REVIEW

The global threat from plastic pollution

Matthew MacLeod[1]*, Hans Peter H. Arp[2,3]*, Mine B. Tekman[4]*, Annika Jahnke[5,6]*

Plastic pollution accumulating in an area of the environment is considered "poorly reversible" if natural mineralization processes occurring there are slow and engineered remediation solutions are improbable. Should negative outcomes in these areas arise as a consequence of plastic pollution, they will be practically irreversible. Potential impacts from poorly reversible plastic pollution include changes to carbon and nutrient cycles; habitat changes within soils, sediments, and aquatic ecosystems; co-occurring biological impacts on endangered or keystone species; ecotoxicity; and related societal impacts. The rational response to the global threat posed by accumulating and poorly reversible plastic pollution is to rapidly reduce plastic emissions through reductions in consumption of virgin plastic materials, along with internationally coordinated strategies for waste management.

Plastic pollution is found globally from deserts to farms, from mountaintops to the deep ocean, in tropical landfills and in Arctic snow. Reports of plastic debris in the marine environment date back half a century (*1*, *2*), with continuing accumulation on the ocean surface over the past 60 years (*3*).

Emissions of plastic are increasing and will continue to do so even in some of the most optimistic future scenarios of plastic waste reduction (*4*). Estimates of global emissions of plastic waste to rivers, lakes, and the ocean range from 9 to 23 million metric tons per year, with a similar amount emitted into the terrestrial environment, from 13 to 25 million metric tons per year as of 2016 (*4*, *5*). Following business-as-usual scenarios, these estimated 2016 emission rates will be approximately doubled by 2025. Scenarios that include concerted, joint global action—such as implementing the Basel convention to prevent transport of plastic waste to countries with poor management systems, or the European Union target to recycle more plastic as part of the transition to a circular economy—still forecast continuous yearly increases in plastic emissions (*4*, *5*).

Accumulation of plastic in the environment occurs when the rate at which plastic pollution enters an area exceeds the rate of natural removal processes or cleanup actions. Plastic is persistent in the environment, with rates of natural removal on the scale of decades to centuries (*6*). Cleanup actions are not feasible in many areas of the global environment where plastic accumulates, particularly in remote locations. Plastic therefore fits the profile of a "poorly reversible pollutant," both because emissions cannot be curtailed and because it resides in the environment for a long time (*7*). A central concern about poorly reversible pollution is that if it accumulates to levels that exceed effect thresholds, this transgression will trigger negative impacts that themselves cannot be readily reversed because it will not be possible to rapidly reduce pollution levels below the threshold (*8*–*10*).

Here, we identify areas of the global environment that are threatened with impacts from plastic pollution that is both accumulating and poorly reversible. We highlight the complex characteristics of plastic pollution that evolve as it undergoes continuous weathering in the environment, and discuss potential large-scale and poorly reversible effects that could be triggered by continuing accumulation. Our analysis confirms that plastic pollution fits the exposure profile of a planetary boundary threat, which we and others have already asserted (*10*–*13*), and that actions to drastically reduce plastic emissions are the rational policy response.

Environmental exposure to poorly reversible pollution by plastic

Obvious plastic pollution occurs where humans directly litter, such as roadsides, beaches, river banks, and urban estuaries. This type of plastic pollution is, in principle, readily reversible at the local scale because it can be physically removed by cleanups, and because littering can be curtailed through public campaigns and with improved waste collection infrastructure. Similarly, the obvious plastic pollution in and around landfills can, in principle, be reduced with improved site management. However, even at the local scale, plastic pollution becomes poorly reversible when weathering processes cause fragmentation into micro- and nanoplastic particles that are not visible to the human eye. Furthermore, there are several known remote areas of the global environment that are accumulating poorly reversible, weathering plastic pollution. The plastic polluting these remote areas is not per se feasible to remove, and pollution levels would only respond slowly to emission reductions (Fig. 1).

Remote coastlines and the ocean surface—in particular, the five gyres of the North and South Pacific, the North and South Atlantic, and the Indian Ocean—are well-known global accumulation zones for floating plastic debris (*14*) (Fig. 1A). Although a variety of direct, empirical measurements of plastic pollution in ocean gyres have been made, inventories of plastic on the ocean surface largely rely on remote sensing measurements of macroplastic and simulations of plastic debris trajectories because of their huge extent and circulating currents. Less than 0.3 million metric tons of plastic are estimated to be currently circulating on the ocean surface (*14*), which represents a small fraction of the estimated 9 million to 23 million metric tons of plastic that are emitted annually into rivers, lakes, and the ocean (*4*, *5*). The small inventory of plastic floating on the ocean surface relative to annual emissions has sometimes been called "missing plastic," but mass balance modeling of plastic in the ocean surface layer suggests that weathering (including fragmentation) and sinking could rapidly remove initially buoyant plastic from the near-surface ocean to the water column and the deep seafloor (*15*) (Fig. 1, B and C). Thus, the inventory of plastic particles on the ocean surface could be quickly transferred to the water column and deep ocean if emissions were shut off. However, plastic pollution on the surface of the ocean is still poorly reversible because the feasibility of reducing emissions of plastic to the oceans is low at present. Plastic pollution beached on remote coastlines presumably has longer residence times than floating plastic, and thus is even more poorly reversible.

The global ocean reaches several thousand meters of depth in many areas, and its water column is a huge potential reservoir for neutrally buoyant plastic pollution that could have very poor reversibility (Fig. 1B). The mass balance modeling mentioned above estimated that 99.8% of the plastic that entered the ocean since 1950 is located below the surface (*15*). Although most plastic particles are expected to eventually reach the seafloor (*16*), a substantial amount is present in the water column (*16*, *17*). One mechanism for plastic to remain suspended in the water column is through incorporation into biological cycles. Biofilms that form on the surface of plastic excrete sticky polymeric substances that facilitate the formation of heteroaggregates of plastic particles with natural organic matter (*18*). Buoyant polymers with increasing biofilm loads in the photic zone sink and then float upward again when the

[1]Department of Environmental Science, Stockholm University, SE-106 91 Stockholm, Sweden. [2]Department of Environmental Engineering, Norwegian Geotechnical Institute, NO-0806 Oslo, Norway. [3]Department of Chemistry, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway. [4]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany. [5]Department of Ecological Chemistry, Helmholtz Centre for Environmental Research–UFZ, DE-04107 Leipzig, Germany. [6]Institute for Environmental Research, RWTH Aachen University, DE-52074 Aachen, Germany.
*Corresponding author. Email: matthew.macleod@aces.su.se (M.M.); hans.peter.arp@ngi.no (H.P.H.A.); mine.banu.tekman@awi.de (M.B.T.); annika.jahnke@ufz.de (A.J.)

biofilm decays at greater depths (*19*). The smallest plastic particles, such as those below 10 μm and particularly those that are cylindrical and elongated in shape (such as fibers), will be suspended throughout the water column as a consequence of drag forces and turbulence, leading to very long residence times (*20*). Rates of degradation of neutrally buoyant plastic are expected to be very slow in the deep water column as a result of cold temperatures, quiescent conditions and, in particular, the lack of ultraviolet radiation. Thus, plastic pollution of the water column is likely poorly reversible. Plastic particles with long residence times in the water column are also subject to subsurface lateral advection in the ocean (*16*), which provides a global transport pathway for plastic pollution.

The seafloor is a major accumulation zone for plastic pollution (Fig. 1C), having some of the highest concentrations of microplastic particles in the environment (*16*). A recent study indicated that near-bed thermohaline currents, which supply oxygen and nutrients to deep-sea fauna, also drive plastic deposition into hotspots of seabed biodiversity (*21*). The seafloor is mostly a placid, dark, cold environment that is not conducive to further degradation (*22*). Thus, the persistence of plastic on the seafloor is likely very high, with its residence time determined by time scales for burial in accumulating sediment (*23*).

Terrestrial soils are another accumulation zone for plastic (Fig. 1D). Sources of plastic pollution to urban and rural soils are plastic litter, road runoff (including tire wear particles), and atmospheric deposition of micro- and nanoplastic particles (*24*). Plastic is also deliberately introduced to agricultural soils through plastic mulching with polyethylene films and increasingly also so-called "biodegradable" plastic films, compost, and sludge-derived biosolids that contain plastic residues (*24*, *25*), as well as by the application of polymeric stabilizers against soil erosion (*26*). Current plastic fractions in soils can reach up to 0.1% of soil organic carbon (*24*). On the basis of estimates of sewage sludge inputs alone (*27*), it is likely that the amount of plastic in the world's agricultural soil is larger than on the ocean's surface. Mismanaged plastic mulches are a source of plastic to the surrounding soil (*25*) and can escape to lakes and rivers. Some plastics that are biodegradable in soils, such as those made of polylactic acid, exhibit half-lives in the marine environment similar to that of polyethylene (*6*). Plastic concentrations in soil are expected to increase because of these ongoing emission sources combined with extremely slow degradation rates. It is estimated that less than 1% of the mass of conventional plastic is lost from soils over several years (*24*), despite conversion into smaller plastic particles (*28*). Thus, plastic pollution of soils is poorly reversible.

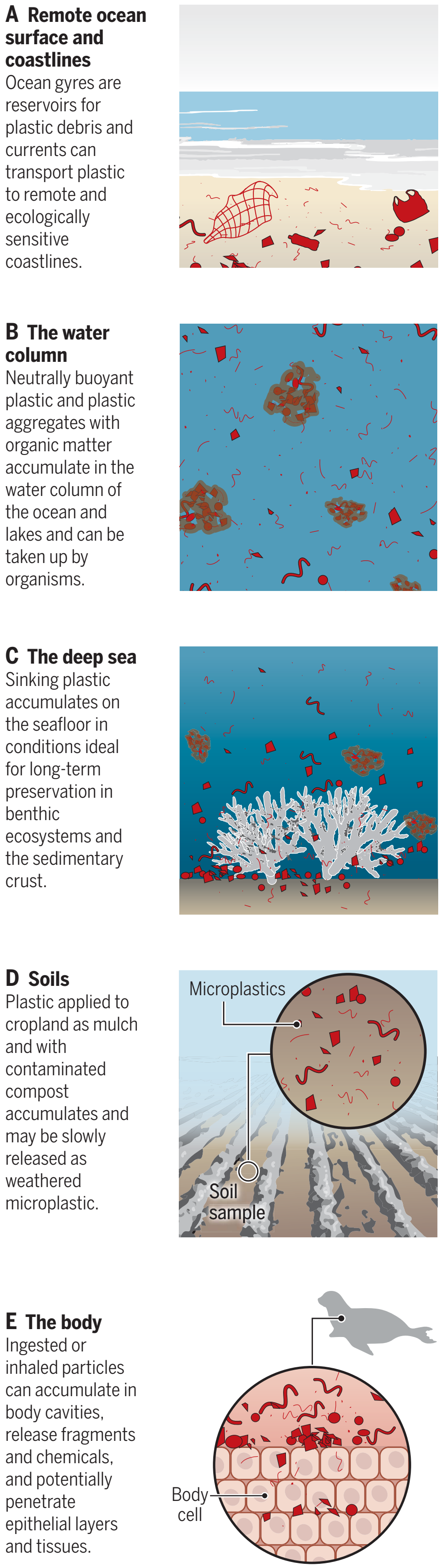

Fig. 1. Locations where poorly reversible plastic pollution accumulates.

Ingestion of plastic particles by diverse biota and humans has been demonstrated in numerous studies (Fig. 1E). Recently, there have been reports that small plastic particles can be taken up from the gastrointestinal tract into tissues [e.g., (*29*)], and small plastic particles have been shown to penetrate biological membranes (*30*, *31*). Current knowledge about absorption, distribution, metabolism, and excretion of plastic by organisms is hampered by limitations of the methods used (*32*) and experimental design (*33*). However, internal tissues and organs of humans and other biota could potentially be another location of accumulating and poorly reversible plastic pollution, in particular for the smallest, nanosized fraction (*34*).

Altered characteristics of poorly reversible plastic pollution due to weathering

Half-lives of plastic in the environment are very long and highly uncertain, and they depend strongly on both the properties of the plastic and environmental conditions (*6*, *35*). Polymer types have been ranked for their tendency to undergo environmental degradation, such as biodegradation rates decreasing in the order polyesters > polyamides (nylon) > polyolefins (e.g., polyethylene), and photodegradation rates decreasing in the order polytetrafluoroethylene > polyesters > polyamides (*36*). In addition to polymer type, degradation rates also depend on properties of the plastic material, such as the surface area/volume ratio and whether antioxidants and other stabilizers were used during formulation and compounding to increase durability. Environmental conditions affecting degradation rates include ultraviolet radiation intensity, temperature, biological activity, and mechanical stress (*10*).

The slow process of plastic weathering begins immediately upon exposure to the environment. The weathering of plastic proceeds along two interconnected and often synergistic tracks (Fig. 2): (i) fragmentation and the release of soluble or volatile components, coinciding with (ii) biofouling and oxidative degradation processes. In the context of the global threat posed by accumulating and poorly reversible plastic pollution, the physical, chemical, and biological weathering processes are important because they affect the ultimate removal and residence time in zones of poorly reversible exposure, as well as the possible impact mechanisms.

Among the first observable indications of environmental weathering of plastic are physicochemical changes in surface properties, including altered surface charge, and cracking and other changes in surface morphology due to increased polymer crystallinity. These changes and the concurrent biological weathering processes discussed below render the surface more susceptible to fragmentation by mechanical forces (*10*)—for example, during movement across river beds, repeated washing ashore in coastal areas, and freeze-thaw action in soils. The increase in surface area that occurs as plastic fragments into micro- and nanoplastic particles also facilitates the release of chemicals present in the plastic material, including additives, residual unpolymerized monomers and oligomers (*10*), and degradation products of the plastic polymer itself (*37*). Thus, over time, plastic in the environment produces an increasingly diverse lineage of small particles and chemicals that are more mobile and accessible for uptake into wider ranges of biota than the material that originally entered the environment.

Synergistic biological weathering starts even before the fragmentation process is initiated (Fig. 2). Within hours of entering a river, lake, ocean, or likely also soil, an "eco-corona" of organic matter and microorganisms forms around plastic particles, ultimately leading to colonization of the plastic surface that occurs within days (*38*). These so-called biofilms affect the fate of plastic pollution in diverse ways. They can favor colonization by sessile organisms, excrete extracellular enzymes that break down the plastic surface, and form extracellular polymeric substances that facilitate aggregation. Biofilms also lead to the alteration of buoyancy as described above, provide an additional sorption phase for chemicals, and slow down the sorption/desorption kinetics of chemicals. By shielding the particle's surface from ultraviolet radiation and other factors that facilitate weathering, biofilms decrease rates of fragmentation. Uptake of plastic particles coated with biofilm is also enhanced when selective feeders mistake them for food. After ingestion, weathering of plastic may continue because particles can fragment in the digestive system (*39*).

Considering how environmental properties influence plastic weathering (*6*, *10*, *12*, *35*), it is possible to rank how rapidly weathering likely proceeds in the accumulation zones in Fig. 1. The most rapid weathering likely occurs on the ocean surface (Fig. 1A), driven by direct exposure to sunlight, mechanical forces (wind, waves), and temperature variations. Plastic in surface soils (Fig. 1D) also has direct exposure to sunlight and a high concentration of active biological organisms. Weathering rates likely decrease with increasing depth in the water column (Fig. 1, B and C) and in deeper soils and sediments that plastics reach through tilling and bioturbation (Fig. 1D). Degradation of plastic within the body (Fig. 1E) is possibly dependent on the presence of suitable enzymes, their specific location in tissues, and excretion rates within the gastrointestinal tract, but this remains a research frontier.

Potential impacts of global plastic pollution

Conventional ecotoxicological risk assessment (comparing measured or predicted levels in the environment to toxicological effect thresholds derived from standard tests) indicates that plastic currently poses a risk to only a small, although likely increasing, fraction of the global ocean (*40*). However, the limitations of current ecotoxicological risk assessment applied to plastic are numerous [e.g., (*41*)]. The forms of plastic pollution that induce toxic effects, and thus the relevant exposure concentrations, are unknown, although they may already exceed proposed impact thresholds in hotspots (*40*, *42*). Exposure concentrations of small plastic particles are likely underestimated because of the continuous fragmentation of weathering plastic and the scarcity of reliable measurements, especially for nanoplastic. Considered in a broad context, the potential impacts of accumulating and poorly reversible plastic pollution of the global environment are wide-reaching, encompassing both geophysical and biological impacts, and could put added pressure on ecosystems already exposed to multiple stresses (Fig. 3A).

Geophysical impacts

Plastic pollution can influence the global carbon cycle both directly and indirectly. The direct effect is due to the small but non-negligible fraction of the 280 million to 360 million metric tons of fossil carbon converted into plastic per year (*43*) that degrades or is industrially converted (e.g., by incineration or landfilling) to carbon dioxide, methane, and other greenhouse gases. Even if the world completely ceases to use fossil fuels, emissions of greenhouse gases from plastic degradation and waste management will continue for centuries. However, indirect effects of plastic on the carbon cycle through effects on the homeostasis of the marine

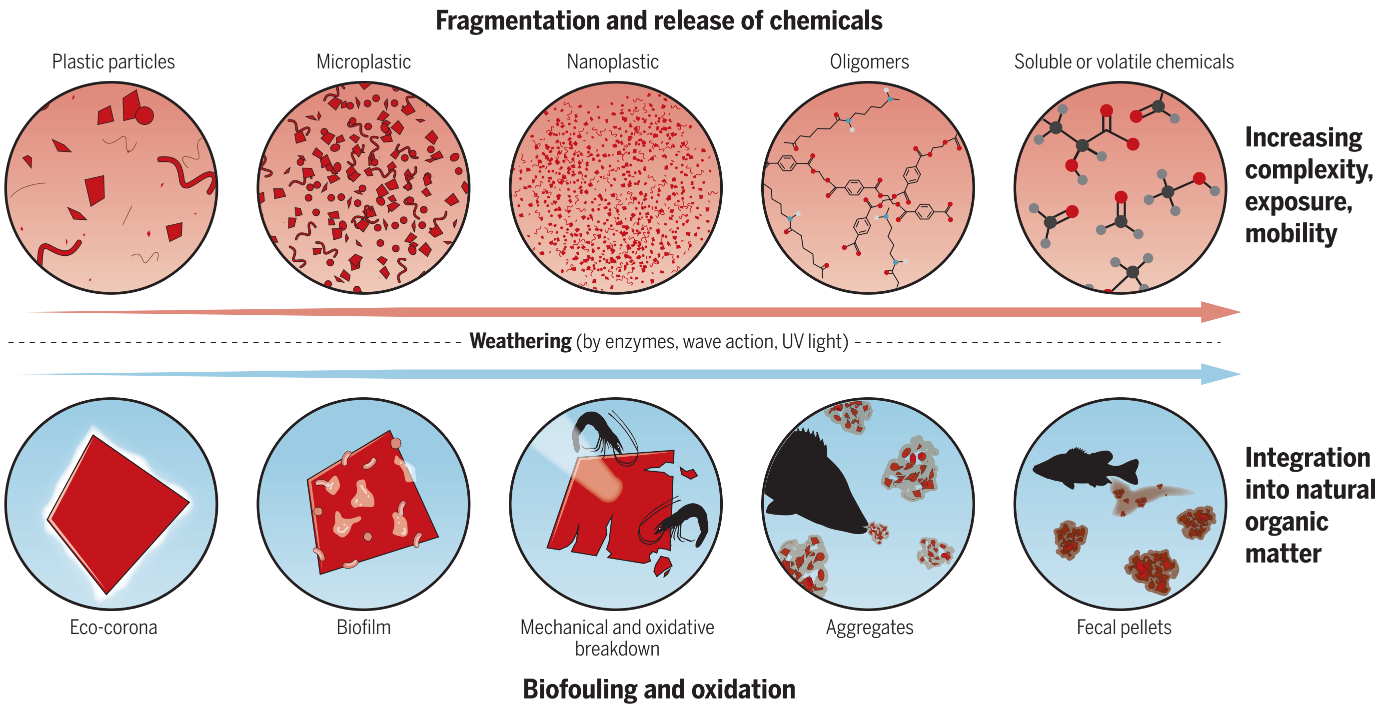

ILLUSTRATION: C. BICKEL/SCIENCE

Fig. 2. Weathering processes of poorly reversible plastic pollution in the environment. Weathering proceeds along two co-occurring and synergistic pathways of fragmentation and release of chemicals, and biofouling and oxidation.

carbon pump are potentially larger than the direct effects of greenhouse gas emissions. It was recently estimated that 7.8 million metric tons of plastic carbon per year currently reach the seafloor (*44*). Before settling on the seafloor, as previously described, a large fraction of the plastic will be suspended in the water column as neutrally buoyant particles (*10*, *45*). Accumulating concentrations of suspended plastic particles and heteroaggregates could affect the food sources or the turbidity levels in the habitats of cyanobacteria and phytoplankton communities. Decreasing populations of bacterial communities would lead to reduced carbon sequestration from the atmosphere. The nonsequestered carbon, which would otherwise be contributing to the marine food web, could instead remain in the atmosphere, where it would contribute to global warming (*45*). Meanwhile, the increasing loads of carbon in nonbuoyant plastic will sink, with one estimate indicating that the amount of plastic carbon being buried in seabed sediments could exceed that of natural organic carbon by 2050 in hot-spot regions (*44*).

The mechanisms that affect the marine carbon pump also affect nutrient cycling in diverse ways (*46*). Nitrogen and phosphorus cycling were shown to be affected by biofilms on microplastic in aquatic systems (*47*). Similarly, a microcosm experiment demonstrated that the presence of microplastic altered nitrogen cycling in sediment (*48*). Microplastic incorporated into marine particles may thus affect the delivery of nutrients to deep sea environments (*18*), and Earth system modeling demonstrates that there is a potential for zooplankton grazing on microplastic to accelerate the global decline of oxygen in the ocean (*49*).

Increased loads of plastic can lead to long-term changes in soil properties, such as water-holding capacity, microbial activity and diversity, nutrient availability, and soil structure (*25*). The accumulation of plastic in soils can lead to effects on plant performance and plant diversity (*50*) as well as potentially irreversible soil degradation (*51*). The formation of (micro)plastic hotspots on seabeds could have analogous impacts by changing sediment structure and composition to an extent that sediment fertility and the marine carbon pump are affected. The quantity of global soils and sediments irreversibly affected by accumulating plastic can only increase in the future.

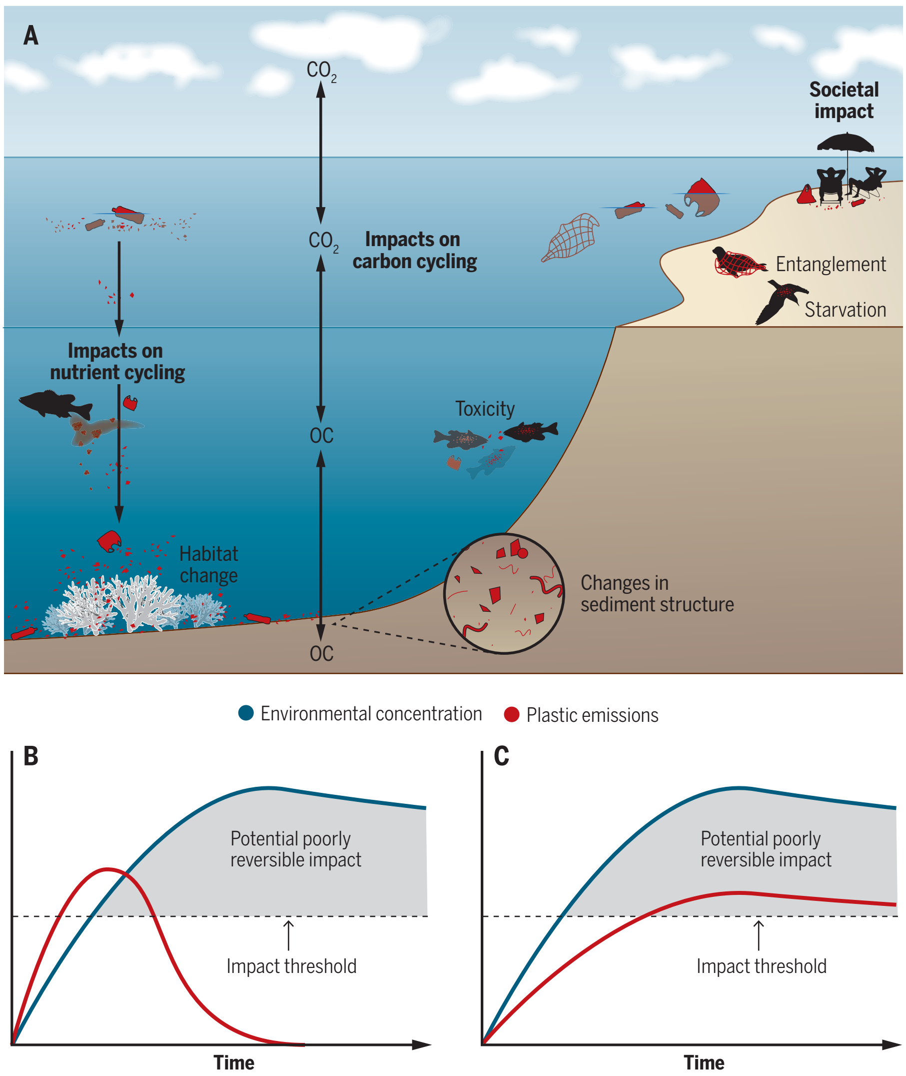

Fig. 3. Diverse potential long-term global impacts of accumulating and poorly reversible plastic pollution. (**A**) Potential impacts include geophysical impacts on carbon cycling, nutrient cycling, soil habitats, and sediment habitats; co-occurring biological impacts on endangered/keystone species and (eco)toxicity; and societal impacts resulting from the public's perception of environmental quality and policy changes. (**B** and **C**) Illustration of how plastic pollution accumulating over an impact threshold can lead to practically irreversible impacts. In (B), plastic pollution has a long residence time in the environment, and therefore concentrations do not respond to emission reductions. In (C), plastic pollution is reversible in the environment (for example, as a result of cleanup actions or degradation), but concentrations remain above the impact threshold because emissions cannot be effectively controlled. CO_2, carbon dioxide; OC, organic carbon.

Biological impacts

Wildlife encounters with macroplastic debris have been widely reported. A recent analysis listed 914 marine megafaunal species (including 226 species of seabirds, 86 species of marine mammals, all species of sea turtles, and 430 species of fishes) affected through entanglement and/or ingestion (*52*). For endangered species, not more than a few encounters are required to threaten population-level consequences. Entanglement and ingestion of plastic jeopardizes 17% of the 693 species on the International Union for Conservation of Nature Red List (*53*). In the northeastern Mediterranean, entanglement of endangered monk seals (*Monachus monachus*, 600 to 700 individuals in total) with fishing gear was identified as the second most frequent cause of mortality after deliberate killing (*54*).

Colonization of plastic surfaces is another type of interaction with organisms. A single tsunami event initiated transoceanic dispersal of nearly 300 living species over 6 years via colonization on rafting debris, indicating the potential for plastic pollution to facilitate species invasions during extreme weather events (*55*). Such complex, system-level impacts of plastic pollution indicate that more effects on species and ecosystems remain to be discovered.

Diverse impacts caused by ingestion of microplastic due to particle and chemical-related toxicity have been reported, including physical injury, changes in physiology, and impaired feeding, growth, reproduction, and oxygen consumption rates (*56*). In sediments, concentrations of macro- and nanoplastics above 0.5% were found to affect macroinvertebrate abundance (*57*). Additives leaching from plastic can also contribute to (eco)toxicological effects. One example is the concern about phthalate esters added to polyethylene mulches that are taken up in grains destined for consumption by humans and livestock (*58*). Another is the recent discovery that a phototransformation product of a ubiquitous antioxidant used in tire rubber causes acute mortality of coho salmon (*Oncorhynchus kisutch*) after stormwater runoff events (*59*).

Multiple stressors

A less-explored aspect of plastic pollution is how it can act in concert with other geophysical, biological, and chemical stressors to cause impacts. For instance, potential impacts on fisheries from overfishing and climate change could be exacerbated by impacts from plastic on carbon cycling, entanglement, and ingestion as well as toxicity. Aquatic organisms forced into adaptation due to habitat change related to altered temperatures, nutrient supply, and chemical exposure experience plastic as an additional stressor that may contribute to biodiversity loss. Soil biodiversity, as well as the limited supply of fertile soils, could be further reduced through long-term effects of accumulating plastic, which could require wetland destruction and deforestation to obtain new fertile soils. Arid areas of the world, where surface water is in short supply, may find their remaining freshwater ecosystem resources further compromised by plastic pollution, specifically through toxic plastic additives (e.g., phthalate esters, heavy metals, bisphenols, poly- and perfluoroalkyl substances) and small plastic particles that may penetrate through drinking water production systems.

Confronting the global threat from plastic pollution

The public considers plastic pollution to be a serious environmental and public health issue (*60*, *61*) (Fig. 3). Important reasons for this perception are first-hand experiences of visible plastic pollution (*62*) and increasing public concern regarding exposure to plastic-associated chemicals such as bisphenol A (*63*). Public concern about plastic pollution has inspired policy initiatives to address marine microplastic that invoke the precautionary principle because the risks to humans from microplastic have not yet been shown (*60*, *64*), and risks to some ecosystems have only recently been demonstrated [e.g., for coral reefs (*65*)]. Largely missing from this debate, however, is assessment of the potential for delayed toxicological effects due to weathering-related degradation, or additionally nontoxicological impacts on carbon and nutrient cycles, soil and sediment fertility, and biodiversity. These impacts may extend long after emissions cease if they are caused by poorly reversible plastic pollution (Fig. 3, B and C), or exceed a tipping point that causes a regime shift. In the case of possible (eco) toxicity of plastic, the potential for delayed effects has been referred to as a "global toxicity debt" (*28*).

Better understanding and management of the threat posed by plastic pollution in the environment requires research that focuses on environmental processes and fate, including the accumulation of small weathered particles (*41*), associated chemicals, and the formation of biofilms and heteroaggregates with natural organic carbon (*10*). Of particular relevance is a better understanding of these processes within the areas where poorly reversible plastic pollution is currently accumulating (Fig. 1). Discovery-oriented research aimed at identifying currently unknown impacts of weathering plastic on biogeochemical cycling and organism health is also needed.

The rational strategy to confront the potential for poorly reversible global impacts to arise from plastic pollution is to curtail emissions of plastic to the environment as rapidly and comprehensively as possible, following the prescription for transformative change suggested by Borrelle *et al.* (*4*). Precise and focused regulation has been called for to limit production and use of virgin plastic and to foster innovation to more benign yet competitive materials (*66*). Further actions could include expanding the Basel convention to only allow export of plastic waste to countries with better recycling infrastructure than the exporting country, eliminating hazardous chemicals in plastic to increase recycling potential, and developing recycling/reuse targets nationally and globally. Broader societal strategies should include eliminating unnecessary uses of plastic and encouraging behaviors that minimize plastic waste. Emerging inventories of sources of plastic pollution to the environment (*27*) can support these efforts by identifying plastic products and supply chains that should be targeted. The threat that plastic being emitted today could cause global-scale, poorly reversible impacts in the future is compelling motivation to take targeted actions to reduce emissions now.

REFERENCES AND NOTES

1. E. J. Carpenter, S. J. Anderson, G. R. Harvey, H. P. Miklas, B. B. Peck, *Science* **178**, 749–750 (1972).
2. E. J. Carpenter, K. L. Smith Jr., *Science* **175**, 1240–1241 (1972).
3. C. Ostle *et al.*, *Nat. Commun.* **10**, 1622 (2019).
4. S. B. Borrelle *et al.*, *Science* **369**, 1515–1518 (2020).
5. W. W. Y. Lau *et al.*, *Science* **369**, 1455–1461 (2020).
6. A. Chamas *et al.*, *ACS Sustain. Chem. Eng.* **8**, 3494–3511 (2020).
7. P. Harremoës *et al.*, *Late Lessons from Early Warnings: The Precautionary Principle 1896–2000* (Citeseer, 2001).
8. L. M. Persson *et al.*, *Environ. Sci. Technol.* **47**, 12619–12622 (2013).
9. M. MacLeod *et al.*, *Environ. Sci. Technol.* **48**, 11057–11063 (2014).
10. H. P. H. Arp *et al.*, *Environ. Sci. Technol.* **55**, 7246–7255 (2021).
11. T. S. Galloway, C. N. Lewis, *Proc. Natl. Acad. Sci. U.S.A.* **113**, 2331–2333 (2016).
12. A. Jahnke *et al.*, *Environ. Sci. Technol. Lett.* **4**, 85–90 (2017).
13. P. Villarrubia-Gómez, S. E. Cornell, J. Fabres, *Mar. Policy* **96**, 213–220 (2018).
14. E. van Sebille *et al.*, *Environ. Res. Lett.* **15**, 023003 (2020).
15. A. A. Koelmans, M. Kooi, K. L. Law, E. van Sebille, *Environ. Res. Lett.* **12**, 114028 (2017).
16. M. B. Tekman *et al.*, *Environ. Sci. Technol.* **54**, 4079–4090 (2020).
17. C. A. Choy *et al.*, *Sci. Rep.* **9**, 7843 (2019).
18. R. Coyle, G. Hardiman, K. O. Driscoll, *Case Stud. Chem. Environ. Eng.* 100010 (2020).
19. S. Ye, A. L. Andrady, *Mar. Pollut. Bull.* **22**, 608–613 (1991).
20. L. Khatmullina, I. Isachenko, *Mar. Pollut. Bull.* **114**, 871–880 (2017).
21. I. A. Kane *et al.*, *Science* **368**, 1140–1145 (2020).
22. M. B. Tekman, T. Krumpen, M. Bergmann, *Deep Sea Res. I* **120**, 88–99 (2017).
23. J. A. Brandon, W. Jones, M. D. Ohman, *Sci. Adv.* **5**, eaax0587 (2019).
24. M. Bläsing, W. Amelung, *Sci. Total Environ.* **612**, 422–435 (2018).
25. S. Bandopadhyay, L. Martin-Closas, A. M. Pelacho, J. M. DeBruyn, *Front. Microbiol.* **9**, 819 (2018).
26. H. P. H. Arp, H. Knutsen, *Environ. Sci. Technol.* **54**, 3–5 (2020).
27. S. Galafassi, L. Nizzetto, P. Volta, *Sci. Total Environ.* **693**, 133499 (2019).
28. M. C. Rillig, S. W. Kim, T. Y. Kim, W. R. Waldman, *Environ. Sci. Technol.* **55**, 2717–2719 (2021).
29. S. Zeytin *et al.*, *Mar. Pollut. Bull.* **156**, 111210 (2020).
30. A. F. R. M. Ramsperger *et al.*, *Water* **12**, 3216 (2020).
31. A. Ragusa *et al.*, *Environ. Int.* **146**, 106274 (2021).
32. S. Primpke *et al.*, *Appl. Spectrosc.* **74**, 1012–1047 (2020).
33. C. De Sales-Ribeiro, Y. Brito-Casillas, A. Fernandez, M. J. Caballero, *Sci. Rep.* **10**, 12434 (2020).
34. M. Shen *et al.*, *Environ. Pollut.* **252A**, 511–521 (2019).
35. J. Duan *et al.*, *Water Res.* **196**, 117011 (2021).
36. K. Min, J. D. Cuiffi, R. T. Mathers, *Nat. Commun.* **11**, 727 (2020).
37. B. Gewert, M. Plassmann, O. Sandblom, M. MacLeod, *Environ. Sci. Technol. Lett.* **5**, 272–276 (2018).
38. C. D. Rummel, A. Jahnke, E. Gorokhova, D. Kühnel, M. Schmitt-Jansen, *Environ. Sci. Technol. Lett.* **4**, 258–267 (2017).
39. A. L. Dawson *et al.*, *Nat. Commun.* **9**, 1001 (2018).
40. G. Everaert *et al.*, *Environ. Pollut.* **267**, 115499 (2020).
41. L. Wang *et al.*, *J. Hazard. Mater.* **401**, 123415 (2021).
42. E. Besseling, P. Redondo-Hasselerharm, E. M. Foekema, A. A. Koelmans, *Crit. Rev. Environ. Sci. Technol.* **49**, 32–80 (2018).
43. J. P. Dees, M. Ateia, D. L. Sanchez, *ACS ES&T Water* **1**, 214–216 (2020).
44. C. Smeaton, *Limnol. Oceanogr. Lett.* **6**, 113–118 (2021).
45. M. Shen *et al.*, *Mar. Pollut. Bull.* **150**, 110712 (2020).
46. T. J. Mincer, E. R. Zettler, L. A. Amaral-Zettler, in *Hazardous Chemicals Associated with Plastics in the Marine Environment*, H. Takada, H. K. Karapanagioti, Eds. (Springer, 2018), pp. 221–233.
47. X. Chen *et al.*, *Sci. Total Environ.* **719**, 137276 (2020).
48. M. E. Seeley, B. Song, R. Passie, R. C. Hale, *Nat. Commun.* **11**, 2372 (2020).
49. K. Kvale, A. E. F. Prowe, C. T. Chien, A. Landolfi, A. Oschlies, *Nat. Commun.* **12**, 2358 (2021).
50. A. A. de Souza Machado *et al.*, *Environ. Sci. Technol.* **53**, 6044–6052 (2019).
51. Z. Steinmetz *et al.*, *Sci. Total Environ.* **550**, 690–705 (2016).
52. S. Kühn, J. A. van Franeker, *Mar. Pollut. Bull.* **151**, 110858 (2020).
53. S. C. Gall, R. C. Thompson, *Mar. Pollut. Bull.* **92**, 170–179 (2015).
54. A. A. Karamanlidis *et al.*, *Endanger. Species Res.* **5**, 205–213 (2008).
55. J. T. Carlton *et al.*, *Science* **357**, 1402–1406 (2017).
56. N. Prinz, Š. Korez, in *YOUMARES 9—The Oceans: Our Research, Our Future: Proceedings of the 2018 Conference for Young Marine Researchers in Oldenburg, Germany*, S. Jungblut, V. Liebich, M. Bode-Dalby, Eds. (Springer, 2020), pp. 101–120.
57. P. E. Redondo-Hasselerharm, G. Gort, E. T. H. M. Peeters, A. A. Koelmans, *Sci. Adv.* **6**, eaay4054 (2020).
58. M. Shi *et al.*, *Environ. Pollut.* **250**, 1–7 (2019).
59. Z. Tian *et al.*, *Science* **371**, 185–189 (2021).
60. A. I. Catarino, J. Kramm, C. Völker, T. B. Henry, G. Everaert, *Curr. Opin. Green Sustain. Chem.* **29**, 100467 (2021).
61. J. Soares, I. Miguel, C. Venâncio, I. Lopes, M. Oliveira, *J. Hazard. Mater.* **412**, 125227 (2021).
62. B. L. Hartley *et al.*, *Mar. Pollut. Bull.* **133**, 945–955 (2018).
63. T. Jansen, L. Claassen, I. van Kamp, D. R. M. Timmermans, *Food Chem. Toxicol.* **136**, 110959 (2020).
64. T. Wardman, A. A. Koelmans, J. Whyte, S. Pahl, *Environ. Int.* **150**, 106116 (2021).
65. J. B. Lamb *et al.*, *Science* **359**, 460–462 (2018).
66. D. M. Mitrano, W. Wohlleben, *Nat. Commun.* **11**, 5324 (2020).

ACKNOWLEDGMENTS

We thank our colleagues as well as previous and current project partners for stimulating discussions. **Funding:** Supported by the Joint Programming Initiative Healthy and Productive Seas and Oceans (JPI Oceans) project WEATHER-MIC [Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS) grant 942-2015-1866, Research Council of Norway (RCN) grant 257433/E40, German Federal Ministry of Education and Research (BMBF) grant 03F0733A], the BMBF project MICRO-FATE (grant 03G0268TA), and the RCN project SLUDGEFFECT (grant 302371/E10). M.B.T. was funded by the Helmholtz infrastructure program FRAM (Frontiers in Arctic Marine Research). **Author contributions:** This paper is the product of equal efforts and intellectual contributions by all four authors during conceptual development, writing, revision, and editing. M.B.T. took main responsibility for the literature research and A.J. conceptualized the figures. **Competing interests:** The authors declare no competing interests.

10.1126/science.abg5433

Science

The global threat from plastic pollution

Matthew MacLeodHans Peter H. ArpMine B. TekmanAnnika Jahnke

Science, 373 (6550), • DOI: 10.1126/science.abg5433

Science (ISSN 1095-9203) is published by the American Association for the Advancement of Science. 1200 New York Avenue NW, Washington, DC 20005. The title *Science* is a registered trademark of AAAS.