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An effect factor approach for quantifying the entanglement impact on marine species of macroplastic debris within life cycle impact assessment

John S. Woods*, Gorm Rødder, Francesca Verones

Industrial Ecology Programme, Norwegian University of Science and Technology (NTNU), Sem Sælands vei 7, NO-7491 Trondheim, Norway

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ABSTRACT

Plastic waste from anthropogenic activities is accumulating in the marine environment and poses a threat to marine biodiversity. Nevertheless, tools to assess the potential ecosystem damage from plastic waste are currently lacking from sustainability assessment approaches, such as life cycle assessment (LCA) methodologies. However, despite incomplete knowledge of the environmental mechanisms involved, the LCA community (researchers and practitioners) is calling for methodological developments to close this gap. We present a preliminary effect factor (EF) for working towards including the impacts of entanglement in plastic waste on marine biodiversity in life cycle assessment (LCA).

Our preliminary EF modelling approach couples spatially-differentiated and taxon-specific estimates of the current fraction of species affected by entanglement with spatially-differentiated floating macroplastic density estimates. Our results indicate that the effect of macroplastic density on the fraction of species potential affected by entanglement is highest in areas with low estimated plastic density, most prominently the Southern Ocean and equatorial Pacific. However, in parameterising our approach, we discovered trade-offs between data source options, e.g. species coverage versus range extent accuracy. In addition, we identify knowledge gaps, e.g. defining species sensitivity effect thresholds to enable statistically relating pressure (density of floating marine macroplastic) with effect (the potentially affected fraction of species), and set out options for future methodological development for achieving quantification of an effect factor ready for incorporation in to a life cycle impact assessment modelling approach.

1. Introduction

Since the commencement of large-scale plastic production in the 1950s, an estimated 8300 million tonnes of virgin plastic have been produced (Geyer et al., 2017). Approximately sixty percent of this, an estimated 4900 million tonnes of plastic, has now accumulated in landfills and the environment (Geyer et al., 2017). Littered or inadequately disposed plastic waste, for example in open uncontrolled landfills, not only accumulate in the land-based environment (Jambeck et al., 2015), but can ultimately be transported to the marine environment, e.g. by wind and via river systems (Lebreton et al., 2017). In 2010, an estimated 1.7%–4.6% of newly generated land-based plastic waste entered the marine environment (Jambeck et al., 2015). In addition, plastic debris in the marine environment also arises from sea-based anthropogenic activities such as fisheries (Bugoni et al., 2001).

Plastic is highly persistent in the marine environment (Kubowicz and Booth, 2017). Whilst only approximately 10% of discarded waste worldwide is plastic, it represents a much greater proportion (50–80%) of the debris accumulating in the marine environment (Barnes et al., 2009). The persistence and buoyancy of plastic, which varies between plastic types, shape and degree of fouling (Ryan, 2015), leads also to dispersion via ocean circulation (Lebreton et al., 2017). Plastic debris is now widespread in the marine environment (UNEP, 2016), with hotspots of accumulation along coastlines (Critchell and Lambrechts, 2016), in subtropical gyres (Eriksen et al., 2014), and on the seabed (Woodall et al., 2014).

The threat of plastic debris in the marine environment to biodiversity is now widely recognised. Marine plastic debris is known to affect biodiversity in a number of ways, most prominently through entanglement, ingestion, direct habitat alteration/destruction, and as a transport vector for non-native species introductions (Aliani and Molcard, 2003; Gregory, 2009; Browne et al., 2015; Gall and Thompson, 2015). All impact pathways are relevant, but in this paper, we chose to focus on entanglement only. Entanglement can cause direct harm (injury) or death to individuals, as well as restricting natural movement (Gregory, 2009). Entanglement is most commonly reported

* Corresponding author.
E-mail address: john.s.woods@ntnu.no (J.S. Woods).

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in relation to rope and netting, other fishing materials, and packaging debris types (Gall and Thompson, 2015). At least 344 marine species have been documented entangled in marine debris (Kühn et al., 2015). However, tools to assess the broad-scale environmental consequences of plastic waste in the marine environment are lacking. To enable informed reductions of biodiversity impacts associated with plastic waste, there is a need for a quantitative inclusion of the potential impacts of mismanaged plastic waste in sustainability assessment tools such as life cycle assessment (LCA).

LCA, one of the most widely used environmental sustainability assessment tools (Sonnemann and Valdivia, 2017), is commended for its ability to assess potential trade-offs between multiple impact types (Hellweg and Mila i Canals, 2014), e.g. accounting for climate change impacts at the same time as impacts from the emission of toxic substances and habitat destruction. However, with respect to packaging, one of the primary sources of plastic waste and the largest market for plastics globally (Geyer et al., 2017), the application of LCA to assess the relative sustainability of different options has drawn criticism due to a lack of consideration of the potential impact of mismanaged plastic waste (Schweitzer et al., 2018). The LCA community has recognised this limitation. The Medellin declaration on marine litter in life cycle assessment and management states that LCA is "*not adequately addressing the impacts generated due to marine debris, plastics and microplastics*" (Sonnemann and Valdivia, 2017). The declaration specifically calls for impact assessment model development to account for potential ecosystem damage caused by marine litter (Sonnemann and Valdivia, 2017).

Despite incomplete knowledge of the plastic problem, particularly with respect to linking negative consequences on individual organisms to consequences on species population viability and species assemblages (Browne et al., 2015), we should not wait before taking action. Knowledge about the amounts of discarded plastic and impacts on marine ecosystems is rapidly increasing, even though not all impact mechanisms are clear yet (Browne et al., 2015; GESAMP, 2015). Development of life cycle impact assessment (LCIA) methodologies to include impacts of plastic debris in LCA is one way that action to mitigate the plastic problem could be informed and motivated.

Here, we present a preliminary impact assessment model for including the impacts of entanglement in plastic waste on marine biodiversity within the context of life cycle assessment (LCA). We start by presenting an overview of the impact pathway that is linking plastic waste to marine biodiversity loss, in the context of the potential for its inclusion in LCA. We then present a preliminary quantitative model that attempts to account for potential entanglement effects of plastic debris on marine biodiversity, one of the key components of an overall impact assessment model for plastic waste in LCA. We conclude with a discussion of the limitations of the proposed impact assessment model and propose future requirements for constructive methodological development.

2. The purpose of LCA and the potential for including impacts of entanglement of plastic waste on marine biodiversity

LCA is a tool for quantifying potential environmental impacts across the whole life cycle of a product (i.e. from mining the raw materials, to production and use until the disposal). Within a product life cycle, plastic is widely used across many life cycle stages and for various purposes, such as packaging, tyres for transport and industrial purposes. To have a comprehensive assessment of potential ecosystem impacts from plastic waste generation, we need to make sure we cover the most contributing potentially damaging activities. Broad coverage of potentially damaging activities is achieved in LCA through the modelling of the product system, such that interdependencies between life cycle stages and activities in supply chains are accounted for. This means that in LCA, impacts generated from plastic waste arising from activities throughout the product system can be accounted for, including impacts from the generation of plastic waste that is potentially "hidden" from the awareness of consumers.

Inclusion of potential plastic waste impacts in LCA would therefore allow for considering the significance of biodiversity impacts from plastic waste generation relative to impacts from other impact types, and identifying the product life cycle stage(s) and locations with the largest potential for improving environmental performance (i.e. reducing biodiversity impacts from plastic waste). In addition, such a plastic waste tool in LCA could be implemented to inform eco-design, e.g. choice of packaging material to minimize overall impacts, including those from plastic waste generation.

Product systems are becoming increasingly global, which means that, since most product systems today include plastic, the distribution of plastic waste generation is also becoming increasingly global. Within such global product systems, the location of the source of plastic waste is important for determining the potential impact on marine biodiversity. Waste management practices vary greatly around the world, thus the fraction of plastic waste that is mismanaged and therefore potentially entering the environment is different from region to region. Furthermore, different source locations lead to different transport routes and sites of accumulation, ultimately resulting in a different collection of species exposed, which have, for example, a different average entanglement sensitivity to plastic waste. Different source locations of plastic waste therefore lead to different effects on marine biodiversity. We therefore need a spatially differentiated global impact assessment model to allow for considering plastic waste arising in any country in the world and, due to widespread fate processes, impacts occurring across the marine environment.

Development of an LCIA impact model for ecosystem damage from plastic waste requires modelling of several impact pathway stages (Fig. 1). Here, we present a preliminary approach to consider the potential effect of plastic debris in the marine environment, focusing on the link from plastic debris in the marine environment to potential

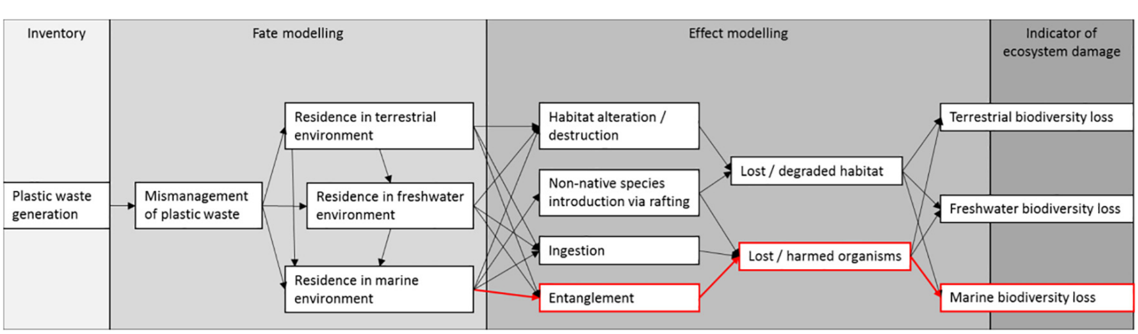

Fig. 1. Impact pathways to ecosystem damage arising from plastic waste generation (including plastic mismanaged on land and transported to the oceans, as well as discarded plastic in the marine environment), in the context of life cycle impact assessment. The preliminary modelling approach of entanglement effects on marine biodiversity (focus of this paper) is highlighted in red. Grey background shading links stages of the plastic waste to biodiversity loss impact pathway to the stages of life cycle impact assessment modelling, linking inventory data to an indicator of ecosystem damage.

Table 1
Coverage of species reported entangled (Kühn et al., 2015) in marine plastic debris by two sources of species distribution data: IUCN/BirdLife (BirdLife International, 2018; The International Union for Conservation of Nature, 2018) and OBIS (OBIS, 2018).

Species Group	No. Species Reported Entangled in Plastic	No. covered by IUCN/BirdLife range maps (%)	No. covered by OBIS observation records (%)
Actinopterygii (bony fish)	67	8 (12)	67 (100)
Aves (birds)	91	78 (86)	91 (100)
Chondrichthyes (sharks and rays)	21	20 (95)	21 (100)
Mammalia (mammals)	48	24 (50)	48 (100)
Reptilia (reptiles)	8	5 (63)	8 (100)

marine biodiversity loss via entanglement (highlighted in red; Fig. 1). Fate modelling and modelling of additional effect pathways are beyond the scope of this short note.

3. Method for quantifying potential entanglement effects of plastic litter on marine biodiversity

3.1. Modelling approach for an effect factor

We calculate the potential effect of additional plastic debris in spatially-defined ocean regions in terms of a potentially affected fraction of species (PAF) per unit of marine floating plastic density (g.km^{-2}), see Eq. (1).

$$EF_{t,i} = \frac{Total\ current\ effect_{t,i}}{Total\ current\ pressure_i} = \frac{\frac{S_{affected,t.i}}{S_{total,t,i}}}{P_i} \tag{1}$$

The effect factor (EF) follows an average LCIA approach, meaning that the EF reflects the average distance between the current state and preferred state of the environment per unit of pressure increase (Huijbregts et al., 2011). We adopt a preferred environmental state of zero pressure and zero effect. As such, the EF is given by the total current effect (PAF) relative to the total current pressure, i.e. the current presence of floating macroplastic (P_i; g.km^{-2}). Furthermore, linking pressure directly with effect implicitly includes species exposure, i.e. this modelling approach implicitly includes both the prevalence of species entanglement in plastic debris (due to exposure) and the subsequent damage of entanglement on the species (effect). The PAF therefore indicates the average sensitivity of species to entanglement within species group t to plastic occurring in pixel i (one decimal degree resolution). PAF is determined by the fraction of affected species ($S_{affected,t,i}$) of species group t in pixel i relative to the total number of species ($S_{total,t,i}$) of that taxon in the same pixel. We assume that a species is potentially affected if it has been documented as entangled, and that the species is potentially affected throughout its geographic range.

The current pressure of marine plastic debris (see Section 3.4) varies between pixels. In addition, to avoid one species-rich species group dominating the impact assessment model, we modelled five species groups separately, namely the classes Actinopterygii, Aves, Chondrichthyes, Mammalia, and Reptilia. Our effect factor is therefore spatially differentiated (i), and specific to species group (t). A concise overview of the effect factor modelling approach and data sources is provided in the Supporting information (SI 01).

3.2. Data source for entangled species

We used a comprehensive list of marine species with documented records of entanglement in marine debris, 344 species in total (Kühn et al., 2015). We examined the references cited by Kühn et al. (2015) to identify the types of marine debris each listed species has been observed entangled in i.e. plastic, metal, glass and ceramics and unknown. Here we focus only on species known to be susceptible to entanglement in marine plastic debris.

3.3. Geographic distributions of species

Geographic distributions of species are required to estimate the total number of species ($S_{total,t,i}$) and the total number of potentially affected species ($S_{affected,t,i}$) within each pixel (i). We firstly applied the distribution maps provided for species of the five selected taxa in shapefile format by the IUCN (The International Union for Conservation of Nature, 2018) and BirdLife (BirdLife International, 2018). For each pixel i, a species contributed to the species totals if its geographic range overlapped, at least in part, with the boundary of i. We excluded species and parts of species' distributions assessed as possibly extinct or extinct, as well as areas where the species is described as introduced or vagrant. All categories of seasonality were included.

However, species coverage by IUCN and Birdlife had incomplete coverage of species with known susceptibility to entanglement in marine plastic debris (Table 1). We therefore also calculated $S_{total,t,i}$ and $S_{affected,t,i}$ using OBIS occurrence records (latitude and longitude coordinates; OBIS (2018)) combined with spatially-defined marine regions. We defined the boundaries of these marine regions using the boundaries of marine ecoregions (Spalding et al., 2007) for the continental shelf supplemented by the International Hydrographic Organisation (IHO) ocean basin boundaries (IHO, 1953) for areas of the high sea. Assuming occurrence of an OBIS record in a marine region indicates presence throughout the marine region, we calculated the total number of species within each species group with an occurrence point within each marine region; i.e. we assume that each pixel i within a marine region has the same species composition.

3.4. Spatial distribution of marine plastic debris

The total current pressure (P_i) is spatially heterogeneous. Eriksen et al. (2014) provide estimates of the spatial distribution of floating marine plastic debris within four size classes. For P_i we apply the combined estimate of size classes 3 (4.76–200 mm) and 4 (> 200 mm), i.e. macroplastics. These estimates indicate the total mass of plastic per square kilometer (g.km^{-2}), averaged for the period 2007–2013, and a resolution of approximately 0.2 decimal degrees. We resampled these data to a resolution of one decimal degree, i.e. the resolution of pixel i. The values from Eriksen et al. (2014) are indicating plastic density for all plastic types combined and we are therefore not able to distinguish between impacts from different types of plastic.

4. Results

We used two types of data source to describe species distributions: species range maps from IUCN (The International Union for Conservation of Nature, 2018) and BirdLife (BirdLife International, 2018), and observation records from OBIS (OBIS, 2018). OBIS provided complete coverage of species known to be susceptible to entanglement in marine plastic debris, whereas the IUCN/BirdLife range maps provided incomplete species coverage (Table 1).

We calculated effect factors for five species groups using two methods of defining species geographic distributions. We use the results for the species group Mammalia (marine mammals) with species distributions calculated from OBIS occurrence records and results for

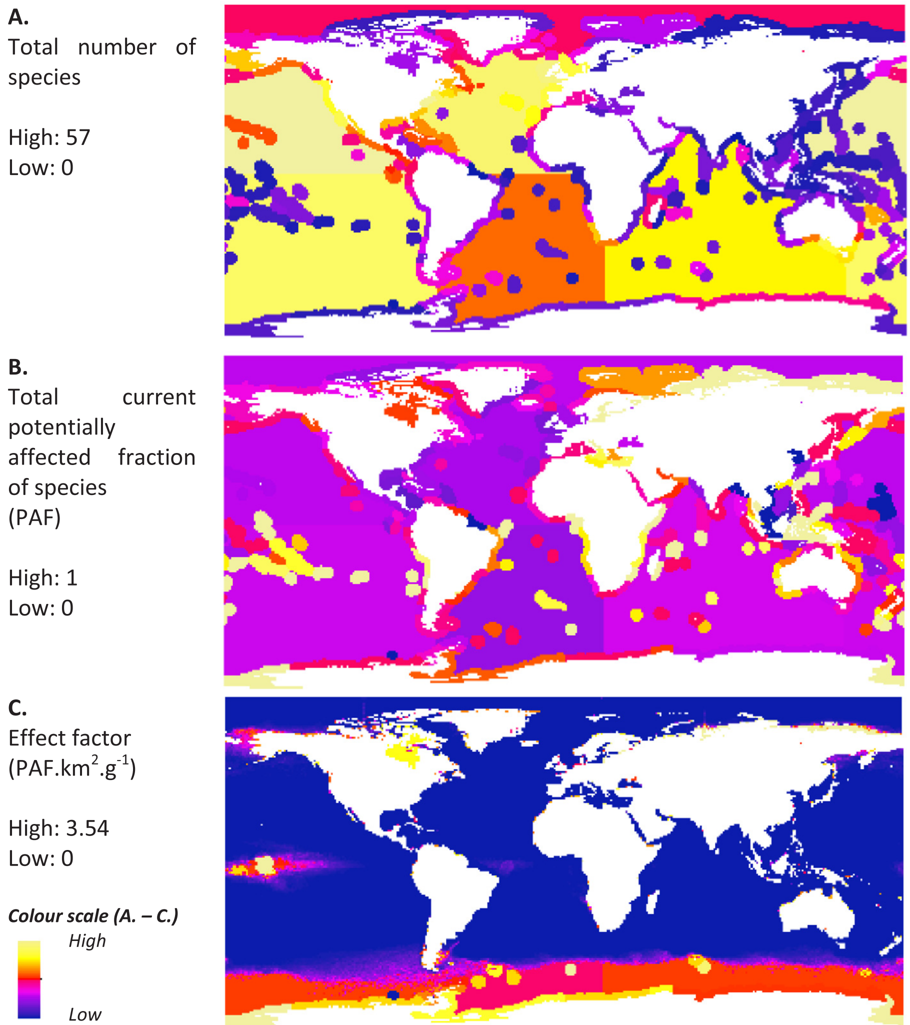

Fig. 2. Estimated marine mammal species richness from OBIS observation records within marine regions (A.), estimated potential fraction of marine mammal species affected by entanglement (B.), and factors for estimating the effect floating macroplastic on marine mammals (C.).

Actinopterygii (bony fish) for showcasing our results (Figs. 2 and 3). Results for all five taxa and distributions based on both OBIS observation records and IUCN/BirdLife range maps are presented in the Supporting information (SI 02).

Marine mammals are widespread, with the highest estimated numbers of species occurring in the large ocean basins and coastal areas of Europe, North America and southern Australia, and the lowest estimates in coastal areas of Asia, Africa and oceanic islands in the southern hemisphere (Fig. 2A). The estimated fraction of marine mammals species potentially affected by entanglement in plastic debris approximately follows an inverse pattern (Fig. 2B), i.e. low species richness is typically coupled with a high fraction of potentially affected species. According to the results, the effect of macroplastic density (g.km^{-2}) on the total PAF is highest in the Southern Ocean and equatorial Pacific, which corresponds with areas of low plastic density (Eriksen et al., 2014). The estimated effect factors for Aves, Chondrichthyes, and Reptilia show a similar concordance between areas of low plastic density and the highest effect factors. This pattern is less prominent for Actinopterygii. Actinopterygii species appear only to be potentially affected by the east coast of North America (IUCN range maps, Fig. 3D) or the northern hemisphere and the South Atlantic (OBIS-derived species distributions, Fig. 3C), despite a more global cumulative distribution (Fig. 3A and B).

5. Discussion

5.1. Limitations of the current approach

5.1.1. Knowledge of species entanglement, species coverage and geographic distributions

Some species, such as the basking shark *Cetorhinus maximus* and the southern elephant seal *Mirounga leonina*, are known to be susceptible to becoming entangled in marine plastic debris (Kühn et al., 2015), whereas for other species there is no documented evidence that entanglement in marine plastic debris occurs. This could be due to lack of observation, sufficiently low levels of exposure due to either avoidance behaviour or low plastic debris density within the species' geographic distribution, or a low likelihood of entanglement following an encounter.

Potential observational bias can be seen in the results for Actinopterygii (Figs. 3 and S2, SI 02). Whilst the species richness maps indicate a widespread cumulative distribution of Actinopterygii species, albeit concentrated on intertropical coastal shelfs according to the IUCN range map data, species only appear to be affected in the Northern hemisphere (OBIS distributions) or restricted to the north east coast of North America (IUCN range data). It is possible that areas with no indicated affected species are zero because of a lack of observation rather than an absence of effect.

The PAF estimates for Actinopterygii also highlight the influence of

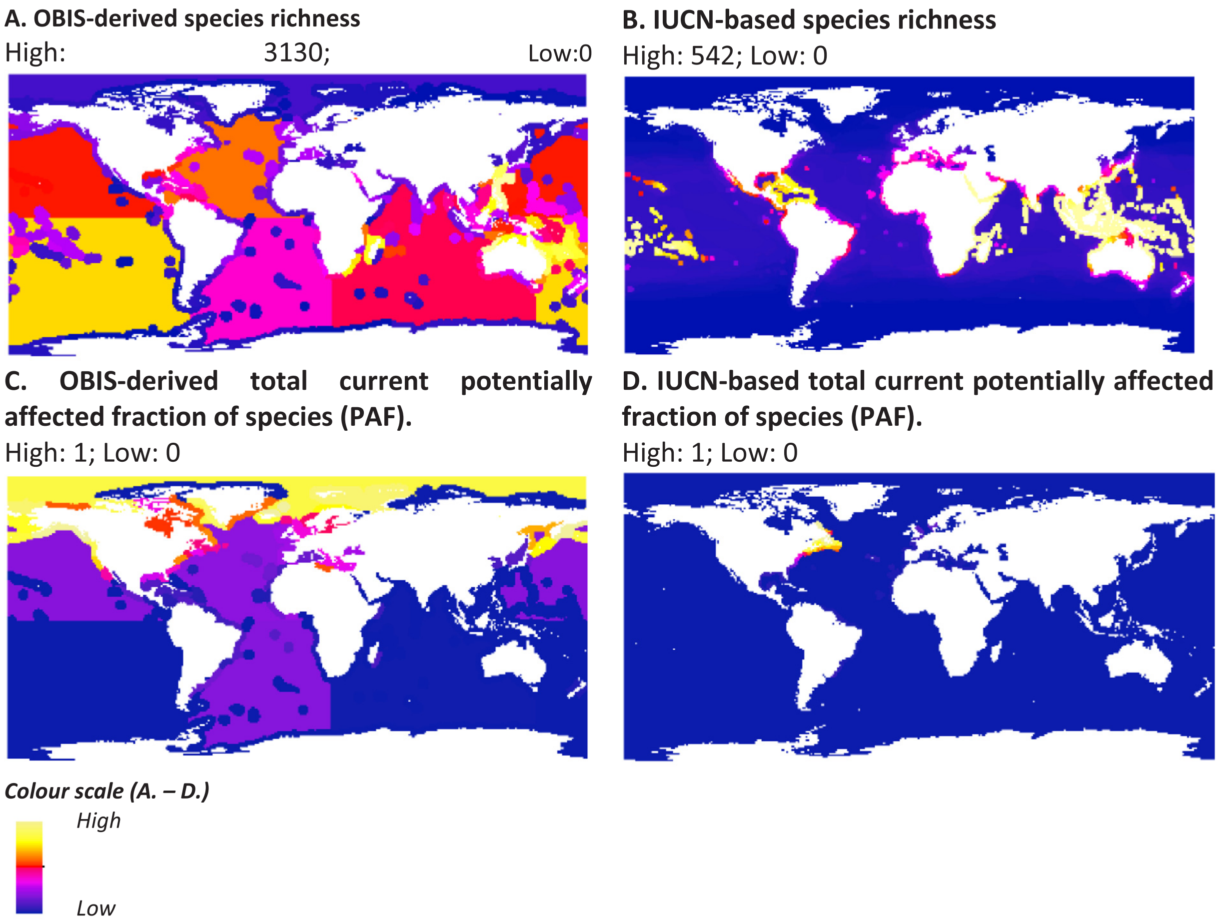

Fig. 3. IUCN and OBIS-derived species richness maps and estimated potentially effected fractions of species for Actinopterygii (bony fish).

differences in species coverage by OBIS distributions and IUCN distributions on the values and distribution of PAF values. The coverage of marine fish species susceptible to entanglement in the IUCN dataset (8 out of 67 species covered) is much lower than the coverage in the OBIS dataset (all 67 species covered). That means that for 59 marine fish species, entanglement has been recorded but no IUCN species range is defined.

Whilst the OBIS dataset has greater species coverage, there is more uncertainty associated with OBIS-derived geographic ranges than those from the IUCN dataset, because of our procedure for converting point data (observation records) into two-dimensional species ranges (see Section 3.3). These OBIS-derived species ranges may underrepresent the actual ranges due to inadequate coverage of observation records, and overestimate geographic ranges due to the assumption that a species occurs everywhere within each marine region containing an observation record. For example, an observation for a species in the South Atlantic close to the equator would result in the geographic range being estimated into the Southern Ocean.

5.1.2. Linking pressure to effect

In our preliminary model for quantifying the potential effect of entanglement in marine macroplastic on marine species groups, we attempted to link the current environmental density of floating macroplastic within pixel *i* with an estimate of the total PAF within pixel *i*. However, the estimates of the total PAF do not correspond well with the pixel-specific macroplastic densities. Knowing that a species is susceptible to entanglement is not sufficient for calculating a meaningful effect factor for inclusion in an operational life cycle impact assessment characterisation approach. In the absence of knowledge of the density of plastic at which a defined effect will take place, we effectively assumed an effect threshold at 0.28 g.km^{-2}, i.e. the lowest density of floating plastic in the ocean (Eriksen et al., 2014), for all species known to be susceptible to entanglement. However, it is likely that these species are only affected within some parts of their geographic ranges, such as in the parts with the highest density of plastic. This oversimplified effect threshold assumption leads to overestimating effect factors in areas of low plastic density, such as the Southern Ocean. The calculated PAF values within pixel *i* relate only to the species composition, i.e. the fraction of species within pixel *i* known to be affected somewhere, and not to the environmental density of floating plastic i.e. the fraction of species within pixel *i* affected by the density of floating plastic in pixel *i*.

With respect to PAFs from OBIS-derived species distributions, a mismatch in spatial scale between PAF and *P* further compounds uncertainty. These PAFs are estimated based on species composition at the marine region scale. We scaled these estimates down, assuming homogenous species composition within the marine regions, to apply pixel-specific values of *P*. Alternatively, P could be aggregated at the marine region scale. However, variation in P_i within marine regions is high. 75% of the 238 regions have a minimum plastic density of 2.93 g.km^{-2} or lower; and 75% of the 238 marine regions have a maximum value of 507.39 g.km^{-2} or higher. Choosing a summary statistic at the marine region scale would remove meaningful spatial variation in *P*. Reducing the size of marine regions, particularly those based on IHO ocean basins, would maintain more variation in P. However, the OBIS-derived species distributions may then underestimate species distribution extents i.e. smaller regions with no observation points would become absent from the species range.

5.2. Future options for methodological development

For a meaningful estimate of PAF of entanglement in marine macroplastic debris, the statistical relationship between the environmental density of plastic and the potentially affected fraction of species needs to be determined i.e. it needs to be determined how the PAF scales with increasing marine plastic debris. Coupling entanglement rates with environmental plastic statistics summarised at the population-range (if known) or species-range level could be a starting point for constructing species sensitivity distribution (SSD-)-based effect factors. An effect 'endpoint' could be e.g. defined as X% individuals in a population becoming entangled at least once annually, for several species. Such data are similar to the estimated encounter rates of North Atlantic right whales in non-mobile fishing gear reported by Knowlton et al. (2012), who found that, annually, 82.9% of individuals were entangled at least once; 59% more than once; and 25.9% acquired new wounds or scars. Due to such data potentially being available for few species, the EFs would be species-generic but spatially-specific in terms of the background working point for calculating marginal EFs, i.e the additional effect of an additional unit of pressure (plastic density), or average EFs i.e. the average effect per unit pressure between the current state and a preferred state (such as no pressure).

In addition, for this preliminary effect factor model we applied plastic density data aggregated across all plastic types and macroplastic sizes. However, species exhibit differing sensitivity to entanglement in different types and sizes of plastic, such as plastic bags, bottle cap rings or discarded fishing nets. Depending on the amount of plastic present, body size (e.g. small-bodied or young species might be more likely to get entangled in a plastic bottle cap ring) and characteristics of species (e.g. some might be more attracted to some plastic types than others), the likelihood of entanglement differ. Future developments of the effect factor should therefore, data-depending, account for differences in species entanglement sensitivity to different plastic types and sizes e.g. through construction of plastic-type-and-size-specific SSDs. Further detail could also be added through inclusion of the vertical dimension of the ocean in both the distribution of plastic debris in the marine environment (here we applied only the density of floating macroplastic), and distribution of species e.g. with consideration of potential differences in species vulnerability between ocean compartments.

For a complete LCIA characterisation factor, the effect factor will need to be linked with a fate model describing the dispersion of plastic waste from terrestrial (and marine) source locations, and quantifying the residence time of plastic debris within ocean compartments. The fate model would combine models describing inputs of plastic waste from terrestrial sources into the marine environment, e.g. Jambeck et al. (2015) and Lebreton et al. (2017), and the transport and accumulation of plastic debris in the marine environment, e.g. Lebreton et al. (2012) and Eriksen et al. (2014).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2018.12.018.

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