies that use marine based surveys, Yorio et al. (2014) and Hardesty et al. (2017) used a more traditional beach survey methodology to quantify RFMD. In a protected area of coastal Argentina, 55% of marine debris resulted from recreational fishing and was composed predominantly of 243 balls of tangled monofilament line (Yorio et al., 2014). In a beach survey of debris at a continental scale around Australia, only 2% of total debris was attributable to recreational fishing, although much of the plastic debris was unidentifiable (Hardesty et al., 2017). Importantly, beach surveys may be biased in the types of debris found, as heavier items such as sinkers may remain in the water. Hardesty et al. (2017) represents the only peer reviewed study available that quantifies recreational fishing debris in Australia. Other studies report more general volumes of marine debris in the Australian Environment (Kiessling, 2003; Edyvane et al., 2004; Smith and Edgar, 2014).

Overall in the RFMD studies identified, the most abundant debris materials were plastic and metal (Supplementary material, Table 1). This is consistent with general global marine debris estimates where plastic dominates (Derraik, 2002). In particular, for RFMD, fishing line (predominantly monofilament) and sinkers dominated debris type.

3.4.3. RFMD component breakdown

Given recreational fishing activity is concentrated in coastal marine systems (Section 3.3.1), these areas include hotspots for both sources and sinks of RFMD. RFMD potentially enters the environment as intact or fragmented items (Section 3.3.2 and Fig. 8) and tend to break down further once in the system. Such fragmentation differs depending on the composition of the debris. Intact items are exposed to chemical and mechanical forces that facilitate breakdown (Cooper and Corcoran, 2010). Fractures, notches, flakes, pits, grooves and vermiculate textures provide loci for chemical weathering that further weaken polymer surfaces. Plastic pieces can break down into 'microplastics' defined by many in the scientific community as plastic particles from a few microns to 500 μm in size (Ng and Obbard, 2006; Barnes et al., 2009; Andrady, 2011). Metal debris can breakdown on the seabed from weathering and chemical dissolution, releasing ionic metals into sediments and the water column (Schroeder, 2010). Breakdown of metals can also occur following ingestion by marine fauna. Birds that ingest grit to aid digestion have ground lead objects (e.g. sinkers or jigs) into smaller particles or ionic lead before releasing them back into the environment (Scheuhammer, 2009; Schroeder, 2010). Organic materials, such as wood, can become part of the natural nutrient cycle, feeding fungal and bacterial colonies and marine crustaceans (Alias and Jones, 2000; Maylon, 2011). Microorganisms and biofilms play a role in the dissolution of glass (Brehm et al., 2005).

Corrosion time differs on recreational fishing gear depending on its composition. Stainless steel hooks are more corrosion-resistant than hooks made from other metal alloys. Most fishing hooks are made of high-carbon steel and these are generally tougher than stainless steel hooks and do rust. The rate of rusting depends on their plating. Coatings vary from bronze varieties, which offer little corrosion resistance, to those that contain more protective elements like nickel, zinc, tin and lacquer. Edappazham et al. (2008) evaluated the corrosion resistance of two common surface finishes, tinned and blued, applied to fishing hooks. Exposure of the hooks to 300 h of salt spray resulted in an appreciable weight loss, with the tinned hooks incurring a loss of 5.37% from the initial weight and blued hooks losing 20.54% of initial weight. In saltwater, therefore, even the most basic plated hooks could last for months before significant corrosion occurs. Stainless hooks would keep their integrity much longer and thus have greater potential for continual impacts after breaking off with other terminal tackle.

The breakdown time of some marine debris is largely unknown but also differs depending on composition. Metal debris deposited in aquatic sediments can take tens or hundreds of years before dissolution (Schroeder, 2010) while the breakdown of plastics is estimated in the order of hundreds of years (Kershaw et al., 2011). Some materials have greater potential for fragmentation than others. Among plastics, polyethylene more readily degrades than polypropylene (Cooper and Corcoran, 2010). Some plastics are degraded by ultraviolet (UV) radiation (i.e. polyethylene and polypropylene) and the integration of UV stabilising agents to extend the life of these plastics has made these more difficult to breakdown (Kershaw et al., 2011). Plastics on or close to the water surface are more exposed to this process than those at depth as seawater absorbs and scatters UV.

3.4.4. Sinks for RFMD

There are consistent patterns in areas that act as sinks for macro-RFMD. Most debris occurs at ledges on the seafloor, and aggregates in areas where boating intensity is highest (Bauer et al., 2008), or concentrated in shallow regions with rugged bathymetry (Cardno, 2007; Love et al., 2010). Macro-debris was associated more with rocky substratum than cobble or sand in coastal California (Watters et al., 2010). These sinks are presumably a result of RFMD entanglement then passive accumulation on areas with raised bathymetric features, however, it is

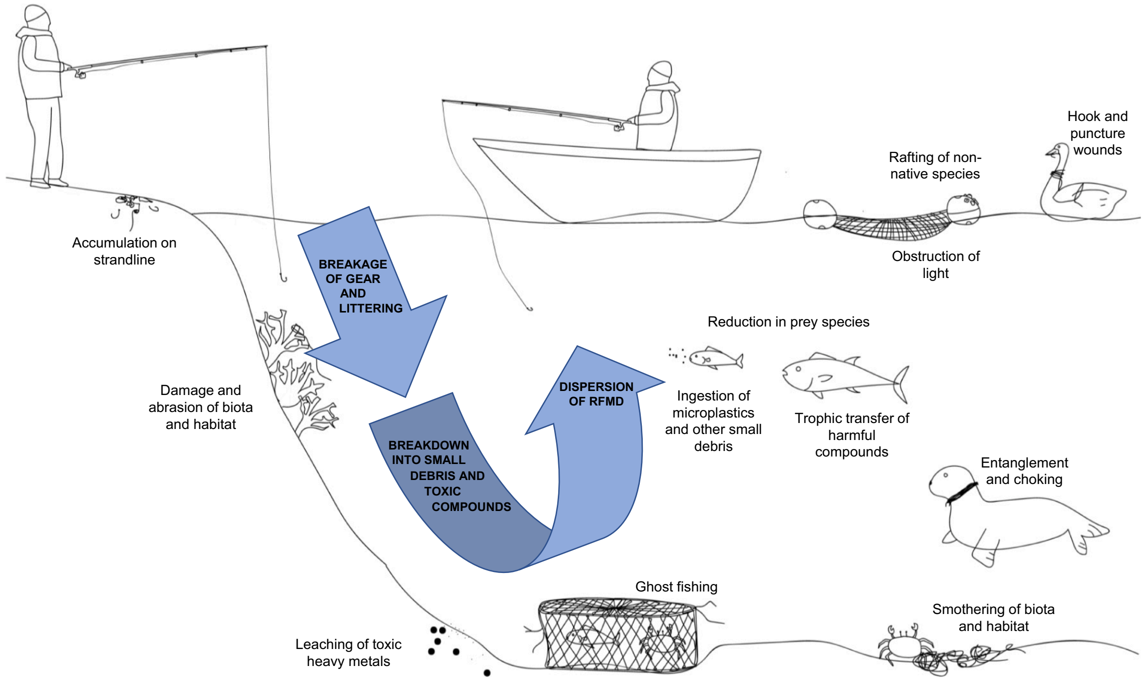

Fig. 8. Potential sources of RFMD and potential impacts.

also proposed that that fishers deliberately target these areas more frequently (Bauer et al., 2008).

Given marine recreational fishing occurs predominantly in coastal areas such as estuaries and bays, much debris from recreational fishing is likely to remain in these systems due to the limited hydrodynamic processes in these areas compared with further offshore (Katsanevakis, 2008). This has been supported by a greater abundance of marine debris observed in bays as opposed to open coast in some areas (Katsanevakis, 2008). An Australian study examined 120 coastal marine sites for marine debris and found that estuarine habitats and embayments were the most contaminated with debris (Smith and Edgar, 2014). Fishing related debris dominated the majority of sites providing support for the source and sink of recreational fishing debris in these areas. However, many studies on marine debris, and the majority identified on RFMD, have been conducted in coastal regions introducing a potential bias to this coastally concentrated pattern of debris (Fig. 2), and smaller and more lightweight items such as fragments of line or plastic bags have the potential to be more readily transported away from these sinks.

More generally, highly populated coastal areas, off-shore canyons, enclosed bays, popular beaches (see Section 3.4.1) and current-based accumulation zones such as gyres, may act as sinks for marine debris (Galgani et al., 2015). Plastics have been found in even the most remote parts of the Arctic and Antarctic oceans and microplastics in particular (particles 5 mm in size, see Masura et al., 2015) have been identified in every marine habitat (Ivar do Sul and Costa, 2014). Ingestion of debris, such as microplastics, may act as a vector of transport to other sinks, however, this is unlikely to be occurring in substantial quantities.

3.5. Impacts on habitat and biota

Continual input of marine debris into the ocean poses a persistent threat to marine and coastal habitats and biota (National Research Council, 2008). Impacts of RFMD on habitats or organisms are dependent on the volume and type of marine debris, along with the source and sink.

RFMD can directly impact on organisms through entanglement, external injury and ingestion, all of which can lead to mortality. Netting, rope and line can entangle wildlife restricting their movement and may lead to strangulation or long term constriction injuries. Similarly, external injuries such as puncture wounds from hooks can impact an organisms' ability to move or feed. Marine debris can also be confused with prey species and ingested by marine wildlife, causing a physical blockage in digestive systems and lead to internal injuries and ultimately starvation (Valente et al., 2007; Pedà et al., 2016; Jovanović, 2017; Otway et al., 2021). Smaller debris may also be consumed unintentionally and the presence of such debris in marine organisms is ubiquitous and concerning.

RFMD also pose indirect consequences to marine organisms, however, these are difficult to quantify. Plastic debris can facilitate the invasion of invasive or non-native species to new regions through rafting (Gregory, 2009). Involvement of recreational fishing debris in this process is likely minimal, however, as much of the debris is likely to remain in relatively isolated coastal systems. Indirect impacts also include the alteration of habitat which may lead to ecological changes to system and behavioural changes among organisms.

3.5.1. Plastics

Much of the researched impacts of marine debris are focused on plastics due to the known risks they pose to organisms. Plastics are not considered to 'biodegrade' in the marine environment as the biodegradability or oxy-degradability of plastics in industrial composters or landfill are linked to a temperature consistently exceeding 58 °C (Song et al., 2009). Thus, many plastics remain suspended in the water column and ultimately are sequestered into benthic habitat for substantial periods of time, increasing risk to organisms across a broad range of marine environments. Plastic represented the most abundant material found in the RFMD quantitative studies by a large margin (Fig. 7). Plastic-based materials associated with RFMD showed line and net to display the greatest impacts on marine organisms in most areas (Dau et al., 2009; Anderson and Alford, 2014; Bo et al., 2014; Franco-Trecu et al., 2017). Expanded polystyrene foam (EPS) used for fishing floats is also pervasive in the marine environment, however, with high impacts to marine fauna (Derraik, 2002).

Impacts from plastics associated with RFMD are well documented over time. Entanglement of marine life in fishing debris, most often by plastic line or netting, has been reported for decades (Gregory, 2009). Lost or abandoned fishing gear has the capacity to retain its integrity for some time and continue to fish and trap animals, a phenomenon coined ghost fishing. While most of the research on ghost fishing has focused on impacts of commercial fishing gear such as long-lines, gill and trammel nets (Kaiser et al., 1996), it can be assumed that monofilament lines and nets derived from recreational fishing activities will have impact in a similar manner. For example, a study in a New Jersey estuary found that 47% of derelict fishing gear contained trapped macrorganisms, such as fish, crustaceans and molluscs, at the time of sampling indicating substantial ghost fishing (Sullivan et al., 2019). Similarly, a study removing abandoned crab traps in coastal Louisiana determined that 65% of derelict traps were actively ghost fishing a variety of crab and fish species (Anderson and Alford, 2014). Interestingly, not all abandoned fishing gear continually ghost fishes. Two studies from California observed little to no ghost fishing by fishing debris, although limitations in the methodology of this research are acknowledged (Love et al., 2010; Watters et al., 2010).

Entanglement by marine debris generally poses a higher risk to larger animals, such as marine mammals, turtles and sharks, than for smaller animals. Two studies from the RFMD search examined the impacts of entanglement of organisms in plastic debris. One study reported the entanglement of 47 individuals from two otariid seal species, with injuries ranging from tight (soft constriction) to very severe (deep cut reaching muscular layers) (Franco-Trecu et al., 2017). While entanglement in fur seals was predominantly caused by commercial fishing material, greater than 60% of material entangling sea lions was from local artisanal and recreational fishing (Franco-Trecu et al., 2017). Although the material that caused entanglement was not specified, it was likely due to various forms of line and netting. The second study reported entanglement of kelp gulls (*Larus dominicanus*) by recreational monofilament lines (Yorio et al., 2014). A total of 27 gulls were found entangled, with 22 already deceased at the time of discovery. Those that were alive had severely damaged feathers which would compromise flight, notably decreasing the ability for post release survival (Yorio et al., 2014).

Within marine food webs, plastic debris can also serve as a transport medium and a potential source of toxic chemicals and diseases. Toxic chemicals in plastics can include polychlorinated biphenyls (PCBs), endocrine-active substances, and chemicals similar to dichlorodiphenyltrichloroethane (DDT). Recent evidence demonstrated that chemicals associated with plastic anthropogenic debris were bioavailable to lugworms and fish upon ingestion (Browne et al., 2013; Rochman et al., 2013). These chemicals are known to compromise immunity and cause infertility in animals, even at very low levels (Commonwealth of Australia, 2008). Plastics can also host pathogens such as those which trigger disease outbreaks on coral reefs (Lamb et al., 2018).

Ingestion of plastic debris relating to fishing activity in larger marine organisms, such as cetaceans and sea turtles, has been recorded for decades (Laist, 1997; Gorzelany, 1998). For cetaceans, numerous studies detail animals that have died as a result of ingested plastic debris (Gorzelany, 1998; Levy et al., 2009; Jacobsen et al., 2010). In the late nineties, for example, deaths of two bottlenose dolphins (*Tursiops truncatus*) resulting from the ingestion of monofilament line from recreational fishing were documented in Florida, USA (Gorzelany, 1998). Similarly, ingestion of fishing line was identified in 68% of loggerhead turtles (*Caretta caretta*) assessed, even in the absence of clinical symptoms (Franchini et al., 2018). Another study on loggerheads determined that although two deceased turtles had hooks, and hook related injuries in the intestinal tract, it was the attached monofilament line that had caused the lethal internal strangulation (Valente et al., 2007). Cetacean and turtle digestion is typically determined post mortem, hence data are skewed towards mortality as an endpoint. Little is known of the sublethal effects of plastic ingestion in these animals. Impacts of ingested plastic debris may pose serious risk to populations of such long lived marine organisms.

Microplastics are a specifically identified subset of marine pollution that has received considerable attention. Microplastics can result from the breakdown of larger plastics but are also manufactured as small beads specifically for use in consumer goods. Through ingestion, they are accessible to a wide array of marine organisms from the smallest (e.g., plankton) to the largest marine fauna (e.g., whales) and this can cause a range of problems including intestinal blockage and other physical and physiological damage, all of which compromise the health of the organism (Jovanović, 2017). Microplastic ingestion can also lead to behavioural changes, with consequences for reproduction, predator avoidance and foraging success (de Sá et al., 2015; Tosetto et al., 2016; Egbeocha et al., 2018). Furthermore, as people consume filter-feeding organisms such as shrimp, scallops, mussels and sea cucumbers, the relationship to human health and food security becomes an increasing concern (Ivar do Sul and Costa, 2014). Fish and shellfish from seafood markets in Indonesia and USA show that approximately one in four individuals sampled from different trophic levels and habitats (coastal seagrass and reefs, pelagic) contained small fragments of fibres, foam, film, or monofilament in their digestive system (Rochman et al., 2015).

Plastics also present a range of chemical threats as they can release their own toxic chemicals and also adsorb harmful contaminants present in the water (Teuten et al., 2009; Engler, 2012). Inorganic and organic contaminants such as PCBs, fertilisers and heavy metals are reported as being associated with microplastics (Teuten et al., 2009). Laboratory based studies have shown that plastics can act as a vector for chemical exposure in fish, and lead to bioaccumulation and adverse health effects such as behavioural change and endocrine disruption (Rochman et al., 2013; Wardrop et al., 2016). However, another study using environmentally relevant concentrations of plastics found no behavioural change in fish following short term exposure to plastic- contaminated prey, suggesting that such adverse impacts from plastic associated chemicals may result from chronic exposure (Tosetto et al., 2017).

3.5.2. Metals

Common components of recreational fishing gear are comprised of metal, including hooks, sinkers, swivels and traces. Metal components can impair the health of target and non-target species. A Korean study monitoring injuries to marine animals found that ingestion of hooks was by far the most prevalent impact, however, fishing line entanglement and ingestion of lead sinkers were also reported (Hong et al., 2013). Blood samples from three whooper swans (*Cygnus cygnus*) revealed lead poisoning, indicating that the sinkers were likely a direct cause of death (Hong et al., 2013). Overall, recreational fishing debris contributed substantially more to injuries or mortality on wildlife ($n = 33$) than commercial debris ($n = 9$) (Hong et al., 2013).

A fish breaking off and retaining terminal tackle is one route that fishing gear becomes marine debris. The retention of hooks and other terminal tackle by target, and non-target species, can result in serious injury or death. Photo identification of hooking incidents (external) with the critically endangered greynurse shark (*Carcharias taurus*) across aggregation sites on Australia's East Coast found a high frequency of hooked individuals (113 individuals from 673 identified) (Bansemer and Bennett, 2010). The majority of these sites have highly limited or no recreational fishing allowed, with only a few having no limit on extractive uses such as fishing (Bansemer and Bennett, 2010), and is, therefore, likely that some of these hooks originated from recreational activity. While not all hooking events resulted in obvious injury at the time of the incident, severe jaw injuries can develop and worsen over time at the site of hooking (Bansemer and Bennett, 2010). Such hooking can also cause severe internal injuries. A recent case study on a carcass of this species documented ingestion of a J-hook that had perforated the intestinal wall, leading to cachexia, chronic bacterial infection and enterolithiasis (Otway et al., 2021). Ultimately it was the retention of this hook that led to the shark's death (Otway et al., 2021). The interaction between retained fishing gear and the greynurse shark is considered to be a key hindrance to the recovery of these populations (Bansemer and Bennett, 2010). Similar cases of internal injury and inflammation from retained hooks including peritonitis, pericarditis, hepatitis and cachexia have also been observed in blue sharks (*Prionace glauca*) (Borucinska et al., 2001; Borucinska et al., 2002). Alternatively, the hook and other tackle may be expelled from the animal after some time, by detaching from the animal or if the animal passes it through the digestive tract. Then, as marine debris, this terminal tackle may interact with other fauna.

The interaction between fishing gear and hooking of non-target species is known to be a substantial impact on marine organisms across fishing activities (Chiappone et al., 2005; Bugoni et al., 2008; Anderson et al., 2011; Afonso et al., 2012). These impacts are also observed from recreational or small scale artisanal fishing (Bugoni et al., 2008; Bansemer and Bennett, 2010).

Metal sinkers from recreational fishing activity have been reported as the predominant component of marine debris in some areas (Lloret et al., 2014; Farias et al., 2018). Many sinkers are comprised of lead, a highly toxic heavy metal with the potential to leach into the environment and become biologically available to organisms that ingest it (Vinodhini and Narayanan, 2008). Such leaching can indirectly impact on the health of marine flora and fauna.

3.5.3. Other impacts

In some instances, RFMD could lead to marine habitat alteration, degradation, or destruction through physical interference such as obstruction of sunlight, smothering, surface scoring, and abrasion (Fig. 8). Although habitat alteration and degradation are typically associated with commercial fishing activities such as trawling, such impacts from recreational fishing are also evident but generally at much smaller spatial scales. In Hawaii, a correlation was established between the impact of monofilament fishing line and dead or damaged cauliflower coral (Asoh et al., 2004). Impacts of RFMD can cascade through trophic levels, with changes to infaunal assemblages altering the natural foraging and home range behaviours of other marine animals (U.S. Commission on Ocean Policy, 2004; Gregory, 2009).

In addition to impacts on biodiversity, marine debris in general has implications for humans in terms of aesthetics and economics, which are tightly intertwined (Hardesty et al., 2017). Presence of marine debris leads to degradation of the aesthetic quality of beaches and shallow areas. Marine debris can deter visitors, as cleanliness is the most important characteristic for most beachgoers (Ballance et al., 2000). For example, after a heavy rainfall event that resulted in a significant increase in coastal debris loads in South Korea, revenue losses from tourism were estimated at $29–37 M USD (Jang et al., 2014). In coastal California, visitors travel longer distances to avoid beaches with more waste (Leggett et al., 2014), and a recent survey reported that 85% of Brazilian beachgoers will avoid beaches with high litter loads (>15 pieces per m^2) (Krelling et al., 2017; Santos et al., 2005). A drop in beach users and tourism can result in less business and revenue for a coastal community. Furthermore, news of possible marine debris or pollution can lead to economic loss for the seafood industry (Ofiara and Brown, 1999). While the relative impact of RFMD on aesthetics and economics in comparison to other debris sources is unknown, it is almost certainly a contributing source given the size and geographical extent of the sector globally.

3.6. Strategies for addressing RFMD

Marine debris generally is a significant environmental problem, but there are feasible strategies and actions to address it. Strategies for addressing the risks associated with marine debris have been prepared at various levels (i.e. at global, regional, national, state and local scales) and all consider two key processes: (1) prevention, that is, the restriction and blocking of debris entering the environment; or (2) clean-ups that attempt its removal. In terms of prevention, strategies tend to distinguish marine debris sourced from land from that which is sourced from the sea and, within the latter, there is consideration of debris sourced from fishing as opposed to commercial shipping. However, there is generally no breakdown in these strategies for addressing the risk of 'fishing' debris by sector. Given the origins of marine debris are not well known, including the component that may come from recreational fishing, most strategies advocate the collection of sufficient knowledge to first determine where management efforts should be targeted. The next step is generally to implement a process to understand how effective intervention measures are over time.

3.6.1. Global, regional and national strategies

In terms of strategies that have been proposed to address marine debris at the broadest level, the complexity of the issue prevents simple solutions. Because the issue involves many societal and economic dimensions, abating harmful marine debris requires multi-faceted approaches involving collaboration of researchers, industry, coastal managers, governments and polluters. Marine debris is also costly to remove, with some countries spending in the order of millions of dollars per year (UNEP, 2016).

While 'global' strategies for dealing with marine debris, such as the recently developed *Honolulu Strategy* (UNEP, 2016), recognise the need for education and better waste management and clean-up practices on land and at sea, they stop short of prescribing specific marine debris reduction targets or actions. The *Honolulu Strategy* suggests that nations will need to develop strategy and policy at a local level as any strategy will depend on the social, cultural, environmental and economic contexts in which they are planned and implemented.

Countries are addressing marine debris in various ways at a national level (Vince and Hardesty, 2018; Jambeck et al., 2015; Lasut et al., 2018), but very few recognise a need to address recreational fishing activity directly in policy. In Australia, even though marine debris is recognised as a key threatening process to marine life at a national level, including recognition that a component of it comes from recreational and commercial fishing gear abandoned or lost to the sea, the threat abatement strategy to reduce its impacts applies only to Commonwealth areas, which do not include coastal areas under the jurisdiction of Australian States where most recreational fishing activity occurs (Australian Department of Environment and Energy, 2018).

3.6.2. Localised and community-based strategies

It is only at the more localised scales where some strategies for addressing marine debris have included specific focus on recreational fishing activity. In addition to the federal level (above), the Australian State of NSW recognises the entanglement in or ingestion of anthropogenically derived marine debris as a key threat to vertebrate life (i.e. additionally to federal recognition) and considers debris from recreational fishing activity contributing to the risk, particularly in relation to threatened species (NSW Fisheries Scientific Committee, 2004). In addition, the Management Strategy for the NSW Marine Estate includes initiatives to work with individual fishing sectors (including the recreational sector) to further evaluate ecological risk of priority threats to the environment, which include boat- and shore-based recreational line and trap fishing. The Marine Strategy also partners with fishing sectors of the government to deliver information and training to fishers to improve self-compliance and sustainable fishing practices (NSW Marine Estate Management Authority, 2018). While the details for such partnerships are not yet fully developed, the intent is for sectors to build capability to self-regulate using tools such as environmental social responsibility policies, codes, or education in a way that justifies their social license to operate (SLO), rather than govern through regulatory measures.

It makes administrative and economic sense to include communities or sectors such as the recreational fishing sector in decision making in resource management (Feeny et al., 1990). Feeny et al. (1990) recognised that shared governance between the community and the state, along with self-management by sectors (or co-management) "can capitalize on the local knowledge and long-term self-interest of users, while providing for coordination with relevant uses and users over a wide geographic scope at potentially lower transaction (rule-enforcement) cost". Co-management, where communities or sectors drive the solution and share responsibilities with regulatory bodies, is a practical option for recreational fisheries to identify potential marine debris issues associated with their activities and then manage that risk. There are numerous examples around the world where local communities including fishing sectors have used SLO to reduce the threat of marine debris (see review by Vince and Hardesty, 2018). Where potential threats from RFMD are identified, we consider the sector would be well-positioned to drive effective solutions through behavioural and gear-based strategies.

The behaviour of recreational fishers in regard to littering, such as attitude to and frequency, is not known. Schultz et al. (2013) suggested that 15% of general littering (i.e. inappropriate disposal of waste) by the broader public, however, were a result of contextual variables, with 85% a result of personal qualities and that 81% of littering occurs with intent.

Public opinion and goodwill are recognised as key components to driving change, and public education is considered the most effective form of litter prevention (The Florida Center for Solid and Hazardous Waste Management, 1998). In some Australian states, for example, OceanWatch Australia's (OWA) 'Tangler bins' are used as a practical environmental solution for promoting correct disposal and recovery of lost recreational fishing line that may litter recreational fishing hotspots. With educational material on stickers, the bins are not only a means to collect fishing tackle but also act as a behavioural change reminder to fishers to keep the fishing spot tidy for a better experience (http://www.oceanwatch.org.au/Backup/our-work/tangler-bin/).

Where RFMD is considered a potential threat in a particular area, the recreational fishing community could drive marine debris clean-ups. In addition to reducing the volume of marine debris at the local level, these could highlight the sources of debris, including the extent to which RFMD contributed to the total, thus increasing awareness of the issue. A longstanding example is the "Clean Up the Pin" initiative that is focussed on cleaning up the Jumpinpin area, which lies between North and South Stradbroke Islands in southern Queensland, Australia – a popular recreational fishing location (https://goldcoastcatchments.org/event/help-clean-up-the-pin/).

3.6.3. Gear-based strategies

Given the range of fishing gear available to recreational fishers, it is likely that some gears have a greater risk of breaking or being lost than others. The recreational fishing sector could investigate and support the use of fishing gears, codes, or strategies that would minimise the risk of gear becoming marine debris.

One obvious option is to prohibit or avoid using certain types of gear that are problematic, especially where other equally efficient alternatives with fewer environmental impacts exist. For example, Broadhurst et al. (2016) showed that Australian portunid crabs can be caught as effectively with lift nets as hoop nets (known colloquially as "witches hats"). Given that the latter can result in marine debris from broken twine (Broadhurst and Millar, 2017), it would make sense to support the use of lift nets over hoop nets.

Another option is to proactively seek alternatives and give recreational fishers a greater choice of acceptable solutions. For example, Broadhurst and Millar (2017) showed that if an alternative twine was used in the construction of Australian recreational portunid crab hoop nets, the marine debris resulting from interactions with crabs and the netting during fishing could be drastically reduced while still maintaining catch rates. Broadhurst and Millar (2017) also explored fishing strategies that could further minimise twine loss and still maintain catch rates, such as length of set durations and fishing in accordance with activity cycles of crabs (diurnal, nocturnal and seasonal).

Some of the solutions proposed by Broadhurst and Millar (2017) for portunid crab hoop nets are based on the use of stronger twine to avoid breakage of gear. While strength-based solutions to reducing debris make sense for traps and nets, they do not necessarily apply to rod and reel. Although heavier gauge line and terminal tackle would break less often than lighter gauge gear when fighting a fish, it would still require cutting off when snagged and would provide a greater risk to biota due to its durability when it became marine debris. Given many types of targeted fish are more difficult to hook with heavier gear, heavier gauge gear is not a practical solution to reducing marine debris from line fishing. Notwithstanding this, recreational fishers are presented with a range of choices for the components of terminal tackle (i.e. trace, sinkers, swivels, hooks and lures) that could be recommended through a code of practice based on each item's potential impact if it were to become marine debris. Stainless steel hooks and trace, for example, probably present a greater risk to biota, compared with gear made from other material, when they become RFMD because they corrode slowly.

Gear-based strategies need not only be confined to fishing apparatus. Alternatives to plastic bags exist for bait bags. In Australia, the Tweed Bait company experimented with biodegradable bags but as yet have been unable to find a product that would degrade in the environment but not degrade in their freezers. Bags made from polyvinyl alcohol (PVA), a synthetic water-soluble biopolymer blended with starch, show promise for the future (http://tweedbait.com.au/our-enviroment-2/).

3.6.4. Monitoring

Monitoring is a necessary part of evaluating strategy effectiveness. Research, assessment and monitoring provide essential information to support the spectrum of marine debris threat-reduction efforts. These include how to design effective actions under a strategy, focus attention on specific impacts and targets of concern, define the geographic scale and location to implement activities useful for determining appropriate partners, and monitor intermediate and threat-reduction results.

4. Key issues and conclusions

To fully assess the extent to which RFMD may be a problem we need to understand its sources and sinks, and the scale of impacts for current and future loads of its various components. In terms of its sources, we considered that activities of recreational fishers provide a potential source of marine debris either from deliberate or accidental loss of material into the aquatic environment. Although recreational fishers in most countries are obliged to store all waste for correct disposal ashore, actual waste disposal practices by fishers are unknown and are likely to be variable. Nevertheless, the limited information available in the literature that correlated the amount of general marine debris with recreational fishing activity indicates that there is some deliberate or accidental loss of general waste. The nature of recreational fishing and the types of gear used indicate that there would be breakage and accidental loss of equipment. This is particularly the case for terminal tackle on fishing lines. Although we found very little information that quantified actual loss rates of equipment the loss rates of commercial gear were a guide as to what could be expected, and this remains a key knowledge gap for RFMD.

In terms of the potential impacts of the components of RFMD it is clear that many fishing items, or their broken-down products, and general waste such as plastic bait bags, have potential to seriously threaten the survival of marine organisms by causing adverse consequences. These range from direct impacts like entanglement, ingestion of harmful materials (including breakdown products) to indirect impacts such as trophic cascades. This conclusion is based not only on studies of discarded fishing gear generally but specific reports on adverse impacts and mortality from the limited literature available on discarded recreational fishing gear (Hong et al., 2013; Yorio et al., 2014; Franco-Trecu et al., 2017; Sullivan et al., 2019).

In terms of the sinks of RFMD, the available data indicate that shallow estuarine and coastal areas and rocky ledges or uneven bathymetry are characterised as sinks for RFMD as recreational fishing activity is most common in nearshore coastal areas and rough bottoms where gear tends to snag. Plastic and metal debris from recreational fishing were the most commonly reported, which is consistent with general marine debris volumes reported (Supplementary material, Table 1) (Derraik, 2002). Given recreational fishing effort can be concentrated around fishing hotspots, these areas, in particular, would be most likely to have relatively greater concentrations of RFMD and there was some evidence of this in the literature.

In terms of loads, there is a lack of available data on the contribution of recreational fishing activity to marine debris, and most of the limited data available was locally concentrated. The expanse and largely inaccessible nature of the marine environment makes it difficult to provide thorough estimates of the marine debris load generally, let alone the proportion contributed by recreational fishing, and this remains another key knowledge gap for RFMD.

Notwithstanding the limited information about sources, sinks and loads of RFMD, we consider that past attitudes towards recreational contribution to, and indirect estimates of, RFMD loads have likely underestimated its impact. We suggest that it may be a problem, at least at hotspots, based on the sheer number of recreational fishers, potential for activity to be concentrated, potential loss rates of some types of fishing gear (particularly terminal tackle on fishing lines) and correlations of loads of marine debris that include fishing material at popular fishing locations (Fig. 6 and Supplementary material, Table 1).

Other factors that have limited us forming definitive conclusions about the scale of impacts of RFMD are that much of the research on the volume of marine debris has been done at local scales with short-term monitoring. These studies thus have the potential to underestimate debris loads (Smith and Markic, 2013). Due to the varying properties of material, either weight or numerical counts of debris may under or over represent its quantity, and there is likely a visual bias towards larger and more colourful debris items during sampling. A broader issue is the lack of common metrics among studies (Serra-Gonçalves et al., 2019). Few studies reported categories of debris load as a percentage of total debris found, deeming a comprehension of the quantity of RFMD impossible. Furthermore, varying scales and methods of sampling marine debris may not only bias assessment of debris found but also make comparisons of debris load between studies difficult. Classification of debris into categories based on material, source, size and/or object is also problematic due to a lack of consistency in categories among studies. To allow better comprehension and comparison among studies of marine debris, we recommend that a standardised classification approach and reporting guideline is developed. Well-designed studies that quantify and characterise RFMD at both the sources and sinks will play a key role in confirming or dismissing its potential for impact and will provide the tools for managing potential impacts where they are identified for particular areas.

It is not surprising that recreational fishing material is generally not referred to in prevention or clean-up strategies for marine debris because the contribution of this component to the total load is not yet well understood. Given we have identified a potential problem of RFMD at local scales, we recommend that specific strategies for managing RFMD are developed, but that these include a first stage to collect sufficient knowledge to verify the level of the issue and then to determine whether intervention (prevention and/or clean-up) and monitoring is necessary. Where an issue is identified, cooperative approaches will ultimately help resolve the issue and we recommend using tools such as environmental social responsibility policies, codes of practice or education. Given the recreational sector has the local knowledge and capacity for self-management it makes sense for it to drive education-based solutions that focus on changes to behaviour and the use of particular types of gear.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2022.113500.

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.

Acknowledgements

We thank Stephanie Bagala for assistance in collating and graphing the data, as well as her suggestions in the preparation of this manuscript. This work was partly funded by a NSW Recreational Fishing Trust Grant (LS046) and the School of Natural Sciences at Macquarie University.

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