ARTICLE IN PRESS

Marine Policy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Marine Policy

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

Marine plastic pollution as a planetary boundary threat – The drifting piece in the sustainability puzzle

Patricia Villarrubia-Gómez[a,*], Sarah E. Cornell[a], Joan Fabres[b]

[a] Stockholm Resilience Centre, Stockholm University, SE-106 91 Stockholm, Sweden
[b] GRID-Arendal, Teaterplassen 3, 4836 Arendal, Norway

ARTICLE INFO

Keywords:
Marine plastic
Pollution
Marine litter
Planetary boundaries
Microplastics
Earth-system processes
Earth system governance
Earth resilience

ABSTRACT

The exponential increase in the use of plastic in modern society and the inadequate management of the resulting waste have led to its accumulation in the marine environment. There is increasing evidence of numerous mechanisms by which marine plastic pollution is causing effects across successive levels of biological organization. This will unavoidably impact ecological communities and ecosystem functions. A remaining question to be answered is if the concentration of plastic in the ocean, today or in the future, will reach levels above a critical threshold leading to global effects in vital Earth-system processes, thus granting the consideration of marine plastic pollution as a key component of the planetary boundary threat associated with chemical pollutants. Possible answers to this question are explored by reviewing and evaluating existing knowledge of the effects of plastic pollution in marine ecosystems and the 'core planetary boundaries', biosphere integrity and climate change. The irreversibility and global ubiquity of marine plastic pollution mean that two essential conditions for a planetary boundary threat are already met. The Earth system consequences of plastic pollution are still uncertain, but pathways and mechanisms for thresholds and global systemic change are identified. Irrespective of the recognition of plastic as a novel entity in the planetary boundaries framework, it is certain that marine plastic pollution is closely intertwined with global processes to a point that deserves careful management and prevention.

1. Introduction: marine plastic pollution as an emerging Anthropocene risk

Human activities are capable of changing the normal functioning of Earth-system processes in ways that amplify risks to societies worldwide [1]. One of the most conspicuous anthropogenic activities is the manufacture, use and disposal of plastic. This synthetic material is so widespread throughout the environment that plastic is now considered as a geological marker of the Anthropocene, the emerging epoch in which human activities have a decisive influence on the state, dynamics and future of the Earth system [2]

Mass production of plastic took off rapidly since the 1950s, shaping the development of modern society [3,4]. Global production of plastic resin increased from around 1.5 million tonnes in 1950 [5] to 322 million tonnes in 2015 [6]. Estimates are that during 2010, between 4.8 and 12.7 million tonnes of mismanaged land-based plastic waste entered the oceans [7]. The absolute amount is difficult to calculate, due to the many different sources and environmental transport pathways, but marine plastic pollution (MPP)[1] is now ubiquitous in the marine environment. It has been documented to negatively affect organisms, ecosystems, human wellbeing, and socioeconomic sectors such as tourism, aquaculture and navigation [8–10]. The recent rise in MPP studies reflects growing concern about its impacts [11]. A first global assessment has been made of the sources, fates and effects of microplastic in the oceans [12,13], highlighting the need for policy and societal action and identifying key research priorities to inform this action.

Recently, scientific attention has turned to plastics as a potential planetary boundary threat [14–16]. The planetary boundaries framework [17] defines precautionary boundaries for several anthropogenic perturbations, set at levels to avoid thresholds or shifts in Earth-system functioning that would generate rising risks for the world's societies. By identifying measurable control variables and setting boundaries, the framework demarcates a global 'safe operating space' for humanity. In

* Corresponding author.
E-mail address: patricia.villarrubia@su.se (P. Villarrubia-Gómez).

[1] The term 'marine pollution' refers to the introduction of harmful or potentially harmful substances into the sea, but it can be politically ambiguous, referring either to the substances themselves or to the moral responsibility for the harm caused by pollution [99]. The use of 'marine plastic pollution' (rather than plastic litter or plastic debris) highlights this sociopolitical nature of the material.

https://doi.org/10.1016/j.marpol.2017.11.035
Received 15 August 2017; Received in revised form 17 November 2017; Accepted 29 November 2017

Please cite this article as: Villarrubia-Gómez, P., Marine Policy (2017), https://doi.org/10.1016/j.marpol.2017.11.035

the scientific synthesis of Rockström et al. [17] and later Steffen et al. [1], chemical pollution/novel entities were flagged as issues of concern, but no quantified planetary boundary was proposed.

Along with efforts to operationalise the planetary boundaries as a global sustainability policy integration framework [18–21], the novel entities boundary is increasingly being discussed in the scientific community. Rockström et al. [17] suggested that control variables could be defined in terms of emissions, concentrations or effects of chemicals such as persistent organic pollutants (POPs), heavy metals, or plastics. Sala and Saouter [22] noted that in principle, chemicals could be prioritized according to their impacts on particular ecological functions, allowing for an aggregate quantified planetary boundary. In contrast, Persson et al. [23] argued that *"there is no single chemical pollution planetary boundary, but rather that many planetary boundary issues governed by chemical pollution exist"*. Persson et al. [23] and MacLeod et al. [24] proposed criteria for a chemical pollutant to pose a planetary boundary threat. These criteria are explored and adapted in the following sections. Steffen et al. [1] outlined the rationale for the chemical pollution boundary more fully, expanding the issue to include a wider range of novel synthetic or anthropogenic entities released into the environment. However, the lack of consensus on the kinds of thresholds that should not be crossed, the great diversity of substances released to the environment, and the high uncertainty about their individual and interacting behaviour, has meant that no boundary has been suggested [25], although the planetary threat from chemical pollution is indeed recognised as an unaddressed societal task [24]. These severe knowledge constraints also apply to MPP.

This study extends from ideas outlined in three recent studies [15,16,26] that have raised the issue of establishing a planetary boundary for marine plastic pollution, and reflect on its implications for operationalization in environmental management and policy. Ecological processes, from sub-cellular to ecosystem scales, can be impacted in many ways by marine plastics [16], and physical-biological interactions may play a determining role in the large-scale and long-term fate of marine plastics [15,26]. These studies outline a research agenda to characterize the sources, pathways, degradation and ultimate fates of plastic in the marine environment. Combining these different perspectives together and focusing on the ways that MPP affects Earth-system processes, informs the assessment of whether and how MPP fulfils the requirements to be designated as a sub-boundary of the novel entities boundary.

2. Rationale: the Earth-system perspective on novel entities

2.1. An Earth-system science and governance gap

At its most fundamental, the Earth system consists of the dynamic interactions of Earth's physical and living components [27–29]. The planetary boundaries framework views this as a coupled social-ecological system, where the world's societies increasingly influence Earth's biophysical trajectory.

Steffen et al. [1] defined novel entities as *"new substances […] that have the potential for unwanted geophysical and/or biological effects."* They argued that novel entities become a planetary concern when they exhibit persistence, cross-scale distribution, and the potential to impact vital Earth-system processes. In investigating MPP as a planetary boundary threat, the primary concern is not with its effects on people, or even on marine organisms as such, but rather on the biophysical behaviour of the Earth system as a whole, with the additional challenge for policy and operationalization that the behaviour of concern is, by definition, unprecedented.

Many open scientific questions arise about which aspects of planetary behaviour matter, over what timescales. For most planetary boundary processes, the Holocene provides a baseline of comparative climatic and ecological stability [30,31]. For novel entities, however, there is no such baseline. They exist because of modern humanity's ingenuity, capacity and technology for bypassing many ambient physical and material constraints. Earth-system science faces persistent difficulty in integrating human activity in its conceptual frames [32–34], and the emergence of novel entities (such as marine plastic) highlights the limitations of current scientific understanding. The Earth-system effects that might make MPP a planetary boundary threat could involve thresholds or regime shifts [35,36] within 'components' of the Earth system, such as ecosystem collapses, and in the dynamic links between system components, 'shifting gears' between physical and ecological processes.

There is only an emerging understanding of plastic pollution as a globally systemic problem. Recent assessments [13,37–40] still tend to document issues with an anthropocentric perspective on human health, or on currently economically significant ecosystems, rather than Earth's resilience. They also highlight fundamental gaps in knowledge about the fate of plastics, and its geophysical and biological effects.

In this context, policy on marine plastics is also still emerging [9,37]. The need for an international convention on marine plastic debris or pollution is presently being discussed [38,39]. Key international instruments dealing with sea-based pollution include the London Convention,[2] especially its 1996 London Protocol,[3] and MARPOL 73/78,[4] implemented through national law in signatory nations. Global instruments regulating land-based pollution, but not specifically plastic, include the Stockholm,[5] Rotterdam[6] and Basel Conventions.[7] Only the UN Convention on the Law of the Sea[8] provides a broad overarching duty to prevent land-based sources of all marine pollution. At European level, the Marine Strategic Framework Directive (Descriptor 10)[9] and Article 9 of the Joint Communication on international ocean governance [40] deal with plastic pollution, in support of Sustainable Development Goal 14 under UN Agenda 2030 [41]. Despite growing attention to marine plastic in these contexts, policy integration and coherence remain a very large governance gap [42].

2.2. A new approach for boundary assessment

This exploration of the feasibility of classifying marine plastic pollution as a sub-boundary contributes to an ongoing debate about chemical pollution and novel entities as a planetary boundary. An entity must simultaneously fulfil three proposed conditions and associated scenarios [23,24], outlined in Fig. 1 below, in order to be considered as a planetary boundary. These conditions were initially proposed for chemical pollution, primarily by synthetic substances, where there is broader agreement on how toxicity and hazard can be defined. In applying this conceptual approach to MPP, two major challenges arise, linked to significant knowledge, governance and policy gaps.

First, the vast majority of plastic has long been viewed as 'safe' (non-

[2] Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, www.imo.org/en/OurWork/Environment/LCLP/Pages/default.aspx.

[3] Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, www.imo.org/en/OurWork/Environment/LCLP/Documents/PROTOCOLAmended2006.pdf.

[4] International Convention for the Prevention of Pollution from Ships, www.imo.org/en/about/conventions/listofconventions/pages/international-convention-for-the-prevention-of-pollution-from-ships-(marpol).aspx.

[5] Stockholm Convention on Persistent Organic Pollutants, http://chm.pops.int/TheConvention/Overview.

[6] Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade, www.pic.int.

[7] Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, www.basel.int, and action under its 2017 COP-13 Decision on marine litter, www.basel.int/Implementation/MarinePlasticLitterandMicroplastics/Overview/tabid/6068/Default.aspx.

[8] United Nations Convention on the Law of the Sea, www.un.org/depts/los.

[9] Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive) http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0056.

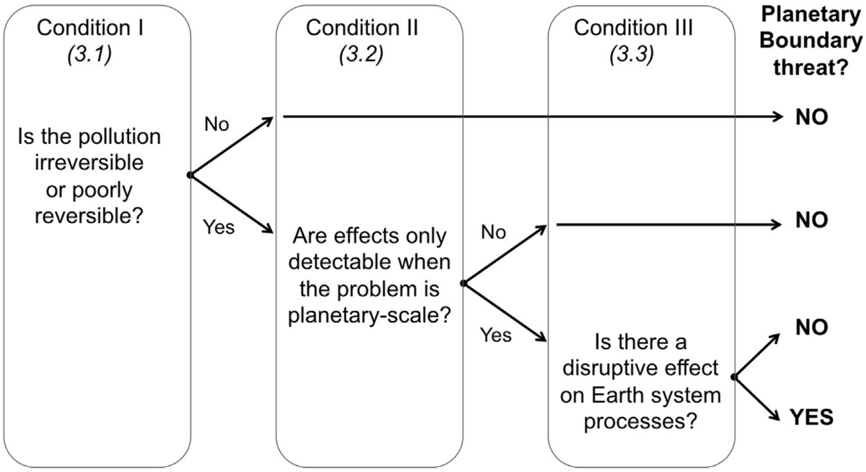

Fig. 1. Conditions under which marine plastic pollution can be regarded as a planetary boundary threat. Numbers in parentheses indicate the section where the condition is reviewed. (Adapted from conditions proposed for chemical pollution in Refs. [23,24]).

toxic or low toxicity). Chemical hazard assessment methods currently in use focus on exposure to organisms, rather than multi-scale ecological functioning of the Earth system. Rather than proposing to identify 'dangerous levels', a planetary boundaries approach should focus on characterising the 'dangerous pathways' that may alter Earth-system dynamics.

Second, the Earth-system effects of plastic are irreducibly complex, with poorly predictable environmental behaviour, fates and interactions with other chemical substances – both natural and synthetic. While some information is available about the quantity of plastic material produced and released, there is still deep ignorance and high uncertainty about the pathways that plastic actually takes in the marine environment. This exploration focuses on two indicative pathways or scenarios: the ecological effects on food webs and the biogeochemical effects on marine carbon sequestration, where scientific evidence can be pieced together robustly, and where the direct, indirect and cascading effects that combine to alter Earth-system dynamics can be distinguished relatively clearly.

3. Does marine plastic meet planetary threat criteria?

3.1. Is exposure to marine plastic pollution poorly reversible?

From a stratigraphic perspective, there is a clear Anthropocene threshold [2] between pre-plastic and post-plastic systems, but for a chemical pollutant to pose a planetary boundary threat [24], its environmental exposure and/or its disruptive effects must be poorly reversible. Marine plastic pollution will always fulfil this condition, as the ultimate end-fate of most mismanaged plastics is the ocean.

The ubiquity of plastic debris and the unfeasibility of its substantial removal from the marine environment, especially in the case of microsized particles, mean that exposure is essentially irreversible [43]. Recent estimates suggest the presence of at least 5 trillion plastic pieces floating in the oceans [44]. Plastic material has been observed in most domains of the physical environment, including the biosphere [45], cryosphere [46,47], ocean sediments [2], and even the atmosphere [48], to the extent that plastic has lately been considered as a stratigraphic marker of the Anthropocene [49]. MPP is accumulating around the convergence zones in the five subtropical ocean gyres [44,50] and the Arctic Ocean [51]. These large-scale accumulation zones are a consequence of the effect of winds, ocean surface currents, and the thermohaline circulation. Furthermore, concentrations comparable to those in the subtropical gyres have been recorded close to highly populated areas such as the Mediterranean Sea [52], Bay of Bengal, South China Sea, and Gulf of Mexico [53]. Organisms ingesting and later egesting MPP also play a role in the global distribution of plastic particles [50,54–56]. This biological pathway cannot be halted or reversed.

The environmental effects of MPP are also essentially irreversible. Plastic serves as a very effective substrate for sessile species (e.g. barnacles, tube worms and bivalve mollusks) as well as a temporary platform or raft for motile organisms [8]. Plastic has been found to host harmful algal bloom species [57], viruses [58] and microbial communities, increasingly recognised as the 'Plastisphere' [59]. It is a vector for transport of alien invasive species [8,60], and of POPs that may then be ingested in concentrations much higher than the ambient seawater [61,62]. Regardless of its size, then, each plastic particle has the ability to transport living organisms and to redistribute harmful substances, altering ecosystem composition and functioning, and changing genetic diversity [10]. These properties cannot be inactivated [43].

The weathering of macroplastics is a major source of the microsized plastic particles currently present in the marine environment [16,64]. The main mechanisms for this are degradation by mechanical wave action, UV photodegradation, and biofouling and biological degradation [16,64,65]. Recent studies also highlight the importance of the land-based breakdown of textile fibres as a source of microplastic [66,67]. Thus, even if inputs of macroplastics into the ocean decrease substantially in the near future, the amount of micro and nano plastic debris in the marine environment will inevitably continue to increase – with an associated outlook of shifting exposure and complex effects on different ecosystems.

3.2. Are effects of marine plastic pollution detected only when the problem is planetary-scale?

MacLeod et al. [24] defined four potential scenarios by which the disruptive effects of a given chemical pollutant are not discovered until they become a problem at a planetary scale:

i. the concentrations of the contaminant are nearly homogeneous at a global scale;
ii. the effects are rapidly distributed globally;
iii. the effects of the contaminant are only observable at a global scale; and
iv. there is a time delay between the exposure of the contaminant and the effects.

These scenarios apply readily to molecular pollutants that are long-lived and hence well mixed in the environment, like the ozone-depleting CFCs and synthetic greenhouse gases that affect the global atmosphere's radiative properties. The CFCs clearly demonstrate the possibility of 'planetary ecotoxicity' even when the substances themselves were assessed as very low toxicity.

As a solid-phase substance rather than a molecular pollutant, plastic in the marine environment requires a different perspective to be taken

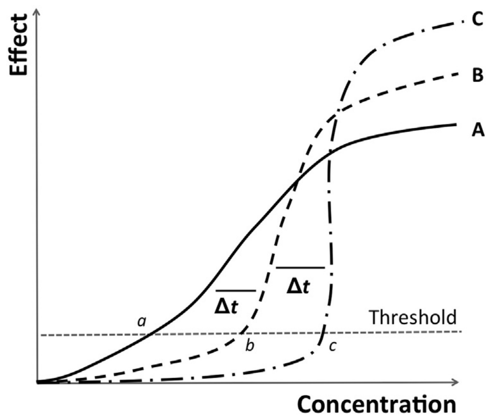

Fig. 2. Cross-scale spatial and temporal dynamics of marine plastic pollution. A. Effect on organisms – direct 'local' effects, observed all around the world. Threshold *a* set normatively as a precautionary boundary (e.g., maximum acceptable exposure of populations). B. Effect on ecosystems – large-region, time-lagged (Δt) effects. Threshold *b* reflects a structural ecosystem-level shift (e.g., loss of keystone species). C. Cascading effect on global ecosystem function (e.g., globalised toxic bioaccumulation impacts on genera or families). Minimal effect seen until critical ecosystem shift (*c*) occurs.

on these scenarios. MPP has *direct effects* on organisms, *indirect effects* as a vector or carrier of other pollutants, and *systemic effects* that cascade across ecosystems on multiple temporal and spatial scales (Fig. 2). The challenge of defining what constitutes a planetary-scale change, rather merely the aggregate sum of lots of local changes, is an on-going debate in various application contexts of the planetary boundaries framework [68–73].

Scenario *i* is already fulfilled: plastic is being redistributed around the world's oceans from high concentration input regions, as outlined previously.

Whether marine plastic fulfils scenarios *ii–iv* depends on the effects in question, and also on how 'global-scale' effects are conceptualised. The direct effects of MPP on organisms (e.g., from ingestion, entrapment) are generally regarded as 'local' problems – resolvable by local-level societal responses – but they are increasingly recognised as global issues of concern because they have accumulated to a point that they are now evident worldwide (Fig. 2, curve A). The interval between exposure (understood as the moment when plastic arrives in the marine environment) and effects at the organism level is typically short. However, against this background of global redistribution and homogenisation, ocean dynamics are also contributing to the creation of high accumulation zones, geographically far removed from sources. The timescale of global surface-ocean connectivity is faster than other ocean circulation processes, due to the presence and action of living organisms [74]. Through ecological dynamics, the effects of MPP thus extend over large regions, as well as in hotspots [14,51], demonstrating a time lag between the environmental exposure to marine plastics and the eventual effects caused.

These indirect and cascading systemic effects may represent a planetary-scale problem, illustrated with a consideration of effects of plastic debris in marine ecosystems. Today, the presence of plastic in the marine food chain is broadly recognised [45]. Ingestion and transfer of plastic particles have been reported across the food chain, from bottom [45,75] to top, including in humans [76]. Suborganism effects (e.g., on cells, organ systems) have been observed [16], as well as effects on organisms and ecological assemblages [11]. In this regard, the rapid global distribution of the effects of plastic (scenario *ii*) is not just a geospatial matter, but also an ecological and trophic one (Fig. 2, curve B).

Marine organisms can bioaccumulate harmful substances through the entire food web, in cross-scale interactions consistent with scenario *iii* (although Koelmans et al. [77] suggest that microplastic ingestion does not significantly increase the risk of hazardous substances being transferred to marine wildlife). The harmful effects of plastic debris can arise from the toxicity of substances added to polymers during plastic production (e.g., plasticisers, flame-retardants, dyes), and of other chemicals sorbed onto plastic surfaces from the seawater [8,78,79]. A scenario *iv* delay could occur between exposure and effects if, for example, the reproductive capacity of some species is altered. A high intake of microplastic has been found to have adverse outcomes on energy allocation, fecundity and reproduction (among other impacts) in oysters [80] and copepods [81]. Copepods play a crucial role in trophic chains and the carbon cycle as they feed on phytoplankton and are prey to larger organisms. Similar concerns have also been expressed about the physical and toxicological effects of plastic ingestion by lanternfish [82]. These impacts may thus have a time-lagged effect upon higher trophic organisms.

Plastic may also affect the biota through changes in the physical environment. Significant concentrations of microplastic have been reported in beach sediments [83], potentially changing physical properties, permeability and flows of nutrients and water [84], and subsurface temperature – with possible effects on sex determination in marine turtles (important ocean herbivores), which is highly temperature-dependent [85].

Thus, despite the fragmented state of current evidence, the mismanagement of discarded plastic is already implicated in globally systemic alteration to food webs, habitats, and biogeochemical flows (Fig. 2, curve C). However, the extent to which marine ecosystems are affected by MPP is still highly uncertain. To date, most of the research on effects of microplastic on wildlife has been in laboratory-based experiments or on particular species, under conditions that differ substantially from those found in the marine environment.

3.3. Is there a disruptive effect on Earth-system processes?

The recognition that plastic may alter the structure and functions of marine ecosystems worldwide (Fig. 2, curve C) leads us to the most challenging and uncertain question in the framework [24]: does MPP have a disruptive effect on Earth-system processes? Disruptive effects, thresholds or regime shifts can be defined in many different ways [86,87]. But whether and how the impacts of MPP could be affecting vital Earth-system processes, or are instead being absorbed and buffered, is an open question. Recent studies [15,16] indicate that it is uncertain whether this third condition is fulfilled. There is a need for precisely articulated hypotheses that can be tested in future marine observation studies, experiments, and with models.

A major uncertainty relates to the disruption of systemic connections between the physical and the living components of the Earth system. Here, carbon sequestration illustrates the issues (Fig. 3), because the global carbon cycle is one of the biophysical foundations of the Earth system. It links ocean processes with the atmosphere, biosphere, and terrestrial environments, and plays a vital role in balancing the climate system [88,89]. Mechanisms can be envisaged where MPP affects the ability of the oceans to sequester carbon into the major global reservoirs of deep water bodies and ocean sediments, by both biological and physicochemical means. In line with the scenarios discussed in 3.2, the consequences on the carbon cycle would only be detectable on a global scale, and after a considerable time lag.

A biologically-mediated disruption to the long-term storage of carbon could occur if biological processes at the base of ecosystem functions are altered because of the presence of plastic. MPP could alter marine populations through either booms or collapses, including extinctions of keystone species [68]. A large-scale shift in ecological assemblages could result in a threshold in the biogeochemical cycling of carbon (and other nutrient elements), with impact on vital Earth-system processes.

MPP may also have the capacity to cause a biophysically-mediated disruption. The flux of faecal pellets is an important component of the 'biological pump' of carbon (including anthropogenic atmospheric

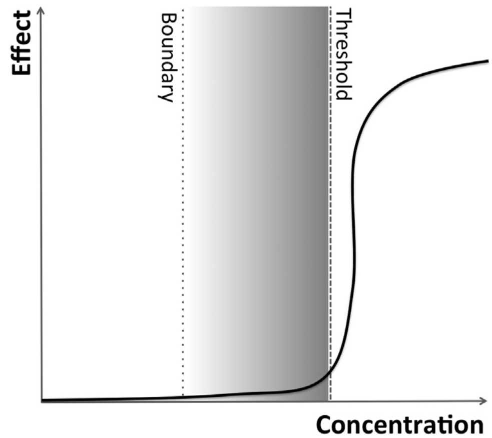

Fig. 3. Disruptive effects on Earth-system processes (e.g., marine carbon sequestration). If a threshold can be determined for a planetary-scale function (corresponding to pathway C in Fig. 2), the boundary should be set at a level that prevents the cascade of ecosystem changes that contribute to that global threshold.

carbon) to ocean sediments [90]. Microparticles of polystyrene alter the properties and sinking rates of faecal pellets egested by marine zooplankton [54]. Particulate material could thus interfere with the flow of carbon and nutrients in the water column, affecting the regulation of global biogeochemical flows [1] in turn affecting future trophic chains.

The physical burial of plastic materials may also represent a shift in long-term carbon storage, since it does not share the element ratios of living material. Recent estimates for the amount of marine plastic debris range between 86 and 150 million tons of plastic [91]. A large fraction of the plastic known to enter the surface ocean is not currently accounted for [52]. Its ultimate fate is to be deposited (directly or through the biota) onshore or on the sea floor [91].

4. Why include marine plastics in the planetary boundaries framework?

The planetary boundaries concept brings multiple global anthropogenic perturbations together into the same frame, in research and policy discourse. It is being considered in policy contexts, including the UN General Assembly [92], Europe's 7th Environment Action Programme [93], which sets out a vision to live well *"within the limits of the planet"*, and national sustainability strategies [18–21]. As a framework on human-caused Earth-system change, it should include the modern world's most conspicuous and globally widespread changes – and this current overview indicates that the environmental fate of plastic waste is indeed one such change.

MPP is a global sustainability challenge, a clear example of the tragedy of the commons, difficult to manage and govern globally [94]. Plastic waste is being addressed by multinational frameworks, including the SDGs [41], specifically Goal 14 'Life below water' and goals linked to production and consumption; resolutions of the first and second United Nations Environment Assembly[10]; and the G7 and G20 marine litter action plans. The potential need for a global instrument, such as a convention on marine plastic pollution, is also being discussed [38,39]. Recognizing MPP as a global-level concern may provide valuable policy leverage for control of other chemical substances of high concern. Acknowledging the potential mismatch between risk perception and real risk [11], worldwide ecological benefits could arise if the environmental release of plastic is regulated because of human public health concerns (e.g., about the effects of plasticizers such as bisphenol A, which has been implicated in cancers, endocrine and metabolic disorders, and behavioural disturbances [95,96].

Bringing MPP into the planetary boundaries framework may provide a common framework for the further development and implementation of these emerging policies in a way that adequately consider wider systemic effects. It may also help to provide the impetus for improved global state and trends assessment, ecological monitoring, and management. For a marine plastics/novel entities planetary boundary to be made operational, knowledge gaps must be filled: basic information needed to define control variables is lacking about the current stocks and effects of plastic debris in the marine environment, and its systemic effects, especially on the sustainability-critical issues in the planetary boundaries framework. A key gap in understanding is the impact of marine plastic on linked social-ecological systems. Less than 5% of the scientific literature on marine plastic pollution addresses social or economic dimensions [97]. Packaging and consumer/household goods currently represent about two-thirds of total demand for plastics [6], with disposable items making up a large fraction. At the same time, there is growing concern about how plastics and their additives could be affecting human health, food security, wealth and wellbeing [60,96]. People's consumption choices and their prioritisation of some concerns over others will determine whether MPP worsens, increasing the risk of crossing some Earth-system threshold, or is halted and mitigated.

It is unlikely that the MPP problem has already passed its worst. Oil, the main raw material for plastic production, is a finite resource, but if current rates of oil conversion into plastic continue until the estimated total cumulative oil production is reached, the final stock of marine plastic debris could be 2.3 times more than is already in the oceans [91]. The rise in plastic production from other raw materials [6], the great amount of mismanaged plastic debris entering the oceans [7,74], and the barely significant impact of clean-up efforts worldwide [98] indicate that there is no globally systemic sustainability perspective. Precaution is needed when there is a situation of ignorance about disruptive effects that pollutants may have on Earth-system processes [24].

5. Conclusions and recommendations

Marine plastic pollution is irreversible and globally ubiquitous, and thus meets two of the three proposed essential conditions for a chemical pollution planetary boundary [24]. Evidence is growing about the ecological consequences of plastic pollution, but it remains an open question whether MPP also meets the third condition and has disrupted Earth system processes.

The proposed threat conditions and scenarios [24] that define requirements for a chemical pollutant to be a planetary boundary candidate have needed to be adapted for MPP, where the solid-phase properties of plastic introduce additional complexity to chemical pathways and ecological impacts. The conditions (as worded in Ref. [24]) are open to different interpretations, particularly regarding time and spatial scales. Trophic webs, ecosystem shifts, and the carbon cycle are complex cross-scale phenomena. Thus, whilst it is already evident that plastic is a planetary problem, there is high uncertainty and even ignorance about its disruptive Earth-system effects. Current literature lacks a broad, holistic view of how sub-systems link to each other and to the Earth-system processes that determine Earth's self-regulating capacity.

As more MPP effects are detected and especially as the implications for human wellbeing become more conspicuous, multilevel and multiscale responses are beginning to take place. These range from social activism, to deliberations in political and governmental arenas, to much-needed business transitions and innovations in material use, trade, and waste management. As public awareness of marine plastic pollution rises, its inclusion in the novel entities planetary boundary may help to mobilize the action that is now urgently needed, on all

[10] UNEP/EA.1/10 Annex 1/6, http://www.un.org/ga/search/viewm_doc.asp?symbol=UNEP/EA.1/10 and UNEP/EA.2/Res.11 http://wedocs.unep.org/bitstream/handle/20.500.11822/11186/K1607228_UNEPEA2_RES11E.pdf?sequence=1&isAllowed=y.

these fronts – ideally, in close cooperation among all actors.

Further transdisciplinary discussion is needed to deepen the evidence-base at each stage of the planetary threat pathway, to identify the thresholds of greatest concern, and to inform the normatively-defined setting of the boundary. Irrespective of whether marine plastic is integrated into the planetary boundaries framework, it is evident that marine plastic pollution is closely intertwined with global processes to a point that deserves careful and precautionary management.

Acknowledgements

We thank Matthew MacLeod and Michael McLachlan for helpful discussions in the development of the ideas in this paper, and we thank the anonymous reviewers for their useful comments. S.C.'s and P.V.G.'s contributions were partially supported by the Swedish Research Council Formas (Grant no. 2012-742). P.V.G. wishes to acknowledge that this paper is based on research carried out for a MSc Thesis at the Stockholm Resilience Centre at Stockholm University, entitled 'Marine plastic pollution as a novel entity within the Planetary Boundaries framework' (2016). GRID-Arendal would like to thank the support received from the Norwegian Ministries of Foreign Affairs and of Climate and Environment to develop our work on marine plastic pollution. The work was carried out at SRC and GRID-Arendal.

Funding

S.C.'s and P.V.'s contributions were partially supported by the Swedish Research Council Formas (Grant no. 2012-742).

Author contributions

PV carried out the major part of the analysis. SC and JF co-supervised the development of the work, and contributed content on the global change science and environmental policy. All co-wrote the manuscript.

References

[1] W. Steffen, K. Richardson, J. Rockstrom, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R. Carpenter, W. de Vries, C.A. de Wit, C. Folke, D. Gerten, J. Heinke, G.M. Mace, L.M. Persson, V. Ramanathan, B. Reyers, S. Sorlin, Planetary boundaries: guiding human development on a changing planet, Science 347 (2015) 1259855, http://dx.doi.org/10.1126/science.1259855.

[2] J. Zalasiewicz, C.N. Waters, J.A. Ivar do Sul, P.L. Corcoran, A.D. Barnosky, A. Cearreta, M. Edgeworth, A. Gałuszka, C. Jeandel, R. Leinfelder, J.R. McNeill, W. Steffen, C. Summerhayes, M. Wagreich, M. Williams, A.P. Wolfe, Y. Yonan, The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene, Anthropocene 13 (2016) 4–17, http://dx.doi.org/10.1016/j.ancene.2016.01.002.

[3] A.L. Andrady, M. a. Neal, Applications and societal benefits of plastics, Philos. Trans. R. Soc. Lond. B Biol. Sci. 364 (2009) 1977–1984, http://dx.doi.org/10.1098/rstb.2008.0304.

[4] R.C. Thompson, S.H. Swan, C.J. Moore, F.S. vom Saal, Our plastic age, Philos. Trans. R. Soc. Lond. B Biol. Sci. 364 (2009) 1973–1976, http://dx.doi.org/10.1098/rstb.2009.0054.

[5] PlasticsEurope, The Compelling Facts About Plastics: An Analysis Of Plastics Productions, Demand and Recovery for 2006 in Europe, 2008, p. 24.

[6] PlasticsEurope, Plastics – the Facts, Plast. – Facts 2016, 2016, zu finden unter ⟨www.plasticseurope.de/informations⟩.

[7] J.R. Jambeck, R. Geyer, C. Wilcox, T.R. Siegler, M. Perryman, A. Andrady, R. Narrayan, L.K. Law, R. Narayan, K.L. Law, Plastic waste inputs from land into the ocean, Science 347 (2015) 768–771, http://dx.doi.org/10.1126/science.1260352.

[8] M.R. Gregory, Environmental implications of plastic debris in marine settings–entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions, Philos. Trans. R. Soc. Lond. B Biol. Sci. 364 (2009) 2013–2025, http://dx.doi.org/10.1098/rstb.2008.0265.

[9] C.M. Rochman, M.A. Browne, B.S. Halpern, B.T. Hentschel, E. Hoh, H.K. Karapanagioti, R.C. Thompson, Policy: classify plastic waste as hazardous, Nature 494 (2013) 169–171.

[10] S. Werner, A. Budziak, J.A. Van Franeker, F. Galgani, G. Hanke, T. Maes, M. Matiddi, P. Nilsson, L. Oosterbaan, E. Priestland, R. Thompson, M. Veiga Joana, T. Vlachogianni, Harm caused by Marine Litter - European Commission, 2016. doi: ⟨http://doi.org/10.2788/690366⟩.

[11] C.M. Rochman, M.A. Browne, A.J. Underwood, J.A. van Franeker, R.C. Thompson, L.A. Amaral-Zettler, The ecological impacts of marine debris: unraveling the demonstrated evidence from what is perceived, Ecology 97 (2016) 302–312, http://dx.doi.org/10.1890/07-1861.1.

[12] UNEP, Marine Plastic Debris and Microplastics – Global Lessons and Research to Inspire Action and Guide Policy Change, United Nations Environment Programme, Nairobi, 2016, p. 179.

[13] GESAMP, Sources, fate and effects of microplastics in the marine environment: a global assessment., IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/ UNEP/UNDP, 2015, in: P.J. Kershaw (ed.), IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, Rep. Stud., 2015, GESAMP No. 90, p. 96.

[14] T.S. Galloway, C.N. Lewis, Marine microplastics spell big problems for future generations, Proc. Natl. Acad. Sci. USA 113 (2016) 2331–2333, http://dx.doi.org/10.1073/pnas.1600715113.

[15] A. Jahnke, H.P. Arp, B.I. Escher, B. Gewert, E. Gorokhova, D. Kühnel, M. Ogonowski, A. Potthoff, C.D. Rummel, M. Schmitt-Jansen, E. Toorman, M. MacLeod, Reducing uncertainty and confronting ignorance about the possible impacts of weathering plastic in the marine environment, Environ. Sci. Technol. Lett. (2017), http://dx.doi.org/10.1021/acs.estlett.7b00008.

[16] T.S. Galloway, M. Cole, C. Lewis, A. Atkinson, J.I. Allen, Interactions of microplastic debris throughout the marine ecosystem, Nat. Ecol. Evol. 1 (2017) 116, http://dx.doi.org/10.1038/s41559-017-0116.

[17] J. Rockström, K. Noone, Planetary boundaries : exploring the safe operating space for humanity, Ecol. Soc. 14 (2009).

[18] B. Nykvist, Å. Persson, F. Moberg, L. Persson, S. Cornell, J. Rockström, National Environmental Performance on Planetary Boundaries: A study for the Swedish Environmental Protection Agency, Stockholm Environment Institute and Stockholm Resilience Centre at Stockholm University, Stockholm, Sweden, 2013⟨http://www.naturvardsverket.se/Documents/publikationer6400/978-91-620-6576-8.pdf⟩.

[19] H. Dao, P. Peduzzi, B. Chatenoux, A. De Bono, S. Schwarzer, D. Friot, Environmental limits and Swiss footprints based on Planetary Boundaries: A study commissioned by the Swiss Federal Office for the Environment (FOEN), UNEP/GRID-Geneva, Université de Genève, Shaping Environmental Action, Geneva, Switzerland. ⟨http://pb.grid.unep.ch/planetary_boundaries_switzerland_report.pdf⟩.

[20] H. Hoff, B. Nykvist, M. Carson, Living Well, within the Limits of Our Planet? Measuring Europe's Growing External Footprint, Stockholm Environment Institute, Stockholm, Sweden, 2014.

[21] M.J. Cole, R.M. Bailey, M.G. New, Tracking sustainable development with a national barometer for South Africa using a downscaled "safe and just space" framework, Proc. Natl. Acad. Sci. USA 111 (2014) E4399–E4408, http://dx.doi.org/10.1073/pnas.1400985111.

[22] S. Sala, E. Saouter, Planetary boundaries and chemical pollution: a grail quest? Chem. Int. (2014) 2–4.

[23] L.M. Persson, M. Breitholtz, I.T. Cousins, C. a. de Wit, M. MacLeod, M.S. McLachlan, Confronting unknown planetary boundary threats from chemical pollution, Environ. Sci. Technol. 47 (2013) 12619–12622, http://dx.doi.org/10.1021/es402501c.

[24] M. MacLeod, M. Breitholtz, I.T. Cousins, C. a. de Wit, L.M. Persson, C. Rudén, M.S. McLachlan, Identifying chemicals that are planetary boundary threats, Environ. Sci. Technol. 48 (2014) 11057–11063, http://dx.doi.org/10.1021/es501893m.

[25] M.L. Diamond, C. a. de Wit, S. Molander, M. Scheringer, T. Backhaus, R. Lohmann, R. Arvidsson, Å. Bergman, M. Hauschild, I. Holoubek, L. Persson, N. Suzuki, M. Vighi, C. Zetzsch, Exploring the planetary boundary for chemical pollution, Environ. Int. 78 (2015) 8–15, http://dx.doi.org/10.1016/j.envint.2015.02.001.

[26] J.R. Clark, M. Cole, P.K. Lindeque, E. Fileman, J. Blackford, C. Lewis, T.M. Lenton, T.S. Galloway, Marine microplastic debris: a targeted plan??For understanding and quantifying interactions with marine life, Front. Ecol. Environ. 14 (2016) 317–324, http://dx.doi.org/10.1002/fee.1297.

[27] E.S.S. Committee, Earth System Sciences: A Closer View (The Bretherton Report), NASA, Washington D.C., USA, 1988.

[28] M. Jacobson, R.J. Charlson, H. Rodhe, G.H. Orians, Earth System Science: From Biogeochemical CyclesElmsford, NY" data-cke-saved-text="Please provide the place of publication in Refs. [28,84,94,95] if available." name="comments" role="MC" > to Global Changes, 1st edition, Academic Press, Cambridge, MA, USA, 2000.

[29] S.E. Cornell, I.C. Prentice, J.I. House, C.J. Downy, Understanding the Earth System: Global Change Science for Application, Cambridge University Press, Cambridge, UK, 2012.

[30] C.N. Waters, J. Zalasiewicz, C. Summerhayes, A.D. Barnosky, C. Poirier, A. Galuszka, A. Cearreta, M. Edgeworth, E.C. Ellis, M. Ellis, C. Jeandel, R. Leinfelder, J.R. McNeill, D. deB Richter, W. Steffen, J. Syvitski, D. Vidas, M. Wagreich, M. Williams, A. Zhisheng, J. Grinevald, E. Odada, N. Oreskes, A.P. Wolfe, The Anthropocene is functionally and stratigraphically distinct from the Holocene, Science 351 (2016) aad2622, http://dx.doi.org/10.1126/science.aad2622.

[31] W. Steffen, R. Leinfelder, J. Zalasiewicz, C.N. Waters, M. Williams, C. Summerhayes, A.D. Barnosky, A. Cearreta, P. Crutzen, M. Edgeworth, E.C. Ellis, I.J. Fairchild, A. Galuszka, J. Grinevald, A. Haywood, J. Ivar do Sul, C. Jeandel, J.R. McNeill, E. Odada, N. Oreskes, A. Revkin, D. deB. Richter, J. Syvitski, D. Vidas, M. Wagreich, S.L. Wing, A.P. Wolfe, H.J. Schellnhuber, Stratigraphic and Earth System approaches to defining the Anthropocene, Earth's Future (2016), http://dx.doi.org/10.1002/2016EF000379 (n/a-n/a).

[32] W. Kuhn, U. Luterbacher, E. Wiegandt, Pathways of Understanding: the Interactions of Humanity and Global Environmental Change, The Consortium for International

Earth Science Information Network (CIESIN), University Centre – MI, USA, 1992〈https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19920024814.pdf〉.
[33] G. Palsson, B. Szerszynski, S. Sörlin, J. Marks, B. Avril, C. Crumley, H. Hackmann, P. Holm, J. Ingram, A. Kirman, M.P. Buendía, R. Weehuizen, Reconceptualizing the "Anthropos" in the Anthropocene: integrating the social sciences and humanities in global environmental change research, Environ. Sci. Policy 28 (2013) 3–13, http://dx.doi.org/10.1016/j.envsci.2012.11.004.
[34] H.A. Mooney, A. Duraiappah, A. Larigauderie, Evolution of natural and social science interactions in global change research programs, Proc. Natl. Acad. Sci. USA 110 (2013) 3665–3672, http://dx.doi.org/10.1073/pnas.1107484110.
[35] M. Scheffer, S.R. Carpenter, Catastrophic regime shifts in ecosystems: linking theory to observation, Trends Ecol. Evol. 18 (2003) 648–656, http://dx.doi.org/10.1016/j.tree.2003.09.002.
[36] C. Folke, S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, C.S. Holling, Regime shifts, resilience, and biodiversity in ecosystem management, Annu. Rev. Ecol. Evol. Syst. 35 (2004) 557–581, http://dx.doi.org/10.1146/annurev.ecolsys.35.021103.105711.
[37] D. Xanthos, T.R. Walker, International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): a review, Mar. Pollut. Bull. 118 (2017) 17–26, http://dx.doi.org/10.1016/j.marpolbul.2017.02.048.
[38] K. Raubenheimer, A. McIlgorm, Is the Montreal protocol a model that can help solve the global marine plastic debris problem? Mar. Policy 81 (2017) 322–329, http://dx.doi.org/10.1016/j.marpol.2017.04.014.
[39] N. Simon, M.L. Schulte, Stopping Global Plastic Pollution: the Case for an International Convention, 2017.
[40] European Commission, International ocean governance: an agenda for the future of oceans, JOIN (2016) 17 (49 final).
[41] United Nations, Transforming our World: the 2030 Agenda for Sustainable Development, Resolution adopted by the General Assembly on 25 September 2015, A/RES/70/1, 2015. 〈http://www.un.org/ga/search/view_doc.asp?Symbol=A/RES/70/1&Lang=E〉.
[42] J. Vince, B.D. Hardesty, Plastic pollution challenges in marine and coastal environments: from local to global governance, Restor. Ecol. 25 (2017) 123–128, http://dx.doi.org/10.1111/rec.12388.
[43] L.K. Law, R.C. Thompson, Microplastics in the seas, Science 345 (2014) 144–145, http://dx.doi.org/10.1002/2014EF000240/polymer.
[44] M. Eriksen, L.C.M. Lebreton, H.S. Carson, M. Thiel, C.J. Moore, J.C. Borerro, F. Galgani, P.G. Ryan, J. Reisser, Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea, PLoS One 9 (2014) e111913, http://dx.doi.org/10.1371/journal.pone.0111913.
[45] P. Farrell, K. Nelson, Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.), Environ. Pollut. 177 (2013) 1–3, http://dx.doi.org/10.1016/j.envpol.2013.01.046.
[46] A.M. Trevail, S. Kühn, G.W. Gabrielsen, The State of Marine Microplastic Pollution in the Arctic, (2015).
[47] R.W. Obbard, S. Sadri, Y.Q. Wong, A.A. Khitun, I. Baker, C. Richard, Earth's future Global warming releases microplastic legacy frozen in Arctic Sea ice Earth's future, Earth's Future (2014) 315–320, http://dx.doi.org/10.1002/2014EF000240.Abstract.
[48] S.L. Wright, F.J. Kelly, Plastic and human health: a micro issue? Environ. Sci. Technol. 51 (2017) 6634–6647, http://dx.doi.org/10.1021/acs.est.7b00423.
[49] J. Zalasiewicz, C.N. Waters, J.A. Ivar do Sul, P.L. Corcoran, A.D. Barnosky, A. Cearreta, M. Edgeworth, A. Gałuszka, C. Jeandel, R. Leinfelder, J.R. McNeill, W. Steffen, C. Summerhayes, M. Wagreich, M. Williams, A.P. Wolfe, Y. Yonan, J.A. Ivar, P.L. Corcoran, A.D. Barnosky, A. Cearreta, M. Edgeworth, A. Ga, C. Jeandel, R. Leinfelder, J.R. McNeill, W. Steffen, C. Summerhayes, M. Wagreich, M. Williams, A.P. Wolfe, Y. Yonan, J.A. Ivar do Sul, P.L. Corcoran, A.D. Barnosky, A. Cearreta, M. Edgeworth, A. Gałuszka, C. Jeandel, R. Leinfelder, J.R. McNeill, W. Steffen, C. Summerhayes, M. Wagreich, M. Williams, A.P. Wolfe, Y. Yonan, The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene, Anthropocene 13 (2016) 4–17, http://dx.doi.org/10.1016/j.ancene.2016.01.002.
[50] A. Cózar, F. Echevarría, J.I. González-Gordillo, X. Irigoien, B. Ubeda, S. Hernández-León, A.T. Palma, S. Navarro, J. García-de-Lomas, A. Ruiz, M.L. Fernández-de-Puelles, C.M. Duarte, Plastic debris in the open ocean, Proc. Natl. Acad. Sci. USA (2014) 17–19, http://dx.doi.org/10.1073/pnas.1314705111.
[51] A. Cózar, E. Martí, C.M. Duarte, J. García-de-lomas, E. Van Sebille, T.J. Ballatore, V.M. Eguíluz, J.I. González-Gordillo, M.L. Pedrotti, The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the Thermohaline circulation, Sci. Adv. 3 (2017) 1–9.
[52] A. Cózar, M. Sanz-Martín, E. Martí, J.I. González-Gordillo, B. Ubeda, J.Á. Gálvez, X. Irigoien, C.M. Duarte, Plastic accumulation in the Mediterranean Sea, PLoS One 10 (2015) e0121762, http://dx.doi.org/10.1371/journal.pone.0121762.
[53] L.C. Lebreton, S.D. Greer, J.C. Borrero, Numerical modelling of floating debris in the world's oceans, Mar. Pollut. Bull. 64 (2012) 653–661, http://dx.doi.org/10.1016/j.marpolbul.2011.10.027.
[54] M. Cole, P.K. Lindeque, E. Fileman, J. Clark, C. Lewis, C. Halsband, T.S. Galloway, Microplastics alter the properties and sinking rates of Zooplankton Faecal pellets, Environ. Sci. Technol. 50 (2016) 3239–3246, http://dx.doi.org/10.1021/acs.est.5b05905.
[55] C.D. Rummel, M.G.J. Löder, N.F. Fricke, T. Lang, E.-M. Griebeler, M. Janke, G. Gerdts, Plastic ingestion by pelagic and demersal fish from the North Sea and Baltic Sea, Mar. Pollut. Bull. 102 (2016) 134–141 〈http://10.0.3.248/j.marpolbul.2015.11.043〉.
[56] P. Davison, R.G. Asch, Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre, Mar. Ecol. Prog. Ser. 432 (2011) 173 https://ezp.sub.su.se/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsjsr&AN=edsjsr.24874560&site=eds-live&scope=site.
[57] M. Masó, E. Garcés, F. Pagès, J. Camp, Drifting plastic debris as a potential vector for dispersing Harmful Algal Bloom (HAB) species, Sci. Mar. 67 (2007) 107–111, http://dx.doi.org/10.3989/scimar.2003.67n1107.
[58] P.H. Pham, J. Jung, J.S. Lumsden, B. Dixon, N.C. Bols, The potential of waste items in aquatic environments to act as fomites for viral haemorrhagic septicaemia virus, J. Fish. Dis. 35 (2012) 73–77, http://dx.doi.org/10.1111/j.1365-2761.2011.01323.x.
[59] E.R. Zettler, T.J. Mincer, L.A. Amaral-Zettler, Life in the "Plastisphere": microbial communities on plastic marine debris, Environ. Sci. Technol. 47 (2013) 7137.
[60] S.C. Gall, R.C. Thompson, The impact of debris on marine life, Mar. Pollut. Bull. 92 (2015) 170–179, http://dx.doi.org/10.1016/j.marpolbul.2014.12.041.
[61] H. Hirai, H. Takada, Y. Ogata, R. Yamashita, K. Mizukawa, M. Saha, C. Kwan, C. Moore, H. Gray, D. Laursen, E.R. Zettler, J.W. Farrington, C.M. Reddy, E.E. Peacock, M.W. Ward, Organic micropollutants in marine plastics debris from the open ocean and remote and urban beaches, Mar. Pollut. Bull. 62 (2011) 1683–1692, http://dx.doi.org/10.1016/j.marpolbul.2011.06.004.
[62] C.M. Rochman, E. Hoh, B.T. Hentschel, S. Kaye, Long-term field measurement of sorption of organic contaminants to five types of plastic pellets: Implications for plastic marine debris, Environ. Sci. Technol. 47 (2013) 1646–1654, http://dx.doi.org/10.1021/es303700s.
[64] A.L. Andrady, Persistence of Plastic Litter in the Oceans, (2015), pp. 57–72, http://dx.doi.org/10.1007/978-3-319-16510-3.
[65] UNEP and GRID-Arendal. Marine Litter Vital Graphics. United Nations Environment Programme and GRID-Arendal. Nairobi and Arendal, 2016. 〈www.unep.org〉, 〈www.grida.no〉.
[66] J. Boucher, D. Friot, Primary Microplastics in the Oceans, Gland, Switzerland, 2017. 〈https://portals.iucn.org/library/node/46622〉.
[67] F. Salvador Cesa, A. Turra, J. Baruque-Ramos, Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings, Sci. Total Environ. 598 (2017) 1116–1129, http://dx.doi.org/10.1016/j.scitotenv.2017.06.179.
[68] A.D. Barnosky, E.A. Hadly, J. Bascompte, E.L. Berlow, J.H. Brown, M. Fortelius, W.M. Getz, J. Harte, A. Hastings, P.A. Marquet, N.D. Martinez, A. Mooers, P. Roopnarine, G. Vermeij, J.W. Williams, R. Gillespie, J. Kitzes, C. Marshall, N. Matzke, D.P. Mindell, E. Revilla, A.B. Smith, Approaching a state shift in Earth/'s biosphere, Nature 486 (2012) 52–58, http://dx.doi.org/10.1038/nature11018.
[69] J.A. Dearing, R. Wang, K. Zhang, J.G. Dyke, H. Haberl, M.S. Hossain, P.G. Langdon, T.M. Lenton, K. Raworth, S. Brown, J. Carstensen, M.J. Cole, S.E. Cornell, T.P. Dawson, C.P. Doncaster, F. Eigenbrod, M. Flörke, E. Jeffers, A.W. Mackay, B. Nykvist, G.M. Poppy, Safe and just operating spaces for regional social-ecological systems, Glob. Environ. Change 28 (2014) 227–238, http://dx.doi.org/10.1016/j.gloenvcha.2014.06.012.
[70] G.M. Mace, B. Reyers, R. Alkemade, R. Biggs, F.S. Chapin, S.E. Cornell, S. Díaz, S. Jennings, P. Leadley, P.J. Mumby, A. Purvis, R.J. Scholes, A.W.R. Seddon, M. Solan, W. Steffen, G. Woodward, Approaches to defining a planetary boundary for biodiversity, Glob. Environ. Change 28 (2014) 289–297, http://dx.doi.org/10.1016/j.gloenvcha.2014.07.009.
[71] T. Häyhä, P.L. Lucas, D.P. van Vuuren, S.E. Cornell, H. Hoff, From planetary boundaries to national fair shares of the global safe operating space - how can the scales be bridged? Glob. Environ. Change (2016).
[72] D.P. van Vuuren, P.L. Lucas, T. Häyhä, S.E. Cornell, M. Stafford-Smith, Horses for courses: analytical tools to explore planetary boundaries, Earth Syst. Dyn. Discuss. 6 (2015) 1711–1741, http://dx.doi.org/10.5194/esdd-6-1711-2015.
[73] S.L. Lewis, We must set planetary boundaries wisely, Nature 485 (2012) 417 〈http://search.proquest.com/openview/eb71d4c8c808517b6ac7ce5fb26bbb8f/1?pq-origsite=gscholar&cbl=40569〉.
[74] B.F. Jönsson, J.R. Watson, B.F. Jo, The timescales of global surface-ocean connectivity, Nat. Commun. 7 (2016) 11239, http://dx.doi.org/10.1038/ncomms11239.
[75] O. Setälä, V. Fleming-Lehtinen, M. Lehtiniemi, Ingestion and transfer of microplastics in the planktonic food web, Environ. Pollut. 185 (2014) 77–83, http://dx.doi.org/10.1016/j.envpol.2013.10.013.
[76] L. Van Cauwenberghe, C.R. Janssen, Microplastics in bivalves cultured for human consumption, Environ. Pollut. 193 (2014) 65–70, http://dx.doi.org/10.1016/j.envpol.2014.06.010.
[77] A.A. Koelmans, A. Bakir, G.A. Burton, C.R. Janssen, Microplastic as a vector for chemicals in the aquatic environment: critical review and model-supported reinterpretation of empirical studies, Environ. Sci. Technol. 50 (2016) 3315–3326, http://dx.doi.org/10.1021/acs.est.5b06069.
[78] C.M. Rochman, R.L. Lewison, M. Eriksen, H. Allen, A.-M. Cook, S.J. Teh, Polybrominated diphenyl ethers (PBDEs) in fish tissue may be an indicator of plastic contamination in marine habitats, Sci. Total Environ. 476–477 (2014) 622–633, http://dx.doi.org/10.1016/j.scitotenv.2014.01.058.
[79] E.L. Teuten, J.M. Saquing, D.R.U. Knappe, M. a. Barlaz, S. Jonsson, A. Björn, S.J. Rowland, R.C. Thompson, T.S. Galloway, R. Yamashita, D. Ochi, Y. Watanuki, C. Moore, P.H. Viet, T.S. Tana, M. Prudente, R. Boonyatumanond, M.P. Zakaria, K. Akkhavong, Y. Ogata, H. Hirai, S. Iwasa, K. Mizukawa, Y. Hagino, A. Imamura, M. Saha, H. Takada, Transport and release of chemicals from plastics to the environment and to wildlife, Philos. Trans. R. Soc. Lond. B. Biol. Sci. 364 (2009) 2027–2045, http://dx.doi.org/10.1098/rstb.2008.0284.
[80] R. Sussarellu, M. Suquet, Y. Thomas, C. Lambert, C. Fabioux, M. Eve, J. Pernet, Oyster reproduction is affected by exposure to polystyrene microplastics, PNAS (2015) 1–6, http://dx.doi.org/10.1073/pnas.1519019113.
[81] M. Cole, P. Lindeque, E. Fileman, C. Halsband, T.S. Galloway, The impact of

polystyrene microplastics on feeding, function and fecundity in the marine copepod *Calanus helgolandicus*, Environ. Sci. Technol. 49 (2015) 1130–1137, http://dx.doi.org/10.1021/es504525u.
[82] T. Romeo, C. Pedà, M.C. Fossi, F. Andaloro, P. Battaglia, First record of plastic debris in the stomach of Mediterranean lanternfishes, Acta Adriat. 57 (2016) 115–124.
[83] H.S. Carson, S.L. Colbert, M.J. Kaylor, K.J. McDermid, Small plastic debris changes water movement and heat transfer through beach sediments, Mar. Pollut. Bull. 62 (2011) 1708–1713, http://dx.doi.org/10.1016/j.marpolbul.2011.05.032.
[84] M. Bergmann, L. Gutow, M. Klages, Marine Anthropogenic Litter, Springer International Publishing, Heidelberg New York Dordrecht London, 2015.
[85] C.L. Yntema, N. Mrosovsky, Critical periods and pivotal temperatures for sexual differentiation in loggerhead sea turtles, Can. J. Zool. 60 (1982) 1012–1016.
[86] T. Andersen, J. Carstensen, E. Hernández-García, C.M. Duarte, Ecological thresholds and regime shifts: approaches to identification, Trends Ecol. Evol. 24 (2017) 49–57, http://dx.doi.org/10.1016/j.tree.2008.07.014.
[87] M. Williams, J. Zalasiewicz, P.K. Haff, C. Schwägerl, A.D. Barnosky, E.C. Ellis, The Anthropocene biosphere, Anthr. Rev. 2 (2015) 196–219, http://dx.doi.org/10.1177/2053019615591020.
[88] D. Archer, The Global Carbon Cycle, Princeton University Press, Princeton NJ, USA, 2010.
[89] P. Ciais, C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J. Galloway, M. Heimann, others, Carbon and other biogeochemical cycles, in: Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang., Cambridge University Press, 2014, pp. 465–570. 〈http://pubman.mpdl.mpg.de/pubman/item/escidoc:2058766/component/escidoc:2058768/WG1AR5_Chapter06_FINAL.pdf〉.
[90] J.T. Turner, Zooplankton fecal pellets, marine snow and sinking phytoplankton blooms, Aquat. Microb. Ecol. 27 (2002) 57–102, http://dx.doi.org/10.3354/Ame027057.
[91] Y.C. Jang, J. Lee, S.Y. Hong, H.W. Choi, W.J. Shim, S.Y. Hong, Estimating the global inflow and stock of plastic marine debris using material flow analysis: a preliminary approach, J. Korean Soc. Mar. Environ. Energy 18 (2015) 263–273, http://dx.doi.org/10.7846/JKOSMEE.2015.18.4.263.
[92] T. Elmqvist, S. Cornell, M.C. Öhman, T. Daw, F. Moberg, A. Norström, Å. Persson, G. Peterson, J. Rockström, M. Schultz, E.H. Török, V. Galaz, C. Ituarte-Lima, Global Sustainability and Human Prosperity: Contribution to the Post-2015 Agenda and the Development of Sustainable Development Goals, Nordic Council of Ministers, Stockholm, Sweden, 2014〈http://norden.diva-portal.org/smash/record.jsf?pid=diva2%3A714418&dswid=gtm_autoEvent_1502809585491#sthash.qLA0Vzrr.dpbs〉.
[93] European Commission, Living well, within the limits of our planet, 7th EAP – the New General Union Environment Action Programme to 2020, 2013. 〈http://ec.europa.eu/environment/pubs/pdf/factsheets/7eap/en.pdf〉.
[94] S. Freinkel, Plastic: A Toxic Love Story, Houghton Mifflin Harcourt, Boston, MA, 2011.
[95] F.S. vom Saal, B.T. Akingbemi, S.M. Belcher, D.A. Crain, M. Eriksen, F. Farabollini, P.A. Hunt, M. Marcus, Chapel Hill Bisphenol A Expert Panel Consensus Statement: Integration of Mechanisms, Effects in Animals and Potential to Impact Human Health at Current Levels of Exposure 24 Elsevier, Elmsford, NY, 2007, pp. 131–138, http://dx.doi.org/10.1016/j.reprotox.2007.07.005.Chapel.
[96] T.S. Galloway, Micro- and nano-plastic and human health, Mar. Anthropog. Litter (2015), http://dx.doi.org/10.1007/978-3-319-16510-3.
[97] A.C. Vegter, M. Barletta, C. Beck, J. Borrero, H. Burton, M.L. Campbell, M.F. Costa, M. Eriksen, C. Eriksson, A. Estrades, K.V.K. Gilardi, B.D. Hardesty, J.A.I. Sul, J.L. Lavers, B. Lazar, L. Lebreton, W.J. Nichols, C.A. Ribic, P.G. Ryan, Q.A. Schuyler, S.D.A. Smith, H. Takada, K.A. Townsend, C.C.C. Wabnitz, C. Wilcox, L.C. Young, M. Hamann, J.A. Ivar do Sul, J.L. Lavers, B. Lazar, L. Lebreton, W.J. Nichols, C.A. Ribic, P.G. Ryan, Q.A. Schuyler, S.D.A. Smith, H. Takada, K.A. Townsend, C.C.C. Wabnitz, C. Wilcox, L.C. Young, M. Hamann, Global research priorities to mitigate plastic pollution impacts on marine wildlife, Endanger. Species Res. 25 (2014) 225–247, http://dx.doi.org/10.3354/esr00623.
[98] NOAA, Interagency report on marine debris sources, impacts, strategies & recommendations, Natl. Ocean. Atmos. Adm. (2008) 62.
[99] M. Tomczak, Defining marine pollution, Mar. Policy 8 (1984) 311–322, http://dx.doi.org/10.1016/0308-597X(84)90023-X.