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Perspective

Weathering Plastics as a Planetary Boundary Threat: Exposure, Fate, and Hazards

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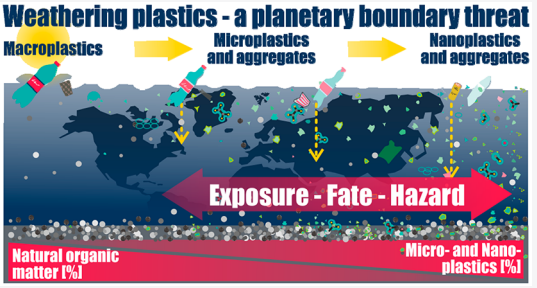
ABSTRACT: We described in 2017 how weathering plastic litter in the marine environment fulfils two of three criteria to impose a planetary boundary threat related to "chemical pollution and the release of novel entities": (1) planetary-scale exposure, which (2) is not readily reversible. Whether marine plastics meet the third criterion, (3) eliciting a disruptive impact on vital earth system processes, was uncertain. Since then, several important discoveries have been made to motivate a re-evaluation. A key issue is if weathering macroplastics, microplastics, nanoplastics, and their leachates have an inherently higher potential to elicit adverse effects than natural particles of the same size. We summarize novel findings related to weathering plastic in the context of the planetary boundary threat criteria that demonstrate (1) increasing *exposure*, (2) *fate* processes leading to poorly reversible pollution, and (3) (eco)toxicological *hazards* and their thresholds. We provide evidence that the third criterion could be fulfilled for weathering plastics in sensitive environments and therefore conclude that weathering plastics pose a planetary boundary threat. We suggest future research priorities to better understand (eco)toxicological hazards modulated by increasing exposure and continuous weathering processes, to better parametrize the planetary boundary threshold for plastic pollution.



KEYWORDS: *environmental plastics, weathering, exposure, fate, hazards, planetary boundary threat*

INTRODUCTION

The planetary boundary concept defines a safe operating space for humanity within the context of global environmental change.[1] Planetary boundaries include, e.g., climate change, biosphere integrity, and the introduction of chemicals or other novel entities.[2] In 2017, we described how plastic pollution fulfills two of three criteria that define the planetary boundary threat for novel entities,[3] specifically (1) planetary-scale exposure, which is (2) not readily reversible.[2,4,5] Plastics in the environment will pose a planetary boundary threat if they also meet the third criterion, (3) eliciting a disruptive impact on a vital earth system process.

The possibility of currently unknown disruptive impacts due to globally accumulating plastics and associated breakdown products[6] is a strong motivation for applying the precautionary principle to reduce plastic emissions worldwide.[3] Such unknown impacts could arise from the influence that environmental weathering has on the exposure, fate, and potential (eco)toxicological hazards of plastics in the environment. The properties of plastics begin to change immediately by weathering processes once they enter the environment.[3] If there is a planetary boundary threat associated with plastics in the environment, it is inseparable from their weathering. For instance, one hypothesis referred to as "global plastic toxicity debt" considers that the plastics currently present in the oceans will become more toxic with time due to future, accumulating releases of small particles, including nanoplastics, and chemical leachates, all with unknown impacts, as a result of weathering.[7] Here, we use the term "weathering" to refer to abiotic (physicochemical) and biotic weathering, as well as to mechanical degradation and fragmentation. We follow this approach for efficiency, due to the interdependency of these processes.

Recent years have brought major discoveries related to plastic weathering and its diverse impacts. We discuss these advances with reference to the three criteria that define a planetary boundary threat: (1) *exposure and weathering*, (2) *fate and weathering*, and (3) *hazard and weathering*. We conclude this manuscript by revisiting (4) the *planetary*

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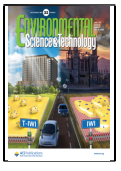

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boundary concept in the context of weathering and reassess if weathering plastics pose a planetary boundary threat.

EXPOSURE AND WEATHERING

Plastic emissions instigate ecosystem exposure. It was estimated that as of 2010 there had been 275 million tons of plastics emitted into the world's oceans and that emissions reached approximately 8 million tons of macroplastics and 1.5 million tons of microplastics entering annually.[8] Increasing ocean macroplastics loads over the past 60 years have been confirmed empirically.[9] A recent projection concluded there would be 710 million tons in the ocean by 2040, even in the scenario of immediate and concerted actions to drastically reduce plastic emissions.[10] This huge inventory of plastics in the oceans will continuously be subject to diverse weathering processes, such that the macroplastics emitted today will contribute to increased exposure to micro- and nanoplastics, and their leachates, in the next decades.[7]

Abiotic Weathering. Once in the aquatic environment, abiotic factors change the morphology and mechanical properties of both the surface and bulk phase of plastics. Photooxidation leads to the formation of polar functional groups such as carbonyl groups in most polymers,[11−13] hence decreasing their surface hydrophobicity.[14] Chain scission, cross-linking reactions, and leaching of additives also occurs, which has a direct effect on molar mass and mechanical properties.[14−17] An increase in crystallinity (and brittleness[18]) occurs for semicrystalline polymers such as polyethylene as a result of chain scissions in amorphous regions.[15,19] Even without mechanical stress, cracks occur due to photooxidation, which increases fragmentation.[12,20,21] X-ray tomography imaging of marine plastics has shown they contain surface cracks that run toward their center.[22]

Biotic Weathering. In addition to abiotic processes, plastic pollution undergoes diverse, co-occurring, and in many cases synergistic biotic weathering (i.e., abiotic weathering that facilitates biological attack). This weathering involves the formation of a biofilm on the surface, mineralization by bacteria, and digestion by marine organisms. Upon the first exposure of plastics to natural waters, an initial surface layer of inorganic and organic substances is formed, the so-called "eco-corona."[23,24] Adsorption of the eco-corona to plastic particles is followed by the formation of a biofilm[25] composed of communities that are phylogenetically distinct from surrounding planktonic communities[26,27] and subject to spatiotemporal differences.[28] The development of biofilms varies as a function of polymer type, changing surface properties and external factors (e.g., light, temperature and oxygen conditions) , which collectively influences the plastic's physicochemical properties.[29] Certain microbes have evolved metabolic capacities to mineralize synthetic polymers to carbon dioxide (CO_2) or methane.[30] Sticky extracellular polymeric substances are excreted from such microbes to connect assemblages and provide stability, and this in turn increases the structural complexity of the biofilm.[31] Thus, the formation of plastic-associated biofilms contributes greatly to the alteration of size, shape, and density of entrained plastics and also plays a major role in the formation of heteroaggregates,[32] which further affects their fate (discussed below).[33]

In addition to these microbiological processes, both entanglement and ingestion of macro- and microplastics by marine organisms can occur.[34] Weathering modulates particle uptake by aquatic organisms, likely because the particles gradually resemble natural prey by size or by biofilm coating.[35] For instance, weathered plastic fragments were shown to be more readily taken up than virgin polystyrene by different organisms,[35] but this is not always the case. For infantile zebrafish, bioaccumulation of weathered polyamide particles (treated with hydrogen peroxide alone or with light irradiation) was less explicit than for the pristine material.[36] Furthermore, the digestive action of marine invertebrates has been demonstrated to facilitate fragmentation of plastic particles to smaller size ranges[37,38] and to provide a pathway for sinking by the excretion of faecal matter aggregates.[39]

Time Scales of Plastic Weathering. Both plastic properties (polymer types and additives) and environmental conditions (e.g., sunlight exposure and temperature) influence the rates of plastic weathering; hence, time scales of weathering are polymer-, site-, and season-specific. Abiotic and biotic factors impacting weathering are also interwoven: Biofilms on plastic surfaces can absorb up to 99% of UV radiation, depending on thickness and composition,[40,41] reducing the rate of photolysis of polymers.[42] Fragmentation rates are influenced by the properties of weathered and biofilm-covered plastic particles. In the case of brittle or highly crystalline (>90%) plastics, fragmentation begins immediately upon exposure to environmental conditions.[43−45] If the polymer is amorphous at low crystallinity (<20%), mechanical fragmentation only starts after chemical degradation, facilitating embrittlement.[16,43] Knowledge from standardized testing of plastic durability under accelerated weathering has the potential to provide helpful insights on abiotic processes, but it is not clear how to extrapolate findings from artificial to natural weathering conditions. To overcome these challenges, researchers have developed their own weathering chambers[19,46] as described in the Supporting Information.

Recent attempts have been made to determine fragmentation and mineralization rates of plastics in the environment. Several quantitative studies have focused on direct exposure to sunlight. Ward et al.[47] showed that complete UV-driven oxidation of polystyrene <200-μm-thick can occur within decades to centuries, producing CO_2 and dissolved organic carbon as the main products. Song et al.[48] found that 4-mm-thick expanded polystyrene foam (PS bubble foam consisting of ca. 98% air) lost 5% of its weight during outdoor weathering within one month, generating millions of micro- and nanoparticles. Zhu et al.[49] assessed UV-facilitated weathering of polyethylene, polypropylene, expanded polystyrene, and field-weathered microplastics and derived time scales of <1 to 33 years for 100% weight loss. Direct exposure to sunlight does appear able to degrade plastics given enough time; however, this situation does not apply to the large amount of plastics below the surface, in sediment beds or otherwise shielded from sunlight (e.g., by biofilms).[50] The time scales for plastic mineralization are ultimately driven by many factors including exposure media, thickness of the plastic, type of plastic, and additives in the plastic to prevent degradation (e.g., antioxidants and UV-filters). Chamas et al.[50] derived specific surface degradation rates in various environments to harmonize diverse degradation rate measurements and extrapolated marine half-lives for polyethylene of 58 years (bottles) to 1200 years (pipes). Recent studies have ranked the degradation rates of different polymer types relative to each other, indicating that polymers such as branched polyester, nylon, polystyrene, and polycarbonate displayed high resistance to weathering.[50,51] The dissolved organic carbon fraction

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from plastic oxidation may not be benign, as it contains unknown, complex mixtures of nanoplastics and chemical leachates, including intentionally added additives and chain-scission degradation products like low-molecular weight fragments with oxidized end groups, in addition to the release of greenhouse gases.[13,46,52]

Role of Weathering for (De)Sorption of Chemicals. Environmental chemicals may be adsorbed on the surface of plastic, absorbed into the bulk polymer, or both[53−55] depending on the polymer type, its weathering state, and the chemical. Weathering-induced changes of the plastics' characteristics[29,56] and their related impact on the (de)-sorption of chemicals[57−59] strongly depend on the specific physicochemical and biological conditions, hence factors determining (de)sorption vary spatiotemporally. The longer a plastic item remains in the marine environment, the more likely sorbed chemicals will reach equilibrium partitioning with their surroundings, implying depletion of additive chemicals in exchange for an enrichment of ambient chemicals. Physical changes of plastics from weathering combined with environmental conditions (e.g., salinity) could modify the sorption capacity of plastics and (de)sorption kinetics, e.g., by (i) increasing the specific surface area for adsorption due to enhanced crack formation and pore size/structure, (ii) decreasing the fraction of amorphous regions for absorption, or (iii) changing the polarity and hydrophilicity of the surface due to oxidation.[60,61] Biotic weathering (e.g., biofilm formation[62]) is also important for both sorption capacities and (de)sorption kinetics, with one study showing it to be the predominant factor controlling the sorption capacity of plastics in a 28-day *in situ* experiment.[63]

FATE AND WEATHERING

Weathering processes influence the fate and transport of plastics toward accumulation in gyres, remote shorelines, the water column, and sediments, as well as mass loss by mineralization or by permanent (geological) burial below the benthic ecosystem. Accumulation rates are determined by the difference between emission rates and ultimate mass loss rates. There is an increasing focus on the fate of (micro)plastics in marine sediments,[64−66] but little information is available regarding ultimate burial rates. A recent study found that deep sea hotspots of microplastics tend to be at biodiversity hotspots, due to nutrients, organic matter, and microplastics being deposited in such areas by thermohaline-driven currents.[67] To better infer the locations and rates whereby plastics can accumulate, there are several abiotic and biotic influenced transport processes that need to be understood.

Abiotic Transport Processes. The most common fate of marine microplastics is often claimed to be settling on the sea bed, or suspension in deep water columns.[68−70] Several studies investigated the settling behavior of individual particles of various polymers in different sizes and shapes,[71,72] subject to (controlled) weathering conditions[73] and biofouling.[74] These studies have confirmed that their settling behavior follows semiempirical fluid mechanic laws for fluid drag resistance of objects in relative motion to their ambient fluid (i.e., Newton's second law, leading to Stokes' law, though empirically corrected for turbulence generation in the particle's wake).[73,75] However, what complicates the prediction of transport and sedimentation of plastics is their wide variety in sizes and shapes, which is made even more complex due to biofilm formation, fragmentation processes, and heteroaggregate formation, diversifying over time and space. Considering these changing properties (e.g., using statistical parameters[76]) in particle transport models is complex and has not yet been achieved for plastics.[77] In addition, the low relative density of plastics makes them very sensitive to drag by currents, and drift by waves[78] and turbulence.[79] Turbulent drift can be more important than buoyancy.[79] Turbulence remains the most difficult phenomenon to predict in computational fluid dynamics. With decreasing particle size, microplastics become more colloidal (even before they become nanoplastics) and hence prone to remaining suspended until being mineralized or incorporated into larger aggregates with other small particles or water-soluble polymers[80,81] to settle as noncolloidal particles or redisperse.

Fragmentation of embrittled particles[18] can occur when exposed to mechanical stress, such as shear stress on shorelines, sediments, and the sea surface microlayer. Depending on various conditions such as tide, waves, and storm surges, plastics on the coastlines can repeatedly move over the sediment substrate. This shearing motion over hard, angular sand and rocks facilitates the particles' fragmentation, particularly if embrittled by weathering.[43−45] Fragmentation and sediment resuspension by ship propellers and bioturbation are other important aspects to consider. Finally, floating microplastics on the surface microlayer can be propelled by wave action and bubble bursting to become a subfraction of marine aerosols,[82] increasing photooxidation and transport distances.

Biotic Influenced Transport Processes. Early microbial colonization and extracellular polymeric substances on plastics decrease their hydrophobicity and buoyancy[83] and enhance downward movement as single particles or in heteroaggregates.[31] Their sinking rates depend on the bulk density of the aggregates, which is a function of the densities and relative proportions of the plastics and biogenic particles.[84,85] Similarly, embedding of microplastics in faecal pellets can result in enhanced sinking rates.[39] However, sinking may not result in ultimate removal from the water column since biofilms could decay (e.g., due to lack of sunlight). Kooi et al.[86] used modeling to demonstrate that plastics might oscillate within the upper 100 m of the water column due to (de)fouling and presented a theoretical model for size-selective removal of small particles from the ocean surface. Gorokhova[87] reported seasonal fluxes of vertical gradients of microplastics in the water column due to the biological activity of zooplankton incorporating plastics. Another study[88] detected the highest concentrations of microplastics in offshore marine waters between 200 and 600 m depth.

HAZARD AND WEATHERING

In addition to plastic-associated chemical leachates, the hazard of plastics and related aggregates is dictated by their inherent toxicity to marine life at the specific size, shape, and biofilm colonization status, all heavily impacted by weathering. Key to characterizing this hazard is benchmarking the uptake and effects against nonweathered plastics and natural particles like detritus and marine clays, as well as their aggregates.

Hazards of Plastic Leachates. Chemicals leaching from plastics can elicit effects in bioassays.[89−91] Coffin et al.[91] assessed estrogenicity and aryl hydrocarbon receptor activation from leachates from UV light-weathered plastics from the North Pacific Gyre. Rummel et al.[92] investigated the activation of cell-based reporter gene bioassays by leachates from mainly

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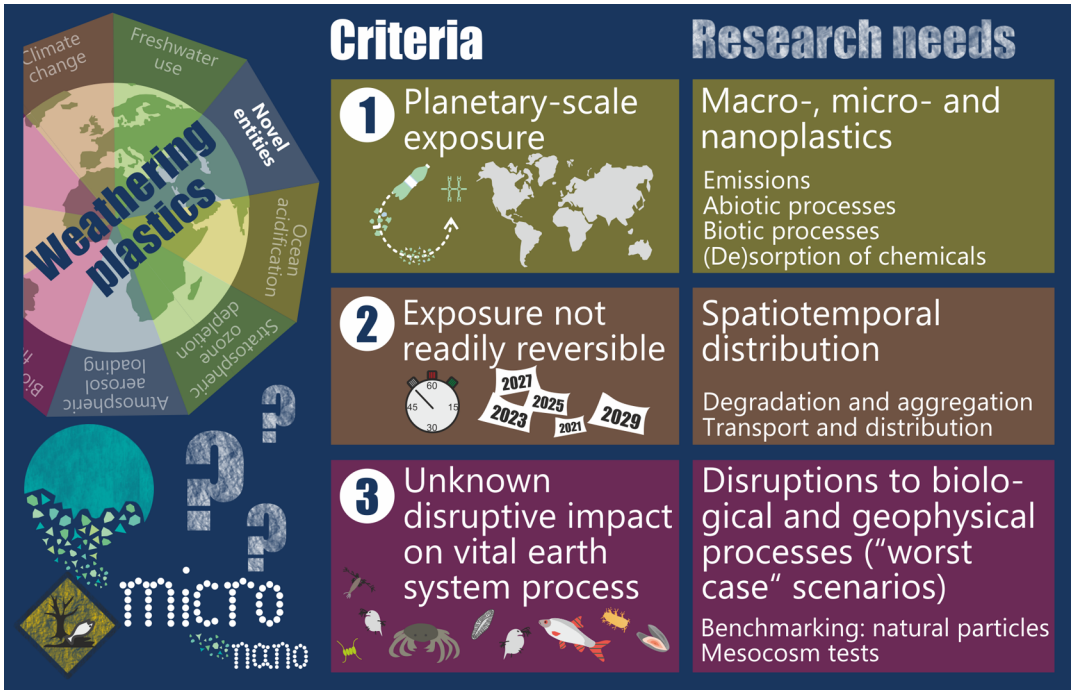

Figure 1. Three criteria that define a planetary boundary threat from a novel entity and corresponding research needs for weathering plastics in the environment.

additive-free preproduction polymers generated by accelerated UV light weathering in artificial seawater. Zimmermann et al.[93] tested exhaustive solvent extracts as a worst-case scenario of cumulative leaching from additive-containing consumer products using *in vitro* bioassays. All three studies linked the observed effects to specific chemicals identified in the leachates. Their common approach was the identification of selected chemicals capable of inducing effects in reporter gene assays,[89−91] but the complexity of the mixtures has so far hampered the identification of the main effect drivers.[93] Leachates of oxo-degradable polymers were also found to elicit negative effects on model organisms, which could mainly be ascribed to metal release.[94]

Impacts of Weathered Plastic Particles toward Organisms. Weathered plastic particles of all sizes have been shown to impact marine organisms. A survey from 2015 reported that at least 690 different species had been documented to encounter macro- and microplastic, including 17% that were near threatened or worse according to the International Union for Conservation of Nature red list.[34] These encounters with marine life are expected to increase.[7]

From the current literature, it appears that for particles of a given size, weathering will either decrease or have a negligible influence on toxicity, in cases where the particle size distribution is not altered. For instance, one study on plastic aging in wastewaters found no weathering-related effects of polyethylene microplastics to three aquatic test species (*Daphnia magna*, *Danio rerio*, and *Lemna minor*),[95] whereas another study reported decreased effects from irregularly shaped polystyrene particles to *D. magna*, hypothesizing that the biofilm may mitigate toxicity.[96] Potthoff et al.[97] combined an aging/sieving approach to fractionate different size classes of UV-aged particles of various polymer types low in additives down to the nanorange for ecotoxicity testing. Overall, there were limited effects of the unaged vs aged particle fractions on *D. magna* and green algae.[97] One of the rare plant-related studies[98] observed a mitigating effect of thermal aging on germination of *Lepidium sativum* seeds. The aging process reduced adverse effects for polycarbonate particles, probably due to leaching of bisphenol A, making the weathered particles less hazardous over time.[98] Although these preliminary findings suggest that individual plastic particles of a given size become less toxic with weathering, this insight must be kept in context of substantially increasing global exposure of a diverse size range and population of plastic particles, both freshly emitted and long-weathered, for the foreseeable future.[10]

Benchmarking Effects of Microplastics to Natural Particles. Benchmarking the effects of plastics to natural particles[99,100] is essential, and a lack of benchmarking severely limits the informative value of effect studies. Ideally, all effect studies should be based on real-world, weathered microplastics benchmarked to local natural particles. The two pathways that could cause distinct effects between plastics and natural particles are (i) differences in the particle size and shape distributions (PSSD) or (ii) polymer- and leachate-related effects with weathering. As for i, the described weathering and fate processes ultimately affect the PSSD of plastics and natural particles (e.g., organic detritus, minerals) differently, due to their wide difference in material properties. Hypothetically, this could lead to unique PSSD patterns of plastic particles that ultimately cause distinct effects.[101] Regarding ii, it currently appears that certain plastic types are inherently more toxic than natural particles. For example, polyvinyl chloride particles appeared to be more toxic than kaolinite and diatomite particles of similar sizes,[102] potentially related to differences in surface chemistry and release of, e.g., additives.

Predicted no-effect concentrations (PNEC) are central for setting observed effects into the context of environmental concentrations. The lowest published PNEC value for micro- and nanoplastics that we identified is 0.14 μg/L.[103] This value is lower than more recently reported values, including a PNEC of 72 μg/L,[104] hazardous concentration for 5% of the species

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(HC_5) values of 1.67 μg/L for microplastics and 5.4 μg/L for nanoplastics,[113] as well as another HC_5 value of 940 μg/L for microplastics.[105] However, no benchmarking to natural suspended solids was done to derive these values, therefore it is not straightforward to apply them to real-world contexts. For sediments, an experimental mesocosm study determined a long-term effect value of 0.05% plastic fraction per sediment weight,[106] regarding the abundance of macroinvertebrates. This value is much higher than typical concentrations for oceanic sediments,[66] but may potentially be encountered at current or future hotspots. Therefore, further research is needed to derive PNEC or HC_5 values benchmarked to natural particles and to evaluate how these compare to projected environmental concentrations at hotspots. The benchmarking is expected to be challenging due to the PSSD shifting toward smaller particles and more diverse shapes and aggregates over time with prolonged weathering.[7] How to ideally benchmark effects of microplastics to natural particles in a quantitative way and the choice of representative natural particles hence remain topics of discussion.

PLANETARY BOUNDARY CONCEPT IN THE CONTEXT OF WEATHERING

There is accumulating, planetary-scale, nonreadily reversible exposure of aquatic systems to weathered macro-, micro-, and nanoplastics and their leachates that will persist for long time scales, even if substantial efforts are made to reduce emissions.[10] We discussed above new research related to the three criteria of a planetary boundary threat for novel entities (Figure 1). The composition and distribution of plastics in the environment evolves through dynamic weathering and fate processes. Therefore, a full understanding of exposure (criterion 1) and fate (criterion 2) of marine plastic pollution requires emission estimates that specify total loads and types of plastics and additionally address parameters related to PSSD, material properties, degradation rates, permanent sediment burial rates, and chemical additive/leachate exposure. As a point of departure, research should target identified hotspots, such as ecologically important estuaries impacted by substantial plastic loads from rivers,[107] coastlines, or biodiverse areas on the seafloor.[108]

More research on disruptive impacts of real-world weathered plastics, benchmarked to natural particles, is central to understanding their overall impact on vital earth system processes (criterion 3). To address the concern of disruptive toxic hazards, we suggest to increase the complexity in effect studies in a stepwise manner: (i) lab-scale assessment of plastics of varying size and shape, benchmarked to natural particles;[102,109] (ii) mixtures of weathered plastics and heteroaggregates from the environment or artificial weathering, benchmarked to natural particles; (iii) mesocosm studies with representative concentrations of naturally weathered particles in diverse local environments reflecting hotspots (e.g., brine ponds mimicking the seabed) including representative key communities and their functions.[106] Future research should also consider (iv) the toxicity of complex chemical mixtures released during weathering and identify components that drive toxicity via, *e.g.*, effect modeling or effect-directed analysis. In these studies, partitioning of the chemicals between plastics, the surrounding medium, and the organisms needs to be considered.[62] Some research has addressed nontoxicological impacts of plastics, such as the specific vulnerability of ecosystems toward eutrophication.[110] While plastics may not add a substantial resource or constraint in eutrophic areas or systems rich in suspended solids, they may contribute substantially as nutrient sources and new habitats for colonizing communities with potential implications for geochemical cycles in ultraoligotrophic systems.[62]

Does Marine Plastic Litter Pose a Planetary Boundary Threat? Revisiting our central question: Do plastics in the environment impose a planetary boundary threat, based on the three criteria of (1) planetary-scale exposure, (2) exposure not being readily reversible, and (3) unknown disruptive effects on a vital earth system process? There is now further consensus that 1 and 2 are met,[3,111] although there are still open questions about the processes driving ubiquitous exposure and poor reversibility (Figure 1). Evidence is accumulating that criterion 3 is also met by at least two potential, yet difficult to quantify, toxicological mechanisms that could act simultaneously and lead to disruptive effects at hotspots: (i) accumulation of plastics within a certain harmful PSSD range for specific key species or (ii) accumulation of toxic plastic leachates until they reach effect thresholds.

Regarding i, all sizes, i.e., macro-, micro-, and nanoplastics, can cause disruptive impacts. The increase in observed ocean plastic debris compared to natural debris (see TOC figure)[7] alongside widespread observations of entanglement and ingestion[32] have formed the basis for this concern. Natural suspended particle concentrations themselves can be disruptive, with effects observed at levels as low as 10 mg/L.[112] Recent mesocosm studies have demonstrated effects from micro- and nanoplastics at fractions between 0.05 and 0.5% of the sediment weight.[106] The nonbenchmarked PNEC[103] and HC_5[113] are in most cases higher than current concentrations at hotspots, but it is likely that these hotspot concentrations are underestimated due to the lack of measurements and continuous weathering-related fragmentation of macroplastics to micro- and nanoplastics over time.[7,113]

As for ii accumulation of toxic leachates, this aspect is a part of the planetary boundary for chemical pollution.[115] The planetary boundary for chemical pollution and novel entities has been established, as there is evidence of global accumulation, with many chemicals exhibiting persistence and potential to elicit (eco)toxicological effects (e.g., pesticides or pharmaceuticals, designed to elicit certain effects).[2,105] However, this planetary boundary is difficult to constrain since each single chemical could represent a planetary boundary threat, but they usually co-occur with other chemicals, with poorly characterized mixture effects.[114,115] The chemicals released from plastics add to these mixtures and hence the complexity of this planetary boundary. Furthermore, particles and chemicals influence each other in multiple ways regarding their toxicity, e.g., due to (de)sorption.

We therefore conclude that weathering plastics meet all three criteria of a planetary boundary threat for novel entities. Due to the complexity of the impacts discussed above, the challenge lies in assessing quantitatively where the threshold is. The difficulties include (i) the scarcity of effect studies of weathered plastic particles benchmarked to natural particles; (ii) difficulties in accounting for complex and changing mixture effects of weathering plastics, their leachates, and degradation products; (iii) the combined impact of weathering plastics and multiple stressors in vulnerable ecosystems; and (iv) a lack of consensus on how to best standardize monitoring and effect testing.[116−118] However, considering that concentrations at hotspots have exceeded or could exceed nonbenchmarked

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threshold values, and that exposure will increase for the foreseeable future due to continuously increasing emissions and weathering-induced degradation of plastic litter, we strongly recommend the utilization of diverse efforts to reduce plastic emissions. Plastics have many uses to mitigate other planetary boundary threats if managed properly, particularly if reused/recycled in a circular economy. Accumulating weathering plastic debris poses a planetary boundary threat, although it cannot be reduced to a straightforward parameter due to its multiple, co-occurring disruptive impacts. There is a risk that a planetary boundary threshold for environmental plastics could be crossed before it is known, or that through weathering it will , inevitably, be crossed in the future.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c01512.

Additional text on accelerated weathering in industry and science (PDF)

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The authors declare no competing financial interest.

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nanoparticles, smart materials, and microplastics and aims at unravelling their specific mechanisms of toxicity, including mixture effects with other pollutants and grouping principles to facilitate their risk assessment. ORCID: https://orcid.org/0000-0003-1712-6278. Research ID: https://publons.com/researcher/AAA-7072-2020.

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