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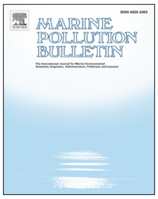

Viewpoint

Global ecological, social and economic impacts of marine plastic

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ABSTRACT

This research takes a holistic approach to considering the consequences of marine plastic pollution. A semi-systematic literature review of 1191 data points provides the basis to determine the global ecological, social and economic impacts. An ecosystem impact analysis demonstrates that there is global evidence of impact with medium to high frequency on all subjects, with a medium to high degree of irreversibility. A novel translation of these ecological impacts into ecosystem service impacts provides evidence that all ecosystem services are impacted to some extent by the presence of marine plastic, with a reduction in provision predicted for all except one. This reduction in ecosystem service provision is evidenced to have implications for human health and wellbeing, linked particularly to fisheries, heritage and charismatic species, and recreation.

1. Main

Marine ecosystems around the world provide a wealth of ecosystem services (the benefits people obtain from nature), including food provision for billions of people, carbon storage, waste detoxification, and cultural benefits including recreational opportunities and spiritual enhancement (Worm et al., 2006; Liquete et al., 2013). Any threat to the continued supply of these ecosystem services has the potential to significantly impact the wellbeing of humans across the globe, owing to the loss of food security, livelihoods, income and good health (Naeem et al., 2016).

There are substantial and increasing quantities of plastic pollution in the marine environment, hereafter referred to as 'marine plastic' (Geyer et al., 2017). An estimated 4.8–12.7 million metric tons of plastic entered the world's oceans from land-based sources in 2010 alone, and the flux of plastics to the oceans is predicted to increase by an order of magnitude within the next decade (Jambeck et al., 2015). While, over time, this plastic may fragment into small pieces, referred to as 'microplastics' (0.1 μm–5 mm), the vast majority is expected to persist in the environment in some form over geological timescales (Andrady, 2015). Though removing some marine plastic is possible, it is time intensive, expensive, and inefficient.

It is now well evidenced that this plastic negatively impacts marine life (Galloway et al., 2017). While research on plastic pollution has been growing exponentially over the past decade, there is poor understanding of the holistic effects of marine plastic and the resultant impact on ecosystem services, and in turn it's bearing on human wellbeing, society and the economy. What is known tends to be based on small scale, local research that cannot be readily transferred or scaled up (Ten Brink et al., 2016). The impact of marine plastic is however a global issue, and a synthesis of the currently available but disparate information is required, ideally detailing global ecological impacts, but also translating them into societal and economic terms.

A solid understanding of the ecological, social and economic impact of marine plastic is necessary to inform a global transition in the way we make, use and reuse plastic, in such a way as to eliminate negative impacts, with implications for public behaviour, legislation and governance, industry and commerce (Pahl et al., 2017). This understanding is integral in providing grounding for effective and efficient global negotiation regarding the sustainable use, management and disposal of plastic, a material with many benefits and in widespread use. In this study, building on a comprehensive literature review of global marine plastic research, we applied for the first time a three-step pluralistic approach to synthesise the currently available research into a global assessment of the ecological, ecosystem service and social and economic impacts of marine plastic (Fig. 1).

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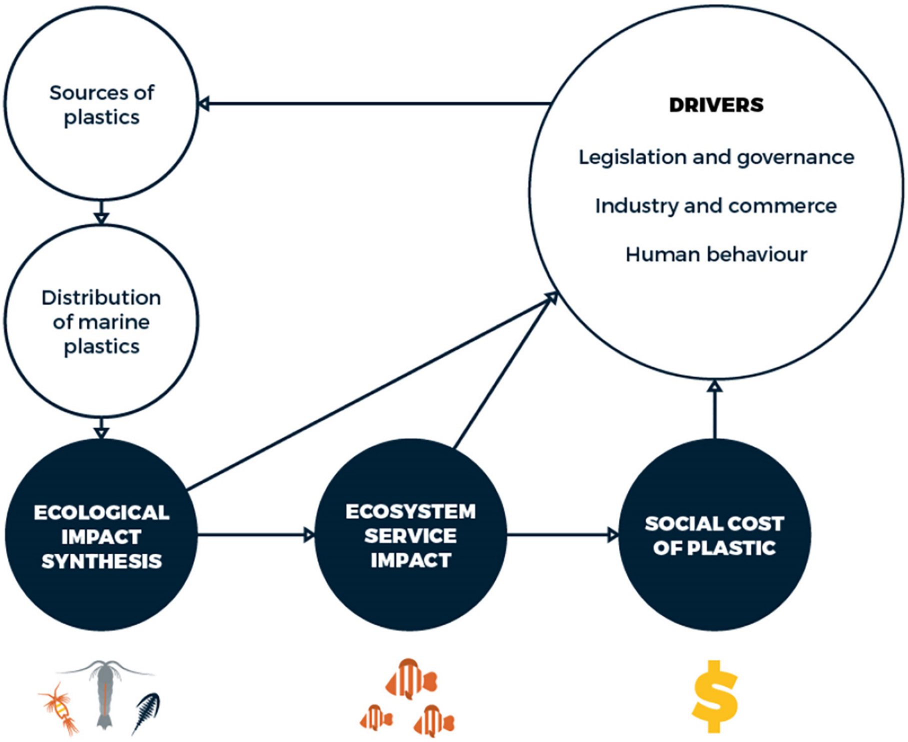

Fig. 1. Conceptual diagram describing the three-step approach used to assess the societal impacts of marine plastic pollution. Outputs from all three steps (in dark blue) can be used to influence the key drivers of the sources of plastic pollution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. A review of global marine plastic research

The semi-systematic review of published data on global marine plastic undertaken in this study (S1) included 1191 data points. This encompassed a diverse array of observational and experimental empirical data, including ingestion, entanglement, and colonisation of plastic and its toxicological effects. Table 1 provides an overview of how the 1191 data points were distributed between the 12 subject types, and 15 different outcomes, demonstrating a greater richness in data relating to studies on birds and fish, and on the ingestion and abundance of plastic.

3. Ecological impact synthesis

The methods and results described in the reviewed research papers were too variable to undertake a meta-analysis of the data. Instead, data relating to the impact of plastic on the eight ecological subjects were systematically scored based on the extent of the impact, the reversibility of the impact, and the frequency of the impact (S2), where impact is defined as an effect on lifespan and/or reproductive potential. The impacts on birds, fish, mammals and turtles were subdivided into ingestion and entanglement as these two effects were reported separately in the literature. A summary of the data is provided in Fig. 2 and demonstrates that there is global evidence of impact with medium to high frequency on all subjects, with a medium to high degree of irreversibility. The majority of these impacts are negative with the exception of algae and bacteria. In this case the plastic increases the range of habitats available for colonisation and enables the spread of these species to new areas, thus increasing their range and abundance.

4. Translation to ecosystem services impact

The impacts on the ecological subjects were translated into ecosystem services impact by employing the CICES ecosystem services classification (CICES, 2013) and following the methodology of Papathanaspolou et al. (Papathanasopoulou et al., 2015). For each ecological subject its potential for providing each ecosystem service was scored, drawing on previous global assessments and ecosystem service reviews (De Groot et al., 2012; Constanza et al., 2014) (S3). This assessment was then combined with the ecological impact results (Fig. 2) to determine the impact of marine plastic on ecosystem services (Figs. 3; S4). The results show all ecosystem services are impacted to some extent by the presence of marine plastic, with some reduction in the provision predicted for all the ecosystem services, with the exception of "regulation of the chemical condition of salt waters by living processes".

5. High value, high risk ecosystem service impacts

Marine ecosystem services comprehensively contribute to human wellbeing, meaning that their reduction will endanger the contined welfare of human societies, especially in coastal communities (Naeem et al., 2016). From the results in Fig. 3 (selecting services with the consistently high (red) impact scores) and the reviewed literature, we identified impacts on three critical ecosystem services, each with specific values at risk and accompanying direct and indirect consequences for human wellbeing:

5.1. Provision of fisheries, aquaculture and materials for agricultural use

Globally, seafood is the principal source of animal protein and makes up more than 20% of food intake (by weight) for 1.4 billion people (19% of the global population) (Golden et al., 2016). Marine plastic has the potential to reduce the efficiency and productivity of commercial fisheries and aquaculture through physical entanglement and damage (Mouat et al., 2010), but also by posing a direct risk to fish stocks. Plastic is frequently ingested by a wide range of marine species, including those directly vital to food provision such as shellfish and fish (Rochman et al., 2015) at all stages of their lifecycle (Steer et al., 2017; Lusher et al., 2012). This plastic can be ingested directly from the environment, or indirectly consumed via plastic contaminated prey (Setälä et al., 2014). Polymers are typically rich in additives (e.g. plasticizers, biocides, flame retardants), and once in the marine environment can readily concentrate microbial pathogens (Kirstein et al.,

Table 1

Summary of semi-systematic review. The 1191 data points was organised into 12 subject types (based on primary topic of research) and 15 different outcomes (based on primary effect of plastic). For example, there were 23 data points relating to algae, focussed on the effects plastic had on abundance (n = 3), colonisation (n = 17) or other issues (n = 3).

Subject types	Outcomes														
	Abundance of biota	Abundance of plastic	Colonisation	Financial cost	Degradation	Entanglement	Growth	Health	Human health and wellbeing	Ingestion	Rafting	Metabolism	Mortality	Reproduction	Other	TOTAL
Algae	3	0	17	0	0	0	0	0	0	0	0	0	0	0	3	23
Plankton	0	0	0	0	0	0	0	0	0	55	0	0	1	0	0	56
Bacteria	0	0	16	0	8	0	0	0	0	0	0	0	0	0	0	24
Birds	0	0	0	0	0	13	0	0	0	290	0	0	0	0	14	317
Fish	0	0	0	5	0	14	0	0	0	227	1	0	0	0	6	253
Mammals	0	0	0	0	0	31	0	0	0	79	0	0	0	0	1	111
Turtles	0	0	0	0	0	3	0	0	0	48	0	0	0	0	4	55
Invertebrates	8	0	3	3	0	4	2	4	0	29	49	1	4	3	13	123
Social	0	5	0	16	0	0	0	0	15	0	0	0	0	0	0	36
Degradation	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	7
Plastic abundance	0	179	0	0	0	0	0	0	0	0	0	0	0	0	0	179
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	7
TOTAL	11	184	36	24	15	65	2	4	15	728	50	1	5	3	48	1191

2016) and toxic persistent organic pollutants (POPS), e.g. dichlorodiphenyltrichloroethane (DDT), and polycyclic aromatic hydrocarbons (PAHs) (Rios et al., 2007); POPs can accumulate in the tissues of marine animals and biomagnify in higher predators including humans (Teuten et al., 2009). The contamination of the food chain with plastic and associated contaminants puts fish and shellfish stocks, and their prey, at risk of lethal and sub-lethal harm (i.e. diminished reproductive success and growth), with capacity for population level impacts (Galloway et al., 2017; Sussarellu et al., 2016).

The consumption of marine plastic by humans will occur when the entirety of a contaminated organism, including the gut, is eaten (e.g. mussels, oysters, sprats, anchovies). Marine plastic may also exacerbate the concentrations of POPs in the flesh of shellfish and fish, posing an additional risk to consumers (Rochman et al., 2015; Rios et al., 2007). While further controlled studies are required to better understand the risk to humans, the existing literature concludes the health risks of marine plastic are minimal (Galloway, 2015; Lusher et al., 2017). Nevertheless, the 'perceived risk' of the contamination of seafood with microplastic may be detrimental to fisheries.

Overall, our evidence suggests that the productivity, viability, profitability and safety of the fishing and aquaculture industry is highly vulnerable to the impact of marine plastic, particularly when coupled with broader factors including climate change and over-fishing. The high dependency on seafood for nutrition leaves the wellbeing of a significant proportion of the world's population highly vulnerable to any changes in the quantity, quality and safety of this food source (Golden et al., 2016).

5.2. *Heritage*

Charismatic marine organisms, including seabirds, turtles and cetaceans, hold a cultural and/or emotional importance to individuals. These megafauna are impacted by marine plastic through entanglement and ingestion, with the plastic and associated co-contaminants having the capacity to cause sub-lethal effects (e.g. reduced reproductive success) and mortality (Fossi et al., 2014). Images and articles describing beached whales and seabirds with stomachs full of plastic are prevalent in mainstream media (Reuters, 2017). Such charismatic marine species hold significant value to humans, and there is extensive evidence that humans experience wellbeing in the knowledge that marine animals are there and will remain for future generations, even if they never directly experience them (Aanesen et al., 2015; Jobstvogt et al., 2014; Börger et al., 2014). The evidence presented suggests that marine plastic pollution may result in a widespread negative impact on charismatic species, with an accompanying loss of human wellbeing. The substantial public attention on the impact of plastic on iconic marine species suggests that even single incidents can have strong and detrimental wellbeing impacts and that the relationship between ecosystem impact and human wellbeing loss is not necessarily linear.

5.3. *Experiential recreation*

A 'social' subject was also included in the review, which detailed direct impacts of marine plastic on recreation. These results supported the ecosystem service analysis in finding plastic to have a substantial negative impact on experiential recreation. Recreational users of coastlines are exposed more frequently to plastic and experience a range of wellbeing impacts. Litter on the shore is disliked (Hartley et al., 2013), and is often stated as a key reason why visitors will spend less time in these environments or will avoid certain sites if they anticipate it will be littered (Anderson and Brown, 1984; Ballance et al., 2000; Tudor and Williams, 2006; WHO, 2003). This has a range of economic costs, from clean-up expenses to loss of tourism revenue.

As well as having economic costs, the presence of litter can also have direct consequences on individuals' physical and mental health. Visitors and maritime workers are susceptible to a range of injuries,

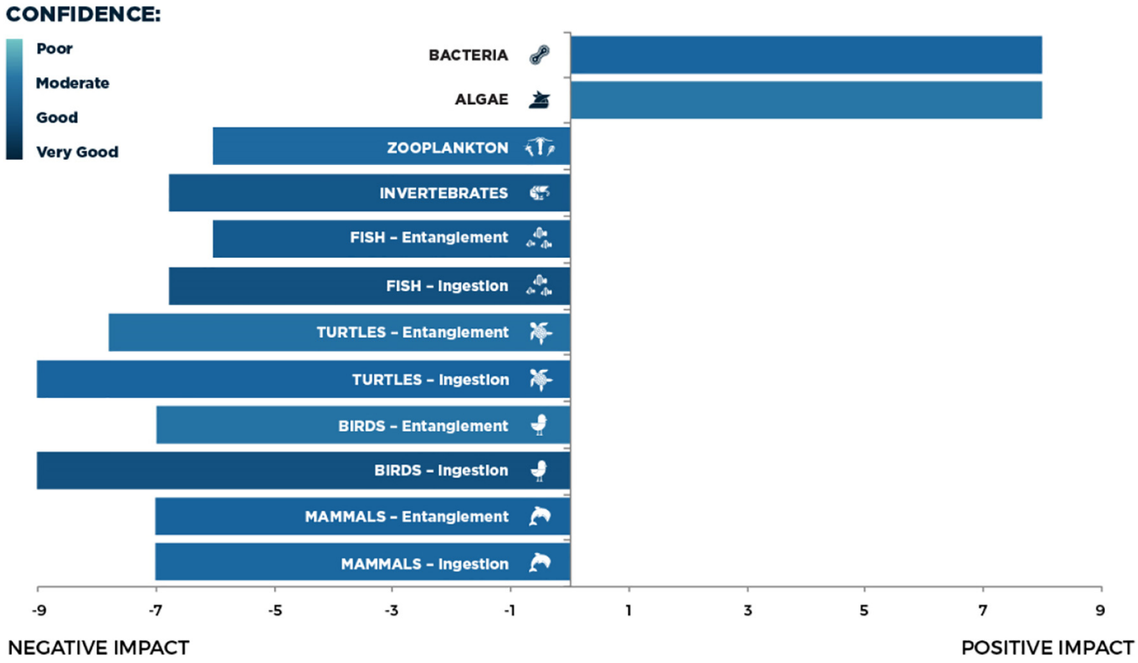

Fig. 2. Ecosystem impacts of marine plastic on biota. A score of −9 means: lethal or sub-lethal effect which is global, highly irreversible, and occurring at a high frequency; a score of +9 means: positive effect in terms of diversity and/or abundance, which is global, highly irreversible, and occurring at a high frequency. Scoring criteria are described in Supplementary materials.

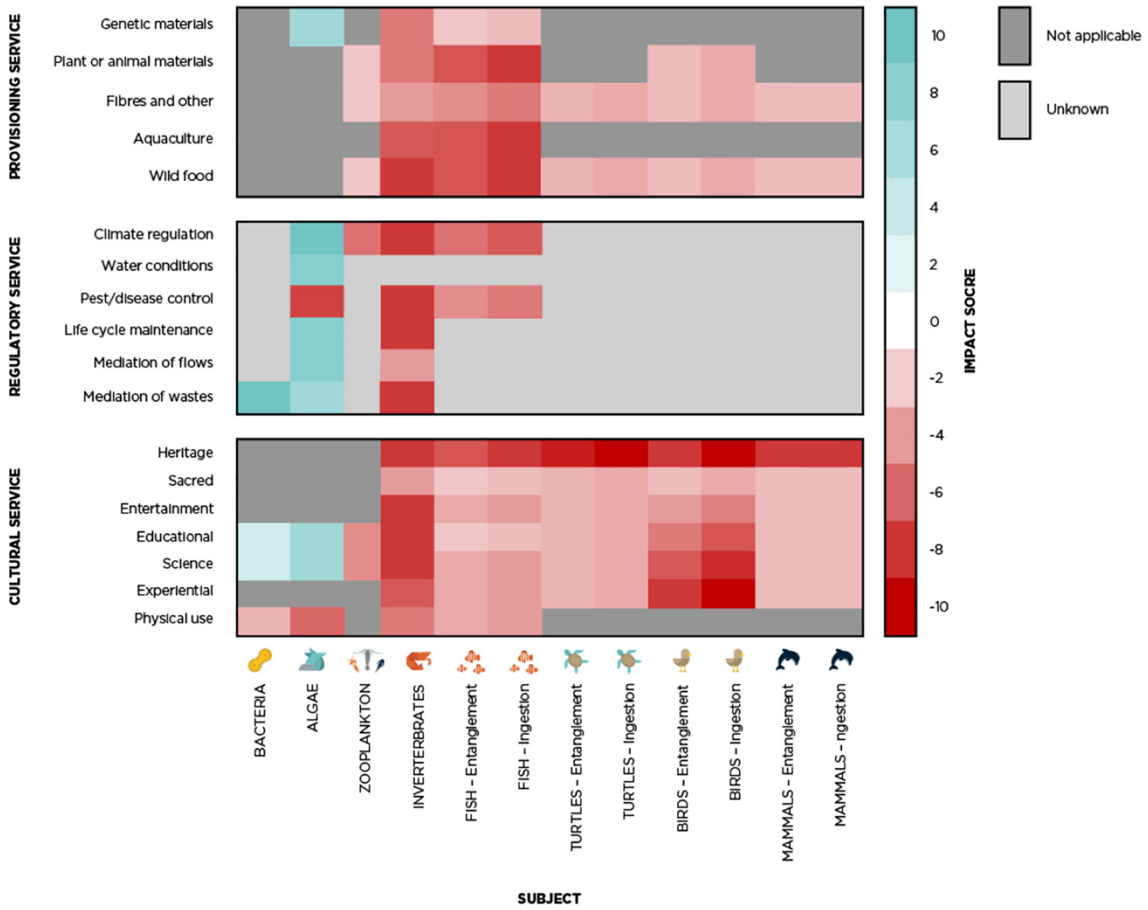

Fig. 3. Ecosystem service impacts of marine plastic. A score of −10 denotes significant risk to this service at the global level with high potential social and/or economic costs; a score of +10 denotes significant potential benefit from this service at the global level, with high potential social and/or economic benefits. Dark grey shading indicates the supply of ecosystem service from the associated subject is negligible. Light grey shading indicates that the relationship between ecosystem service and subject is unknown. Scoring criteria are described in Supplementary materials (S2, S3, S4).

such as cutting themselves on sharp debris, getting entangled in nets, and being exposed to unsanitary items (Santos et al., 2005). Spending time at littered coastlines has also been demonstrated to be detrimental to their mood and mental wellbeing (Wyles et al., 2016). In turn, refraining from going to the coast due to these risks, can also have health implications, inhibiting the opportunity to reap the benefits coastlines typically offer, e.g. promoting physical activity, facilitating important social interactions such as strengthening family bonds, and improving physical and mental health (Ashbullby et al., 2013; Papathanasopoulou et al., 2016).

6. Additional risks to ecosystem services

Beyond the immediate ecological impacts documented here, the presence of plastic has the potential to dramatically shift the ecology of marine systems (Galloway et al., 2017). An altered environment and shifts in biodiversity can have potentially wide-reaching and unpredictable secondary societal consequences (Worm et al., 2006), not least through impairing the ecosystem resilience and recovery potential in a time of global change. Plastics are a stressor, which can act in concert with other environmental stressors such as those arising from other pollutants, changing ocean temperatures, ocean acidification, and the over exploitation of marine resources. The cumulative impacts of these stressors may result in marine plastic causing far greater damage than suggested here.

In addition, although the results show increased bacterial and algal colonisation and abundance, this might have a negative effect for the wider ecosystem. Marine plastic is an attractive substrate that is quickly and intensively colonised by a wide range of opportunistic species (Kirstein et al., 2016). Natural flotsam such as kelp and wood tend to degrade and sink within a matter of months; conversely, plastic can withstand prolonged exposure to UV radiation and wave action, and can remain buoyant for longer periods (decades or even longer) and travel distances of more than 3000 km from source (Barnes and Milner, 2005). Colonisation of plastic provides a mechanism for movement of organisms between biomes, thus potentially increasing their biogeographical range and risking the spread of invasive species and disease (Lamb et al., 2018). Indeed, marine plastic has been linked to increased rates of invasive species and unprecedented rates of species dispersal using man-made flotsam have been documented, including an estimate that marine plastic has doubled organisms' opportunities for dispersal in the tropics (Barnes, 2002). This additional impact is not included in this analysis, but has clear potential for causing substantial ecological, social, and economic consequences.

7. Economic costs of marine plastic

The ecosystem service impacts (Fig. 3) can be used to inform an initial assessment of the economic costs of marine plastic as related to marine natural capital (the worlds' stocks of natural assets). Based on available research it is not yet possible to accurately quantify the decline in annual ecosystem service delivery related to marine plastic. However, the evidence set out in Fig. 3 suggests substantial negative impacts on almost all ecosystem services at a global scale (S4 for detail). In light of this evidence, it is considered reasonable to postulate a 1–5% reduction in marine ecosystem service delivery as a result of the stock of marine plastic in the oceans in 2011. Such a conjecture is conservative when compared to the reduction in terrestrial ecosystem services due to anthropogenic disturbances available in the literature, e.g. a 11–28% decline of global terrestrial ecosystem services (by value) arising from land use changes between 1997 and 2011 (Constanza et al., 2014), and a reduction of up to 31% (by value) due to urbanisation in China (Su et al., 2014; Su et al., 2012).

On a global scale, it has been estimated that for 2011 marine ecosystem services provided benefits to society approximating $49.7 trillion[1] per year (Constanza et al., 2014). Most of the values on which this approximation was calculated were based on maximum sustainable use (actual or hypothetical) of natural (or semi-natural) systems, reflecting functioning biomes with minimal anthropogenic disruption. While limitations in its accuracy are acknowledged, this figure is considered to provide sufficient precision for global analysis and an estimate of the decline in its value, due to the presence of marine plastic, can be taken as a first order approximation of an economic cost.

This 1–5% decline in marine ecosystem service delivery equates to an annual loss of $500–$2500 billion in the value of benefits derived from marine ecosystem services. With the 2011 stock of plastic in the marine environment having been estimated between 75 and 150 million tonnes (Jang et al., 2015; McKinsey, 2015), this would equate in 2011, under 2011 levels of marine plastic pollution and based on 2011 ecosystem services values to each tonne of plastic in the ocean having an annual cost in terms of reduced marine natural capital of between $3300 and $33,000.

This postulation of an economic cost relates only to the impacts of marine plastic on marine natural capital and as such represents a ‘lower bound’ of the full economic costs of marine plastic. This figure does however illustrate the potential order of magnitude of the impacts.

In recognition of the limitations of this economic cost, we identify four key areas of research to further develop the economic cost: (1) we recognise that the economic cost presented here is an underestimate as there are broader social and economic costs that need to be quantified and included, for example, direct and indirect impacts on the tourism, transport and fisheries sectors as well as on human health. Moreover, there are obvious data gaps in the current evidence base and a clear publishing bias towards certain species and geographic areas, bringing some uncertainty to any global inferences. There is also considerable complexity in the ecological data, for example within an ecological subject there are many species, all of which have variable contributions to the provision of ecosystem services. Here, these differences have been averaged but we recognise the limitations associated with losing the nuances within the data. However, the extent of the data analysed, both in terms of the number and variability of studies, brings confidence to the results and provides a global context from which future research and management strategies can be formed; (2) the economic cost presented here is an average per tonne of plastic, while in reality the cost per tonne will vary depending on the place of emission, where it moves to and accumulates, its size and type, and the amount already in the ecosystem. Each tonne of marine plastic is therefore likely to have a cost that is either greater or smaller than the average since plastic is not ‘perfectly mixing’. Plastic emissions, accumulation and resultant ecological damage will be spatially heterogeneous and this must be considered in the development and use of any cost per tonne value for plastic; (3) since this cost per tonne value is a global average, it is not equivalent to the notion that every future tonne added to this stock will have a similar average cost. It is possible that the damage cost of each marginal tonne will increase, meaning the relationship between the cost per tonne value and increasing amounts of marine plastic is unlikely to be linear. Since we cannot from our current knowledge determine the rate of this increase, a key recommendation for further research is to understand better the marginal damage cost of each additional tonne of marine plastic entering the oceans, so as to be able to calculate future total costs; (4) a final complication with regard to plastic is that one piece goes through different ‘life stages’, from macro to micro, with accumulation and disassociation of toxins and biological material, and ideally these changes should be incorporated within any cost per tonne value attributed to plastic.

8. Discussion

Our analysis evidences a direct relationship between the

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[1] All values in US$ at 2007 levels.

proliferation of marine plastic and negative impacts across most ecological subjects and ecosystem services, from a local to global scale. We demonstrate clear costs to the economy and human wellbeing, particularly relating to the provision of sustainable and safe fisheries and aquaculture, recreation, and heritage values. The economic costs of marine plastic, as related to marine natural capital, are conservatively conjectured at between $3300 and $33,000 per tonne of marine plastic per year, based on 2011 ecosystem service values and marine plastic stocks. Given this value includes only marine natural capital impacts, the full economic cost is likely to be far greater.

Drawing on our analysis, we recommend a systematic global research agenda for the recording and reporting of marine plastic research, especially relating to the most vulnerable and valuable ecosystem services, and on the potential contamination of the human food chain. It is also recommended to undertake further research on the heterogeneity and timescale of impacts to enable the efficient development of future policy and regulation.

Drawing on previous experiences of global pollutants (Van den Bergh and Botzen, 2015), we propose that the calculation of the economic costs per tonne of marine plastic is fundamental in future global negotiations to change the way plastics are designed, produced, used, reused and reprocessed. For example, in the case of climate change and specifically CO_2, the concept of a 'Social Cost of Carbon' (SCC) has been applied to enable a broader understanding of the impacts of greenhouse gas emissions, informing global action to manage and mitigate the risks (Van den Bergh and Botzen, 2015). The SCC is a shadow price of carbon emissions and is derived from the net present value of the costs of the cumulative, worldwide impact of one additional tonne of carbon emitted to the atmosphere today divided by its residence time in the atmosphere. We propose that a similar approach is needed to fully understand and therefore manage the issue of marine plastic. While explicitly recognising the limitations of the economic cost estimate presented here, we propose this as a foundation on which a Social Cost of Marine Plastic could be calculated. As such this research is intended as an initial step towards building a more comprehensive and rigorous figure that would require a far greater evidence base to compute.

Since the majority of marine plastic take decades, if not centuries, to fully degrade (Andrady, 2015), and given annual increases in plastic production and losses to the environment (between the 2011 and 2017, an additional 28–71 million tonnes of plastic are predicted to have been added to the marine environment from land-based sources (Jambeck et al., 2015)), it is likely that the negative ecological, social and economic impacts of plastic pollution will continue to increase into the future. The evidence presented here demonstrates that by acting to reduce marine plastic pollution society would be an investing in both the current and future provision of marine ecosystem services and the human benefits they provide.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author contribution

N.B., P.L., T.H., T.B.,K.W and M.Au conceived the project. N.B., T.H., K.W. and M.Au. designed protocols and supervised review data collection. N.B. T.B., J.C., T.H, P.L., C.P., K.W. undertook the literature review. P.L., T.H., C.P. undertook the ecological summaries and scoring. N.B., T.B., and M.Aa. performed the economic analysis. J.C. and N.B. conceived the design of the figures. N.B., T.B. and M.C. wrote the manuscript with input from M.Aa, M.Au., J.C., M.C., T.H, P.L., C.P., K.W.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2019.03.022.

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