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Plastic pollution under the influence of climate change: implications for the abundance, distribution, and hazards in terrestrial and aquatic ecosystems

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Abstract

Of the numerous anthropogenic pressures that are being exerted on ecosystems globally, plastic pollution and climate change are potentially the most pressing. This is particularly true when they co-occur as joint stressors. These are interlinked with respect to their root cause (the overconsumption of finite resources) and their effects in natural and anthropogenic systems and processes. This review focuses on a growing area of research into how climate change can, by transforming plastic pollution from a reversible to a poorly reversible contaminant, exacerbate the abundance, distribution, exposure, and impacts of plastics and associated chemicals in our waters, soils, biota, and atmosphere. There is a growing body of evidence suggesting that climate change and plastic pollution can have significant and often interactive ecological effects, particularly among the higher trophic levels within the food web. The rational response to confront these effects is to address the pollution at source by rapidly and meaningfully reducing emissions into the environment. We discuss challenges but also solutions, through future research, policies and public awareness, that must harness the same enthusiasm that made plastic a fundamental cornerstone of the modern world in the first place. The threat that plastics produced, used and discarded today could cause global-scale impacts in the future is compelling motivation to take appropriate action now.

KEYWORDS

plastic pollution, climate change, microplastics, ecotoxicity, interactive hazards, joint stressors

Key points

- Ample evidence now exists that climate change conditions are contributing to the abundance, distribution, exposure, and impacts of plastic in the environment.
- Investigations into the ecotoxicity of plastic pollution under climate change are still in their infancy, but studies have already demonstrated interactive effects on terrestrial, freshwater and marine biota and ecosystems, suggesting that these become stronger at higher trophic levels.
- While large, long-lived aquatic organisms high in the food chain may be among the most vulnerable species to intensifying plastic pollution under climate change, thereby representing promising bioindicators of the impacts of both stressors, species lower in the food web appear much less sensitive to both stressors and many even exhibit positive responses.
- Impacts of climate–plastic interactions within terrestrial ecosystems are typically more complex and harder to predict than those in aquatic ecosystems, with evidence ranging from antagonistic to additive and synergistic effects.
- The integration of micro- and nanoplastic pollution with climate stressors offers a way to steer, coordinate and prioritize research and monitoring, along with policy and action.

Introduction

Anthropogenic climate change and plastic pollution constitute major and growing global threats, and both are novel stressors that first arose in the 20th century due to the consumption of fossil fuels (Figure 1). The former is already affecting every region of the world, with consequences that include rising temperatures, intense droughts, wildfires, rising sea levels, melting polar ice and catastrophic storms that are causing widespread ecological and socioeconomic harm and impacting human health (4, 5). Plastic pollution constitutes highly persistent waste that is accumulating rapidly in both managed systems and the natural environment, with ecological impacts that can span multiple levels of biological organization—from genes to ecosystems (6, 7). Although both stressors have traditionally been treated as two distinct issues and, at times, have vied for public and policy attention (8, 9), there is growing recognition that they are in fact closely interlinked, with respect to their ultimate origin, increasing threat level, and the potential for (non-additive) synergistic impacts to arise in combination. The magnitude of plastic production, use, and disposal is such that it is considered, alongside the climate crisis, an exemplar of the Anthropocene, with the potential to breach the "planetary boundaries" that define the safe operating space for humanity (10).

To date, research, media, and policy discussions on the relationship between these stressors have primarily focused on how plastics contribute to climate change (11–13): over 98% of plastics are made from chemicals sourced from fossil fuels (coal, oil and natural gas) (14), with current manufacturing accounting for 12% of global oil consumption (15). Moreover, greenhouse gases (GHGs) are emitted at every stage of the plastic life cycle, from the extraction and transportation of fossil fuel feedstocks through production to end-of-life processes (16). In 2019, GHG emissions across the plastics life cycle were estimated to be 1.8 gigatons (Gt) of carbon dioxide (CO_2) equivalents—approximately 3.7% of global GHG emissions and higher than the total net emissions of the majority of the individual countries (17). The contribution of pre-production phases to plastics' total carbon footprint includes emissions associated with land clearance, release of methane during gas extraction, and transportation of feedstocks to production facilities. The greatest fraction of GHG emissions (approximately 90%) comes from energy-intensive production processes such as cracking, which breaks down saturated hydrocarbons into smaller, often unsaturated ones that are made into plastic resins. The carbon footprint associated with plastic manufacturing has doubled since 1995 (18). End-of-life processes account for the remaining 10% of plastics' GHG emissions (16). Incineration is considered to have the greatest climate impact, accounting for approximately 70% of all end-of-life GHG emissions, followed by recycling and landfill (16). Of the plastics tested, polyethylene is the highest emitter of GHGs, methane and ethylene, during degradation and weathering processes, in addition to being the most produced and discarded synthetic polymer globally (19). Investigations into the direct radiative effects of airborne microplastics have also begun (20). Other types of atmospheric aerosols, such as mineral dust and sulfates, scatter radiation and thus exert a cooling effect, whereas black carbon absorbs radiation and warms the atmosphere. Initial calculations, based on pure (i.e., non-colored) fragments and fibers and a global mean concentration of one microplastic particle per cubic meter, revealed that the influence of airborne microplastics on the global climate is currently small and that a cooling effect dominates. However, this will be strongly dependent upon the geographical and vertical distribution of microplastics in the atmosphere, which is currently not well understood (20). Further uncertainties due to the current lack of data include the influence of microplastic–cloud interactions and the wavelength-dependent refractive index, which depend on properties such as composition and color resulting from pigments and other additives that are bound to the polymer, along with organic coatings that can accumulate in the environment. The current global mean concentration of microplastics in the atmosphere is low, but given projections of a doubling of plastic waste over the coming decades, their abundance and impact on Earth's climate system will continue to increase. Indeed, microplastics may already be influencing local/regional climate in urban environments, where concentrations are in the order of hundreds to thousands of microplastic particles per cubic meter (21, 22).

How climate change contributes to plastic pollution and ecological hazards, by exacerbating its abundance, distribution, exposure, and impacts has received less attention. Nevertheless,

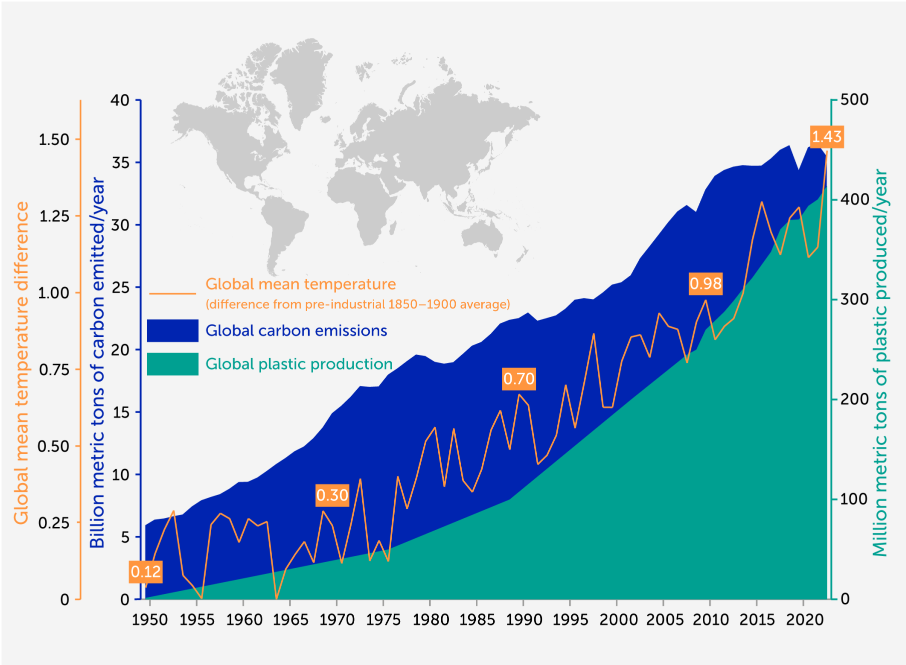

FIGURE 1
Comparison of global mean temperature [orange (1)], carbon dioxide emissions [blue (2)] and plastic production [turquoise (3)].

this is not only a growing area of research, but it is also subject to international negotiations advocating for integrated approaches that recognize the relationship between plastic production and climate change, highlighting the necessity of comprehensive global action and policies to mitigate their combined impacts (23). Here we review the current evidence and identify key knowledge gaps that will need to be addressed on a future Earth that will be both warmer and more polluted.

About plastics

Plastics are complex, highly heterogeneous, synthetic or semi-synthetic materials comprising a carbon-based polymer backbone composed of hundreds or thousands of monomers that are linked by strong covalent bonds. They are usually mixed with a wide range of additives to introduce color, flexibility, stability, water repellence, flame retardation, and ultraviolet resistance (24). However, many of these additives are highly toxic and include carcinogens, neurotoxicants and endocrine disruptors. The unique properties of plastics include a high strength-to-weight ratio, high moldability, impermeability to liquids, and affordability, making it versatile, durable and the signature material of the modern age (25). Its ability to substitute for other materials (e.g., glass, wood, metal, and natural fibers) has supported significant advances in construction, vehicle parts, electronics, aerospace, and medicine, and thus plastics are both ubiquitous and essential for society, the economy and our everyday lives. In fact, the benefits of plastics, such as lightweighting and reducing food spoilage through product packaging, play a vital part in reducing GHG emissions and thus mitigating climate change (26, 27).

Production

Annual plastic production volume has grown from under 2 million tons (Mt) in 1950, when large-scale manufacturing began, to over 400 Mt in 2023 (3). Emerging economies have largely driven the significant growth in recent global plastic production: more than half of all plastics ever produced (equating to 8.3 billion tons) have been made since 2002 (28). Single-use plastics currently account for 35% of current plastic production and are the most rapidly growing manufacturing sector (29). The versatility of plastics stems from the vast array of polymers that can be produced, with polypropylene (16%), fibers (e.g., polyester and nylon; 13%), high-density polyethylene (12%), and low-density polyethylene (12%) predominating (30). Demand continues to accelerate with production predicted to triple to 1,231 Mt by 2060 (31).

Disposal and recycling inefficiencies

Plastic disposal strategies include controlled and uncontrolled landfilling, open burning, thermal conversion, and exporting from high- to low-income countries that often have poor management systems. The three traditional strategies to reduce, reuse, and recycle for waste management programs have proven highly effective for glass, paper and aluminum, but have largely failed for plastics. Aluminum, container glass, and paper achieve global recycling rates of approximately 76%, 68% and 32%, respectively. While the former two are infinitely recyclable without loss of quality, paper can be recycled 5 to 7 times and for all three materials, less energy is needed to recycle a product versus creating one *de novo*. Plastics, however, cannot be recycled repeatedly as they quickly degrade in quality, and in many cases recycling is more costly and energy-intensive than creating them from raw materials. These challenges contribute to recycling rates as low as 9%, which, in combination with the rapid growth in production, results in an estimated 22 Mt of plastic waste (the majority of which has a short life span or is single-use) entering our environment each year. Due to their longevity, plastics accumulate, adding to the 6 billion tons of plastic pollution that have accumulated in our soils, surface waters, biota, and atmosphere since 1950 (28), and in addition it is often transformed from large macroparticles into progressively smaller particles and breakdown products that are more mobile and potentially much more biologically harmful.

Transport, weathering and accumulation of plastics in the natural environment

Plastic pollution from this overspill can originate at sites where litter is directly deposited, such as roadsides, beaches, oceans, riverbanks, and urban estuaries. Theoretically, this type of pollution is reversible as it can be physically removed through local cleanup actions and littering can be reduced through public campaigns and improved waste collection infrastructure. Visible plastic waste at landfill sites can also be curtailed by improving site management to protect the environment (e.g., by dumping at high depths). However, in the absence of removal, plastic waste becomes a poorly reversible pollutant because rather than readily decomposing, it undergoes a slow process of environmental weathering that causes fragmentation into macro-, micro-, and nanoplastic particles. This creates new and potentially more harmful forms of pollution that can interact with other environmental stressors, including climate change.

Plastics are weathered through abiotic (physiochemical) and biotic (biofouling) mechanisms, both of which can be accelerated by warming, microbial metabolism, and mechanical degradation (e.g., abrasion during storm events and runoff, and transportation through terrestrial and aquatic ecosystems) (6). The long and highly uncertain half-lives of plastic pollution in the environment depend strongly on its properties (e.g., polymer chemistry, surface area/volume ratio, and the presence of stabilizers) and environmental conditions (32, 33). Physical weathering changes bulk structure via cracking, embrittlement, and flaking, while chemical degradation induces bond cleavage by the hydrolysis and oxidation of long polymer chains to form lower molecular weight polymer fragments and polar functional groups (e.g., carboxyl and carbonyl groups) (34–36), which decreases surface hydrophobicity (37). These changes, together with mineralization by microbes (38, 39), increase susceptibility to further iterations of mechanical fragmentation (32). The relative increase in surface area during fragmentation facilitates (i) the leaching of the chemical additives incorporated during plastic production (32), in addition to chemical by-products of plastic degradation (40) and (ii) the adherence of potentially harmful microbes (41) and environmental contaminants such as metals (42), pesticides, and other persistent organic pollutants, including “forever chemicals” of concern such as polyfluorinated alkyl substances (PFAS) (43, 44).

Macro-, micro- and nanoplastics

Fragmentation of plastics occurs when a product is being used, for example in synthetic textiles, and vehicle tires (45), during mechanical recycling (46), and as described above, while degrading following disposal. Macroplastic debris refers to plastic items larger than 5 mm, and their fragmentation can generate millions of smaller (secondary) microplastic fragments, fibers, films, foams, and beads (1 µm to 5 mm), which in turn degrade into nanoplastics (<1 µm) (47). Since the majority of micro- and nanoplastics stem from the degradation of a wide variety of larger plastics, they have many different morphologies and compositions that include an array of polymers and additives (48). In contrast to these derivative forms, primary microplastics (MPs) and nanoplastics are particles that are intentionally manufactured to be small from the outset (e.g., abrasives, cosmetic exfoliants, synthetic textiles, liquid detergents, and air-blasting media). Small-particle plastic pollution represents a ubiquitous and often persistent suite of chemicals and morphologies that is invisible to the human eye, but which can account for contamination of and harm to aquatic (freshwater, estuarine, and marine), terrestrial (soil), and atmospheric environments at local-to-global scales (49, 50). The global leakage of MPs into the environment in 2019 was estimated to be 2.7 Mt (30). Major sources included road transport (tire abrasion 0.7 Mt; brake wear: 0.1 Mt; eroded road markings: 0.2 Mt), dust from the abrasion of shoe soles, paint wear, construction and demolition activities, household textiles (0.8 Mt), and wastewater sludge (0.8 Mt). Plastics are now so prevalent in the environment that they are considered an integral, albeit unnatural, component of the Earth’s carbon cycle (33). The small size and often low density of MPs make them vulnerable to mobilization from soil surfaces (51) and aquatic ecosystems, after which they can then be easily carried for considerable distances by ocean currents or entrained into wind- or sea spray (52, 53). This interconnected transportation and transformation via terrestrial, aquatic, and atmospheric systems echoes the natural biogeochemical cycles of other elements and compounds. Studies have demonstrated the release of MPs from rivers into the marine environment (54, 55) and back onto land, once aerosolized through wind and wave action (56), highlighting the cumulative role of historic plastic sources in the atmosphere (57).

Potential impacts of global plastic pollution

Currently, the biotic hazards, risks, and impacts of MPs are relatively poorly understood, partly due to their heterogeneous and complex composition, combined with the host of potential direct and indirect impact pathways through the food web. Toxicity can arise from the physical (e.g., particle size and shape) and chemical properties of the polymer, leaching of chemicals from the plastic matrix (e.g., monomers, plasticizers, flame retardants, and UV stabilizers), the sorbing of environmental toxins, and varying degrees of weathering (32, 58). Gauging the bioavailability and impact of MPs is hindered by a lack of standardized methods for quantifying exposure concentrations and debated vector effects (59, 60), and the fact that ecotoxicological experimental studies tend to use high concentrations of laboratory-grade pristine, homogeneous particles of a pre-determined size, rather than the highly diverse, naturally weathered micro- and nanoplastic debris encountered in the environment.

Recent studies have unearthed a growing range of microplastic impacts, from altered soil and plant ecology on land (61–64) through to modified nutrient cycles in freshwater and marine ecosystems (65–67). Direct impacts via the ingestion of MPs by biota can lead to physical injury and compromised vital rates, including impaired physiology, feeding, growth, reproduction, and oxygen consumption (68, 69). The impacts then become increasingly indirect following the trophic transfer of microplastics and associated chemical contaminants along aquatic (70) and terrestrial (71) food chains. These impacts range from the actual physical transfer of pollutants (e.g., biomagnification) to more subtle effects such as reduced prey availability or habitat loss (72, 73).

As with climate change, a major concern about plastic pollutants is that their legacy effects may be difficult to reverse, even long after any direct toxic effects of the stressor itself have been removed from the system (32, 74). Perturbations can take a long time to play out and our ability to predict them is inversely related to the complexity of the system, in terms of both drivers and biotic responses (75). Direct effects on individual health are typically the easiest to observe and predict. However, the biggest knowledge gaps remain at larger scales and higher organizational levels, where our ability to audit and predict the full spectrum of plastic–climate interactions is still in its infancy.

In terms of the wider environmental impacts, the “global toxicity debt”, whereby plastics in the environment become more toxic over time due to fragmentation and chemical leaching, represents a potentially significant but still largely unquantified threat to ecosystem health (76).

Impact of climate change on the generation and distribution of plastic pollution

Similar to plastic pollution, climate change is a complex phenomenon that operates across multiple spatial and temporal scales, via a combination of pulsed extreme events (e.g., wildfires, droughts, floods, and storms) overlain on more gradual progressive changes (e.g., global warming and ocean acidification). Its impact also spans all levels of chemical and biological organization, from molecules to ecosystems and ultimately the entire global biosphere, with significant scope for interactions with plastic pollution, both in terms of the latter’s generation and distribution, but also in terms of modulating its biological impact (Figure 2), as discussed in the following sections.

Increased temperature, UV intensity, and humidity in a warming climate will intensify weathering by accelerating polymer degradation via oxidation, photodegradation, and hydrolysis (77–79), which enhance embrittlement and surface cracking, accelerating fragmentation and MP release (80, 81). A 10°C rise in temperature could double plastic degradation rates (82), with humidity and UV exposure further accelerating polymer degradation (82–84). Increased irradiation can accelerate the leaching of hazardous products (85), while warming can enhance the sorption and potential mobilization of contaminants into/from plastics (86–92). These interactions are often scale-dependent, and commonly interlinked with the level at which biological impacts are manifested: at larger temporal and spatial scales there is often a corresponding increase in biocomplexity, with larger-scale drivers and responses coming increasingly into play as we move from individual organisms to entire ecosystems (93) (Figure 2).

Within terrestrial habitats and ecosystems, at local to regional scales, droughts and wildfires are widely predicted to increase in frequency, duration, and intensity under climate change (94, 95). These extreme events have the potential to release large amounts of polymeric materials and toxicants from urban areas (96), many of which are also situated on floodplains. The latter ecotones are important terrestrial–aquatic conduits that ultimately connect with the global ocean, and MPs will be transformed by and interact with a wide range of biota and abiotic variables as they move across space and time and through the food web.

At the other extreme of the hydrological gradient associated with climate change, storms and floods operate at a similar scale to wildfires and have the potential to generate and mobilize plastic pollution via aquatic ecosystems. The rate of input and fragmentation of plastic debris from terrestrial and freshwater systems into coastal and oceanic regions, and vice versa, can be dramatically amplified by extreme storm events (97–99). For example, beach sediment concentrations in Hong Kong increased nearly fortyfold after a typhoon (100), and inshore freshwater (55, 101–103) has also exhibited marked increases following heavy rainfall (55, 102).

Flooding associated with extreme weather events and longer-term sea-level rise can (re)mobilize plastic debris trapped in coastal sediments (29, 104–109). The majority of discarded plastics end up in landfills and open dumps (110), which are especially susceptible to flooding and erosion as they are commonly positioned on low-value, low-lying flood or coastal plains close to urban centers (111). A study in the United Kingdom predicted that the erosion of just one waste cell could release up to 3,860 tons of plastics into the Thames estuary (111). The (re)mobilization of MPs is therefore likely to be especially prevalent in populous, low-lying regions dominated by floodplains (112, 113): for instance, in a recent study, Bangladesh was found to

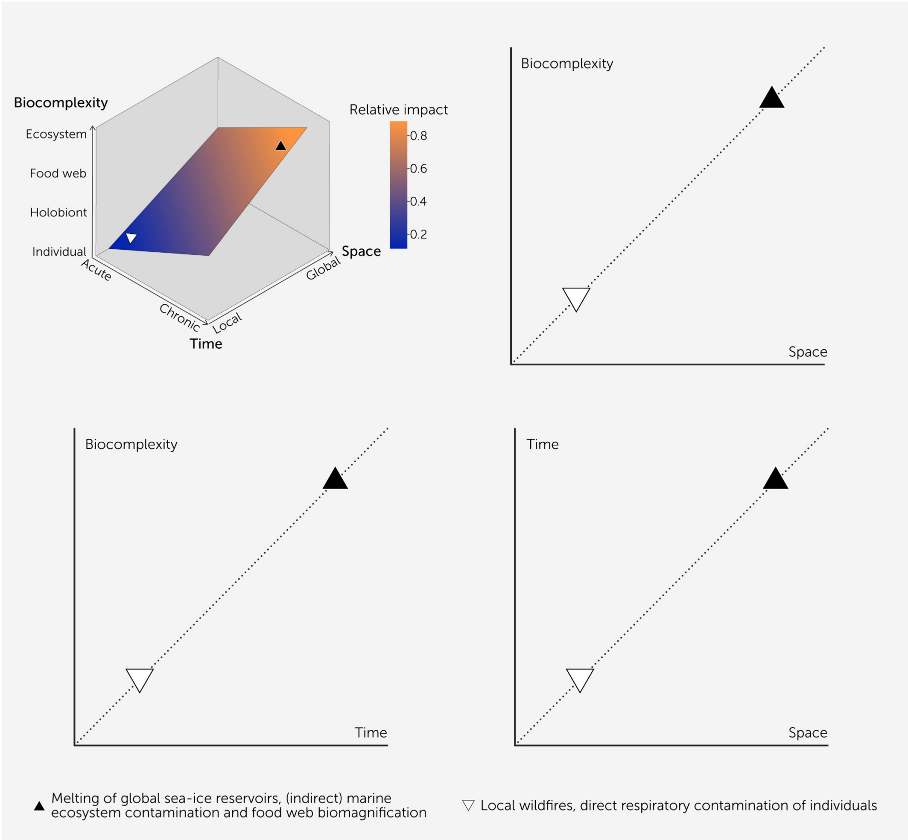

FIGURE 2
Schematic of the three dimensions across which climate change and plastic pollution operate. An illustrative figure showing the general pattern of how spatial and temporal scaling and organizational complexity commonly co-vary in most studies to date. These tend to be small and simple, with far fewer that capture the relevant scales and levels of biocomplexity in the field. These three dimensions (i.e., space, time and biological organization) are often strongly correlated (as shown by the exemplars denoted by the triangle symbols), although exceptions can potentially arise under certain conditions (e.g., the localized but long-term impacts of bioaccumulation on long-lived sedentary organisms in urban hotspots).

have the highest (>40 times) increase in plastic mobilization during floods (113). Novel plastic-rock complexes, which are thought to have been generated following a major flood in China (114), were identified as hotspots for further microplastic generation, with rates 4–5 orders of magnitude higher than those in landfills (115).

Moving further out to sea and increasing in scale over time and space, persistently stronger winds and changes in ocean currents and circulation patterns in a warming atmosphere (116, 117) will affect the abundance, transport, and redistribution of microplastic particles (118). High wind speeds and stronger waves increase the vertical mixing of plastic debris within the upper water column (52, 119), while previously settled debris in coastal sediments may be remobilized in the pelagic zone (120). Correlations between wind speed and the abundance of coastal MPs have been reported recently at local to regional scales (121), while surface circulation and field data have revealed the transfer of debris at oceanic scales (122).

In the global ocean, long-term sea-ice formation scavenges and concentrates man-made particulates from the water column (123). This creates a significant historic microplastic sink (124, 125), which could ultimately switch to becoming a major source as the ice melts due to global warming (126–129), although the scale of these potential future inputs is still unknown (105).

There is clearly scope for complex feedback loops to emerge between the biotic and abiotic drivers and responses to these stressors: for instance, suspended plastic particles in the global ocean, through interactions with phytoplankton and microbes, could have further potential impacts on climate by compromising carbon sequestration from the atmosphere (130), with some evidence suggesting that materials leached from plastic particles can indeed impair the photosynthetic efficiency of microalgal species (131, 132). Interactions with microbes in the lipid-rich sea surface layer could modify CO_2 uptake in the ocean (133) and change the rate of carbon export to the deep sea as a consequence of more buoyant fish-produced fecal pellets containing plastic particles (134). Changes in both surface and deep-water ocean circulation predicted under future climate change could therefore have far-reaching implications for plastic pollution and how it interacts with biota on large scales in time and space. Given that plastic pollution impacts are concentration-dependent, it is unlikely that the full scope of potential impacts is already manifesting at current levels, but rather it is probable that these impacts are concentrated in hotspots, with the potential to exceed thresholds more widely in the future under business-as-usual scenarios.

Climate–plastic interactive effects

We now know that climate change stressors, individually and in combination, can have profound implications for (and feedback with) biological systems. The last 20 years have focused particularly on how warming alters individual metabolism, which ultimately sets the pace for life and drives biological processes from the molecular to the ecosystem levels of organization. A large body of metabolic theory, underpinned by growing empirical and experimental evidence, has identified temperature as a master variable that sets the pace of life, and this is now relatively well understood (75, 135). Traits that make certain types of organisms and systems especially vulnerable to warming appear to align with those associated with plastic pollution, with the strongest effects often seen among larger organisms high in the food web and in aquatic ecosystems (136).

However, how climate change interacts with other stressors, and plastics in particular, is less well understood. Nevertheless, there is growing evidence that such interactions will probably be commonplace and rarely simply additive. Antagonistic or synergistic effects, which are less or more than the sum of their parts, respectively, appear to be the rule rather than the exception (137). In the case of interactions with plastics, climate change may affect their bioaccumulation and (eco)toxicity to biota due to weathering, leaching, the emission of transformation products and the provision of novel substrates. The impacts of micro- and nanoplastics in the context of climate change has focused on lower organizational levels (individuals and populations) versus multispecies systems (communities, food webs, and ecosystems) and under laboratory rather than field conditions (138). However, as with the physical and chemical interconnections between climate change and plastic pollution, biotic impacts will also be strongly dependent on temporal and spatial scales and will differ between aquatic and terrestrial systems.

Combined impacts of climate change and plastic pollution on terrestrial and aquatic ecosystems

Agricultural systems and crop yield

In agricultural systems, heat stress (139) and microplastic pollution from mulch films can impair nitrogen cycling and reduce crop yields (140). The combination of heatwaves and MPs was found to reduce rice production and quality and increase leaching of MPs in soil, causing impaired nitrogen metabolism (141). In another study, the combined effects of elevated CO_2 and plastic pollution were found to inhibit the nutrient uptake of rice (142). In a laboratory study involving soil inoculated with different fungal strains, warming combined with the addition of plastic microfibers was found to decrease the percentage of water-stable aggregates and eliminate the positive effects of rising temperature in 80% and 60% of strains respectively (143). Another study suggested that although MPs can affect maize health, soil quality, and ecosystem multifunctionality, these effects are not necessarily exacerbated by warming (144). Moreover, plastic microfibers were not found to amplify the negative effects of drought on the productivity of natural plant communities in temperate grassland ecosystems (145), the above-ground biomass of *Allium cepa* (146), or soil ecosystem functions (147). There may therefore be a level of contingency linked to crop type—possibly linked to underlying species-specific thermal performance curves—that merits further investigation.

Freshwater ecosystems

The interactive effects of MPs and other global warming factors have the potential to be especially potent in freshwater, an ecosystem that is already particularly vulnerable to the individual effects of both climate change and pollution (135, 148). A recent study at the base of the food web revealed that tire-derived leachate and warmer temperatures, both separately and in combination, enhanced the growth of duckweed and microbes in its microbiome but at the same time disrupted the underlying plant–microbiome mutualism (149). A comprehensive study of the freshwater alga *Scenedesmus obliquus* used full-factorial screening, with multiple concentrations of nanoplastics, CO_2, temperature and light intensity to evaluate 2000 + combinations across current, predicted future, and extreme conditions (150): concentration-dependent inhibition of growth was consistent in the presence of nanoparticles but this was attenuated by elevated CO_2 and warmer temperatures. With combined exposure to global warming events and microplastic pollution on carbon and nitrogen storage of the marine diatom, *Phaeodactylum tricornutum* revealed enhanced growth and increased rates of nitrogen uptake (151): metabolomics and transcriptomic analyses of this model species revealed that MPs and warming mainly promoted fatty acid metabolism, the urea cycle, glutamine and glutamate production, and the tricarboxylic acid cycle due to increased 2-oxoglutarate levels.

At the next trophic level, keystone primary consumers that shape the “green pathways” in freshwater food webs, such as the zooplankter *Daphnia magna*, manifested exacerbated toxicity following exposure to microplastic pollution under thermal stress (152–154). The responses of this model species included increased mortality, reduced fecundity and reduced population growth rates, and these impacts generally increased with temperature (152, 154). Another study showed how warming impacts can switch from masking (antagonistic) effects to amplification as plastic concentrations rise (155). Others found limited or no thermal impacts on microplastic toxicity in *D. magna* (156–158). Within the detrital “brown pathways” of the food web warming can alter the effect of MPs on the metabolic rate of benthic invertebrate detritivores (159). Other studies on primary consumers at the base of the food web (such as deposit-feeding midge larvae and filter-feeding mussels) reported that climatic stressors (e.g., elevated temperatures and salination) (160, 161) can interact antagonistically with MPs.

Given the potential for both stressors to have stronger effects on larger organisms, we might expect to see more intense effects higher in the food web. Indeed, the increased toxicity of nano- and MPs at warmer temperatures was recently reported in freshwater fishes (162–164). Synergistic responses between nanoplastics and temperature can increase toxicity via histopathological changes and DNA damage (162), alter circadian rhythm, and cause brain damage (163). In Nile tilapia, a common tropical fish species and a major aquaculture resource for human consumption, warmer temperatures were found to increase both ingestion of and toxicity from MPs (164).

Marine ecosystems

Marine ecosystems share many of the features of freshwater that also shape responses to warming and plastic pollution, including size-structured food webs dominated by ectotherms and the ability of consumers, resources, and pollutants to move across three dimensions (165, 166). There are also some important differences, however, in terms of ecosystem size, the potential for thermal inertia, pollutant dilution, and nutrient limitation, all of which are typically far more pronounced in the marine realm (93). Large-scale oceanic circulation patterns, along with the greater size and longevity of organisms at the top of the food web (typically several orders of magnitude greater than in freshwater), affect sensitivity to climate change and plastic pollution. Even within marine ecosystems the biotic, chemical, and physical environments differ markedly among habitat types and across latitudes, with shallow tropical reefs having orders of magnitude more biodiversity and productivity than the deep open ocean. At higher trophic levels, sensitivity to multiple stressors, including MPs combined with warming, can also differ among even closely related organisms within coral reefs (167–171): for instance, increased heterotrophy was seen in some coral species following thermal stress, and subsequent bleaching affected MP ingestion but was not evident in other species (168). Reduced photosynthetic activity in *Acropora* spp. exposed to microplastic fibers at ambient temperature showed no additional response under warming (169), whereas plastic pollution when combined with ocean warming and acidification led to upregulation of immunity in another coral species (171). Laboratory experiments demonstrated that sea anemones can ingest a range of plastic microfibers (172) and these are retained longer in consumers that have been bleached (a stress response to warming). Higher still in the food web, a recent study found that the survival of coral reef fish declined with exposure to either MPs or dead coral, but there was no evidence of synergistic effects in this case study (138).

At higher latitudes, the exposure of pteropod “sea snails,” which ultimately transport carbon to the interior of the Southern Ocean (173, 174), to nanoplastics compromised their ability to counteract ocean acidification (OA stress), leading to elevated mortality (175). In Northern temperate waters, sea urchins are keystone species in kelp forests (176, 177), echoing their functional significance in tropical coral ecosystems (176), and experiments with the former (*Paracentrotus lividus*) exposed to decreased pH (178) and increased temperature (179) revealed that MPs aggravate the suppression of growth and development caused by climate stressors. In contrast, microbial taxa (bacteria and algae) species that are lower in the food web appeared to be relatively insensitive to microplastic pollution under OA (178). Our understanding of the full scope of responses of these taxa and their associated plant or animal holobionts is currently limited, but new technologies suggest that they have great potential as bioindicators of multiple stressors (180).

Filter-feeding marine mussels were found to be very effective at concentrating particulates extracted from the water column, with these intermediate consumers providing a gateway into the wider food web and acting as another form of ecosystem engineer (181). The combination of MPs and OA was found to significantly inhibit their digestive enzymes (182), with polystyrene nanospheres impairing digestion (183), metabolic rate, and immune competence under hypoxia (184).

At higher trophic levels, MP-induced mortality among gobies quadrupled with a rise of just 5°C in water temperature (185). Microplastic levels in predatory Atlantic cod, which sit above smaller fishes such as gobies in the food web, reflected a shift in diet from fish to benthic invertebrates under differing levels of hypoxia: the proportion of cod with MPs in their digestive tract more than doubled when switching from feeding on the latter to the former, suggesting a potential biomagnification pathway mediated by climate change and plastic pollution (186).

Above the food web level of organization, the functioning of estuarine and marine ecosystems, which support significant cycling of carbon, nitrogen, and phosphorus (187–191), can be sensitive to the interactive effects of plastic pollution and climate change. For instance, high concentrations of plastic pollution were found to slow decomposition rates of coastal kelp and eelgrass detritus, whereas the opposite was observed at higher seawater temperatures (192). Decomposition rates in the presence of ocean warming, when combined with plastic pollution, did not differ from control conditions, i.e., both had strong individual effects, but masking occurred in combination.

Impact summary

Although there is still a shortage of studies quantifying the interactive impacts of climate change and microplastic pollution that span both spatiotemporal scales and organizational levels, some broad patterns appear to be emerging. For instance, certain traits of species and ecosystem types have the potential to experience exacerbated impacts when both stressors occur together, especially among large, long-lived organisms at the top of (aquatic) food webs. The metabolic constraints, together with the capacity for bioconcentration, bioaccumulation, and biomagnification of toxins (and of associated compounds that adsorb to particulate surfaces), as well as the strong correlation between body size and trophic status, and the prevalence of top-down control in many aquatic food webs, suggest that apex predators could suffer the most from the joint effects of these stressors. These species are also the most sensitive to extreme events, in addition to the more incremental effects of global warming. Thus, again, there is good reason to expect a convergence of impacts. In aquatic systems in general, and especially in the pelagic zone, food webs are largely structured based on gape-limitation constraints on the size of particles (or prey) ingested by consumers (93, 166)—so MPs and smaller particles have the potential to enter via multiple direct and indirect pathways. Some filter-feeding species, such as bivalves, are very effective "bioconcentrators" at intermediate trophic levels and act as conduits for pollutant transfer between pelagic and benthic habitats. Many bivalves, similar to top predators, are also often keystone species or ecosystem engineers that shape species interactions and habitats in which they operate, so any impairment to their functional roles has the potential to ripple through the wider food web. Species of global conservation concern tend to be even higher up the food chain and have a longer lifespan than either invertebrates or fish (e.g., *Orcinus orca* and other marine mammals), and these may be among the most vulnerable species on the planet to intensifying plastic pollution and climate change. The combination of both strong response and effect traits indicates that these species are likely to be especially promising bioindicators of the impact of both stressors. In contrast, species lower in the food web appear much less sensitive to these stressors and some even exhibit positive responses (e.g., via elevated nutrient turnover and increased surface areas favoring microbial biofilm growth, or via release from top-down control by larger consumers).

In terms of broader ecosystem-level processes driven by more basal species, such as microbial primary productivity and decomposition rates, there also appears to be some scope for masking to occur, with warming accelerating overall vital rates via elevated metabolism, but with plastic pollution exerting a retarding effect. The underlying impacts of plastic pollution may be obscured here, such that net effects may be antagonistic to those driven by elevated temperatures. This requires further study, but recent meta-analyses have suggested that warming can indeed mask the effects of other local stressors (137).

The majority of ecological concerns have focused on aquatic systems because this is where these plastics were first detected as pollutants. Having already been exposed to repeated breakdown and fragmentation processes prior to reaching aquatic ecosystems, the smallest plastic particles are particularly prevalent, relative to larger fragments, and hence should be more readily available for direct uptake into the food web. In terrestrial ecosystems, the impacts may therefore be markedly different and potentially much weaker (for a given total plastic concentration), although this is where most plastic pollution originates. If particles are less mobile and larger, they should be less prone to direct consumption by multiple consumers within the food web. Since chemical, physical, and microbial processing and *in situ* transformation are more likely to predominate here, understanding the processes at the base of the food web will likely be especially critical for predicting future impacts.

The combined impacts of pollution and climate change in terrestrial ecosystems are likely to be far more contingent and difficult to predict than in aquatic systems, where simpler sets of ecological rules seem to apply. Terrestrial ecosystems are typically more complex, with a greater range of species interactions and habitat types, and responses are therefore harder to predict, especially since many of those associated with high levels of plastic pollution have also been heavily modified under agriculture or urbanization. A growing body of research has revealed that climate change–plastic interactions range from antagonistic to additive and synergistic, but more work needs to be done to disentangle how, when, where and why these different impacts are manifested and whether there are clear typologies associated with artificial (agricultural and urban) versus natural systems and with the aquatic versus terrestrial realms.

Discussion

Of the numerous anthropogenic pressures that are being exerted on ecosystems globally, plastic pollution and climate change are potentially the most pressing, particularly, when they co-occur as joint stressors. Ample evidence now exists that climate change conditions are contributing to the conversion of plastics into highly persistent and ubiquitous contaminants that are continually accumulating in the natural environment. The potential impacts of this are far-reaching, encompassing geophysical and biological systems. Investigations into the ecotoxicity of plastic pollution under climate change are still in their infancy, but there is a plethora of studies that have already demonstrated interactive effects in terrestrial, freshwater, and marine ecosystems, and they suggest that these become stronger at higher trophic levels.

Solutions

The rational response to confront the potential for poorly reversible negative impacts to occur through the increased generation, mobility and toxicity of MPs is to rapidly and meaningfully reduce the emissions of plastic pollution into the environment. The efforts required to achieve this are extraordinary and require significant societal, economic, and commercial shifts (193). Therefore, it is reassuring that the consensus is that this is a largely avoidable environmental problem, insofar as the benefits of plastics to the environment and society can be retained without the need for end-of-life plastics to accumulate in the environment (194). This requires an international and coordinated approach, encompassing the manufacturing industry, sectors (including consumers) using plastics, waste management services, environmental organizations, activists, regulatory authorities, governments, world leaders, investors, and the research community in both plastics and the environment (Figure 3). The world is already responding on an impressive scale, with examples, including grassroots action (195), globally active charities, for example the Ellen MacArthur Foundation (196), national-level product bans (197), initiatives to support the management of hazardous plastic waste (198) and public–private partnerships for waste management, including the Alliance to End Plastic Waste. However, the biggest achievement and greatest hope for success would be to establish an international, legally binding Global Plastics Treaty to end plastic pollution by transforming the way it is sourced, produced, used, and disposed of (23). Unfortunately, the latest round of negotiations in

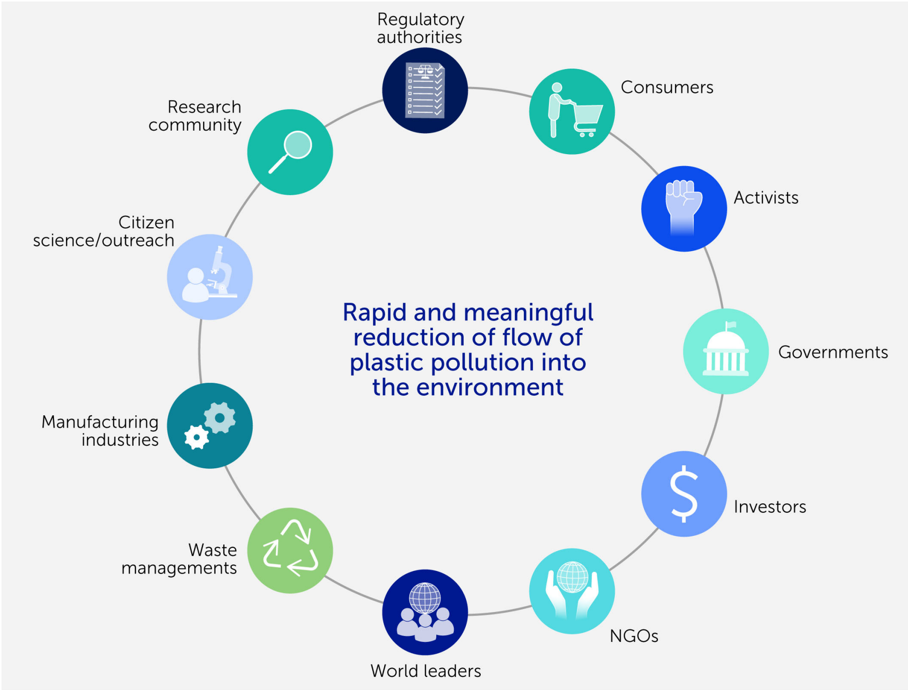

FIGURE 3
Key stakeholders in the transformation of the way plastics are produced, consumed and disposed of.

Geneva in August 2025 failed to produce the Treaty, as deep disagreements, particularly over whether to cap plastic production and regulate toxic additives, led to a breakdown of consensus despite the presentation of two draft texts. Negotiations were adjourned, to be resumed at an undetermined future date (199).

Key policies and solutions to achieve systemic change must harness the same enthusiasm that made plastics into a core material of the modern world in the first place. This not only includes the three *Rs*—*reduce, reuse*, and *recycle*—advocated on the first Earth Day in 1970, but also more recent *Rs*, such as *redesign*, *rethink*, and *refuse* (as in to say "no"), alongside *eliminate*, *innovate*, and *circulate*. These stem from the transition from a linear take-waste-make model to a more circular economy for plastics (Ellen MacArthur Foundation, 200, 201; Figure 4). All these terms call for a reduction or elimination of unnecessary single-use plastics, in addition to setting global limits on the production and consumption of virgin plastics, i.e., the most efficient and cost-effective solutions to microplastic pollution (202). Similar to cleaning up an oil spill, prevention by curtailing plastic production and promoting circulation of products that cannot be eliminated is best, followed by containment before it reaches the environment and finally cleanup of legacy litter and ecological restoration. However, reducing demand for virgin polymers is being challenged by the fossil fuel industry. Oil companies are confronting the clean energy/transportation transition by shifting investment toward petrochemicals to produce more plastics (203).

A recent perspective laid out ways to identify and uproot the deep-seated lock-ins [i.e., "technological, institutional, and behavioral phenomena that collectively hinder transformative change" (13)] designed to sustain the petrochemical industry (13). Priority must also be given to the creation of globally aligned standards for commodity plastics that are practically safe (i.e., eliminating hazardous chemicals), and reusable and recyclable by design, to keep them in the economy and out of the environment. Policies also call for the development and scaling of internationally coordinated strategies and targets for plastic processing, recycling technologies, and waste management. However, transformative shifts must take a multidimensional approach based on robust scientific evidence to evaluate any negative impact they may have on economies, social justice, the environment and human health (204). Waste-to-energy processing, despite reducing plastic waste volumes, increases GHG emissions and may cause human health impacts via toxic emissions, thereby creating social injustice (205, 206). The environmental implications, including the hindering of efforts to tackle climate change, of replacing conventional plastics with alternatives, be they non-plastic materials (26, 27), biodegradable formulations (207), or products made from plastic waste collected from the environment, must be carefully considered alongside possible advantages.

Efforts to contain plastics and cleanup of legacy litter have spawned numerous remediation technologies, ranging from household wastewater filters and laundry balls to large-scale booms, receptacles, and watercraft vehicles (208–210). While these efforts may have value in key hotspots including heavily polluted harbors, and beaches, crucial knowledge gaps remain regarding the state, transport, and fate of plastics (211, 212), along with concerns and challenges. Concerns include environmental consequences during collection and subsequent

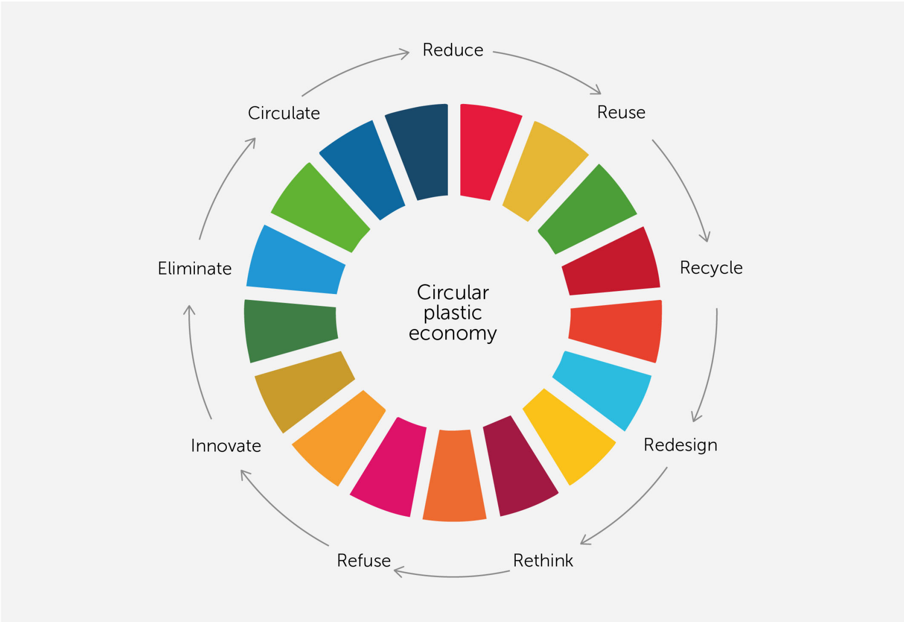

FIGURE 4
Policies and principles for the transition from a linear to a circular plastic economy.

disposal, equity, and justice; scientific validation; greenwashing; and distraction from efforts to stem the flow of waste at the source (208–210). There is also the danger of more plastics being discarded into the environment if local communities wrongly perceive that cleanup technologies are solutions to remove them. Challenges include deployment location, scalability, efficiency, and associated costs when attempting to combat such a vast and complex problem. These issues have called for standardized, science-based assessment criteria and legislation to monitor the environmental impact and associated costs of these technologies (213) in addition to a framework to help stakeholders choose the most efficient and sustainable cleanup system (214).

Bioremediation, which leverages the biology of naturally occurring organisms to degrade MPs, represents a potentially more sustainable, affordable, and environmentally friendly strategy to help manage plastic pollution in aquatic and terrestrial systems (215–217). Microbes, including several bacteria and fungi, can enzymatically (through hydrolysis, oxidation, and hydroxylation) break down MPs into monomers that can be further metabolized or mineralized into CO_2, nitrogen, methane, and water molecules, monomers, dimers, and oligomers (218). Biofilms are also considered potential candidates as they create an environment that protects microorganisms from harsh environmental conditions while promoting plastic degradation (219, 220). In contrast, microalgae-based bioremediation relies on adsorptive actions and physical entanglement (221). Phytoremediation is a plant-based bioremediation strategy, involving the uptake and accumulation of MPs in the tissues of plants such as seagrass and macrophytes (222). Although bioremediation is feasible, significant challenges remain that limit its practical application (223, 224). The main ones are low efficiency (slow pace and often incomplete mineralization), substrate specificity exhibited by microorganisms, optimization of environmental conditions, scalability, potential ecotoxicity, lack of standard methodologies/metrics, and an evolving regulatory landscape. Technological advances such as gene-editing tools (e.g., introducing or enhancing specific enzymes) and synthetic biology (e.g., creating novel organisms specifically tailored to degrade certain types of MPs) continue apace, however, offering potential enhancement in the plastic-degrading capabilities of naturally occurring organisms.

Future research directions

The full scope of the forms and exposure concentrations of small plastic particles that induce harmful effects in aquatic, terrestrial, and atmospheric environments is unknown: nonetheless, these pollutants may have already exceeded impact thresholds in sensitive hotspots. Challenges to our understanding arise from the heterogeneity and chemical complexity of naturally aged MPs and their ability to interact with physical stressors. In addition, an accurate assessment of exposure concentrations is compounded by the continuous fragmentation of plastics in the environment—it is predicted that even if the emission of larger plastic items to the environment were to stop immediately, we would likely still see an increase in the quantity of microplastics as a consequence of the fragmentation of larger items that are already in the environment (225). Since the influence of climate change has the potential to be significant, more realistic exposure scenarios are needed to better understand the threat posed by plastic pollution in the environment owing to the impacts of weathered plastics on biogeochemical cycling and its ecotoxicity (6). Many of the studies identified in this review utilized pristine macro/nanoplastic particles purchased from suppliers. It remains to be seen whether similar results will be generated in carefully designed laboratory and field studies that use real-world particles. A greater understanding of the mechanisms and products of polymer degradation under different climate conditions is needed to detect and ultimately predict environmental hazards. Approaches that can successfully extrapolate from short-term experiments to forecast long-term degradation pathways will be particularly valuable given the longevity of plastics (226). *In situ* experimental studies and observations carried out over long periods of time could supply modeling tools with the means to project future scenarios of the interactive effects in complex, multi-stressor environments.

Public understanding

Education and awareness of the problems produced by plastic pollution are important steps toward shifting behavior from using and throwing away to reducing, reusing, repurposing, and recycling. Therefore, it is encouraging that the public views plastics to be not only a serious issue for the environment but also for health, despite the risks to humans from MPs having not yet been demonstrated (227, 228). In a survey conducted in Australia to examine beliefs and attitudes, 80% of respondents showed a desire to reduce plastic use, and issues relating to plastics in the oceans and waste production/disposal received the highest mean rating for seriousness out of nine environmental issues (229). Reasons for this sensitivity may relate to several factors. For example, the view that plastic pollution is unequivocally due to human actions, decisions, and behavior (230), and that marine debris is clearly visible in coastal areas and has a measurable negative effect on people's well-being (231, 232) spurs increasing concern over exposure to plastic-associated chemicals (233). This creates fewer "plastic pollution deniers" compared to "climate change deniers." Largely missing from the public understanding of plastic pollution are more granular issues such as the effects of a warming climate on the abundance, distribution, exposure, and hazards of plastics in the environment, along with the potential for delayed ecotoxicological effects due to weathering-related degradation. Issues such as those discussed in this review may generate new opportunities by building on the success of mobilizing action on plastics in a way that acts as a gateway to the issue of climate change. However, awareness alone of the magnitude of the problems produced by plastic debris is unlikely to change individual behavior. Firsthand access to the issue is key since from access comes attention, from attention comes engagement and this is what galvanizes society to take an interest in the world. Further encouragement therefore stems from citizen science and outreach activities that are focused on plastic pollution (234) and successful educational initiatives with children (235) who, being the next generation of consumers, will face the long-term consequences of our current actions. Public participation can also collect data for research, one example being the lightweight, low-cost paddle trawl towed behind paddle surfers and designed to collect samples to characterize and quantify MPs in the marine environment (236).

Conclusion

A warming climate has consequences for the abundance, distribution, exposure, hazards, and impacts of plastics in the environment. Further examination of these links will help our understanding of and ability to manage the risks. The integration of micro- and nanoplastic pollution with climate stressors offers a way to steer, coordinate, and prioritize research and monitoring, in addition to policy and action. While comparability of methods is critical, and rigorous examination of the science being published is critical in all fields of research, it is of particular importance in this complex and evolving field because policy around plastic pollution is being developed in tandem. The future will not be free of plastics but going forward, it must become free of further microplastic pollution. The prospect that the plastics we produce, use and discard today could have global-scale, poorly reversible impacts in the future is compelling motivation to take the appropriate action now.

Statements

Author contributions

FJK: Writing – original draft, Supervision, Methodology, Conceptualization, Project administration, Funding acquisition.

SLW: Funding acquisition, Conceptualization, Methodology, Writing – review & editing.

GW: Conceptualization, Writing – review & editing.

JCF: Investigation, Conceptualization, Project administration, Writing – original draft, Visualization.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

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References

1. World Meteorological Organization. *State of the global climate 2024*. Geneva: WMO (2024). Available at: https://wmo.int/publication-series/state-of-global-climate-2024

2. Global Carbon Project. *Figures from the Global Carbon Budget 2024*. Robbie Andrew - Github (2024). Available at: https://robbieandrew.github.io/GCB2024/

3. Plastics Europe. Plastics – the fast facts 2024. *Plastics Europe* (2025). Available at: https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2024/

4. Rocque RJ, Beaudoin C, Ndjaboue R, Cameron L, Poirier-Bergeron L, Poulin-Rheault RA, et al. Health effects of climate change: an overview of systematic reviews. *BMJ Open* (2021) 11(6):e046333. doi: 10.1136/bmjopen-2020-046333

5. World Health Organization. Climate change [online] (2023). Available at: https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health

6. MacLeod M, Arp HPH, Tekman MB, Jahnke A. The global threat from plastic pollution. *Science* (2021) 373(6550):61–5. doi: 10.1126/science.abg5433

7. Limonta G, Mancia A, Benkhalqui A, Bertolucci C, Abelli L, Fossi MC, et al. Microplastics induce transcriptional changes, immune response and behavioral alterations in adult zebrafish. *Sci Rep* (2019) 9(1):15775. doi: 10.1038/s41598-019-52292-5

8. Stafford R, Jones PJS. We should not separate out environmental issues, but the current approach to plastic pollution can be a distraction from meaningful action. A response to Avery-Gomm et al. *Mar Policy* (2019) 107:103585. doi: 10.1016/j.marpol.2019.103585

9. Backhaus T, Wagner M. Microplastics in the environment: much ado about nothing? A debate. *Glob Chall* (2020) 4(6):1900022. doi: 10.1002/gch2.201900022

10. Villarrubia-Gómez P, Carney Almroth BC, Eriksen M, Ryberg M, Cornell SE. Plastics pollution exacerbates the impacts of all planetary boundaries. *One Earth* (2024) 7(12):2119–38. doi: 10.1016/j.oneear.2024.10.017

11. Ford HV, Jones NH, Davies AJ, Godley BJ, Jambeck JR, Napper IE, et al. The fundamental links between climate change and marine plastic pollution. *Sci Total Environ* (2022) 806(1):150392. doi: 10.1016/j.scitotenv.2021.150392

12. Client Earth. Fossil fuel and plastic: what's the link? – we ask our lawyers [online] (2021). Available at: https://www.clientearth.org/latest/news/fossil-fuel-and-plastic-what-s-the-link-we-ask-our-lawyers/

13. Tilsted JP, Bauer F, Deere Birkbeck C, Skovgaard J, Rootzén J. Ending fossil-based growth: confronting the political economy of petrochemical plastics. *One Earth* (2023) 6(6):607–19. doi: 10.1016/j.oneear.2023.05.018

14. European Environment Agency. *Plastics, the circular economy and Europe's environment — A priority for action*. Copenhagen: EEA (2021). Available at: https://www.eea.europa.eu/en/analysis/publications/plastics-the-circular-economy-and

15. International Energy Agency. *The future of petrochemicals. Towards more sustainable plastics and fertilisers*. Paris: IEA (2018). Available at: https://www.iea.org/reports/the-future-of-petrochemicals

16. Zheng J, Suh S. Strategies to reduce the global carbon footprint of plastics. *Nat Clim Change* (2019) 9(5):374–8. doi: 10.1038/s41558-019-0459-z

17. Organisation for Economic Co-operation and Development. *Climate change and plastics pollution. Synergies between two crucial environmental challenges*. Paris: OECD (2023). Available at: https://www.oecd.org/en/publications/climate-change-and-plastics_5e0bfe87-en.html

18. Cabernard L, Pfister S, Oberschelp C, Hellweg S. Growing environmental footprint of plastics driven by coal combustion. *Nat Sustain* (2022) 5(2):139–48. doi: 10.1038/s41893-021-00807-2

19. Royer SJ, Ferrón S, Wilson ST, Karl DM. Production of methane and ethylene from plastic in the environment. *PloS One* (2018) 13(8):e0200574. doi: 10.1371/journal.pone.0200574

20. Revell LE, Kuma P, Le Ru EC, Somerville WRC, Gaw S. Direct radiative effects of airborne microplastics. *Nature* (2021) 598(7881):462–7. doi: 10.1038/s41586-021-03864-x

21. Li Y, Shao L, Wang W, Zhang M, Feng X, Li W, et al. Airborne fiber particles: types, size and concentration observed in Beijing. *Sci Total Environ* (2020) 705:135967. doi: 10.1016/j.scitotenv.2019.135967

22. Levermore JM, Smith TEL, Kelly FJ, Wright SL. Detection of microplastics in ambient particulate matter using Raman Spectral Imaging and chemometric analysis. *Anal Chem* (2020) 92(13):8732–40. doi: 10.1021/acs.analchem.9b05445

23. United Nations Environment Programme. End plastic pollution – towards an international legally binding instrument [resolution EA.5/Res.14]. Fifth session of the United Nations Environment Assembly (2022). Available at: https://digitallibrary.un.org/record/3999257?ln=en&v=pdf

24. Andrady AL, Neal MA. Applications and societal benefits of plastics. *Philos Trans R Soc Lond B Biol Sci* (2009) 364(1526):1977–84. doi: 10.1098/rstb.2008.0304

25. Yarsley VE, Couzens EG. *Plastics*. London: Penguin (1945).

26. Kouloumpis V, Pell RS, Correa-Cano ME, Yan X. Potential trade-offs between eliminating plastics and mitigating climate change: an LCA perspective on Polyethylene Terephthalate (PET) bottles in Cornwall. *Sci Total Environ* (2020) 727:138681. doi: 10.1016/j.scitotenv.2020.138681

27. Meng F, Brandão M, Cullen JM. Replacing plastics with alternatives is worse for greenhouse gas emissions in most cases. *Environ Sci Technol* (2024) 58(6):2716–27. doi: 10.1021/acs.est.3c05191

28. Landrigan PJ, Raps H, Cropper M, Bald C, Brunner M, Canonizado EM, et al. The Minderoo-Monaco commission on plastics and human health. *Ann Glob Health* (2023) 89(1):23. doi: 10.5334/aogh.4056

29. Axelsson C, Van Sebille E. Prevention through policy: urban macroplastic leakages to the marine environment during extreme rainfall events. *Mar pollut Bull* (2017) 124(1):211–27. doi: 10.1016/j.marpolbul.2017.07.024

30. Organisation for Economic Co-operation and Development. *Global plastics outlook: economic drivers, environmental impacts and policy options*. Paris: OECD (2022). Available at: https://www.oecd.org/en/publications/2022/02/global-plastics-outlook_a653d1c9.html

31. Organisation for Economic Co-operation and Development. *Global plastics outlook: policy scenarios to 2060*. Paris: OECD (2022). Available at: https://www.oecd.org/en/publications/2022/06/global-plastics-outlook_f065ef59.html.

32. Arp HPH, Kühnel D, Rummel C, MacLeod M, Potthoff A, Reichelt S, et al. Weathering plastics as a planetary boundary threat: exposure, fate, and hazards. *Environ Sci Technol* (2021) 55(11):7246–55. doi: 10.1021/acs.est.1c01512

33. Stubbins A, Law KL, Muñoz SE, Bianchi TS, Zhu L. Plastics in the earth system. *Science* (2021) 373(6550):51–5. doi: 10.1126/science.abb0354

34. Andrade J, Fernández-González V, López-Mahía P, Muniategui S. A low-cost system to simulate environmental microplastic weathering. *Mar pollut Bull* (2019) 149. doi: 10.1016/j.marpolbul.2019.110663

35. Cai L, Wang J, Peng J, Wu Z, Tan X. Observation of the degradation of three types of plastic pellets exposed to UV irradiation in three different environments. *Sci Total Environ* (2018) 628–629:740–7. doi: 10.1016/j.scitotenv.2018.02.079

36. Gewert B, Plassmann MM, MacLeod M. Pathways for degradation of plastic polymers floating in the marine environment. *Environ Sci Process Impacts* (2015) 17 (9):1513–21. doi: 10.1039/c5em00207a

37. Garnai hirsch S, Barel B, Segal E. Characterization of surface phenomena: probing early stage degradation of low-density polyethylene films. *Polym Eng Sci* (2019) 59(S1). doi: 10.1002/pen.24886

38. Rummel CD, Jahnke A, Gorokhova E, Kühnel D, Schmitt-Jansen M. Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment. *Environ Sci Technol Lett* (2017) 4(7):258–67. doi: 10.1021/acs.estlett.7b00164

39. Albertsson A-C, Karlsson S. The influence of biotic and abiotic environments on the degradation of polyethylene. *Prog Polym Sci* (1990) 15(2):177–92. doi: 10.1016/0079-6700(90)90027-X

40. Gewert B, Plassmann M, Sandblom O, MacLeod M. Identification of chain scission products released to water by plastic exposed to ultraviolet light. *Environ Sci Technol Lett* (2018) 5(5):272–6. doi: 10.1021/acs.estlett.8b00119

41. Shi J, Wu D, Su Y, Xie B. Selective enrichment of antibiotic resistance genes and pathogens on polystyrene microplastics in landfill leachate. *Sci Total Environ* (2021) 765:142775. doi: 10.1016/j.scitotenv.2020.142775

42. Ashton K, Holmes L, Turner A. Association of metals with plastic production pellets in the marine environment. *Mar pollut Bull* (2010) 60(11):2050–5. doi: 10.1016/j.marpolbul.2010.07.014

43. Rios LM, Moore C, Jones PR. Persistent organic pollutants carried by synthetic polymers in the ocean environment. *Mar pollut Bull* (2007) 54(8):1230–7. doi: 10.1016/j.marpolbul.2007.03.022

44. Barhoumi B, Sander SG, Tolosa I. A review on per- and polyfluorinated alkyl substances (PFASs) in microplastic and food-contact materials. *Environ Res* (2022) 206:112595. doi: 10.1016/j.envres.2021.112595

45. O'Brien S, Rauert C, Ribeiro F, Okoffo ED, Burrows SD, O'Brien JW, et al. There's something in the air: a review of sources, prevalence and behaviour of microplastics in the atmosphere. *Sci Total Environ* (2023) 874:162193. doi: 10.1016/j.scitotenv.2023.162193

46. Suzuki G, Uchida N, Tuyen LH, Tanaka K, Matsukami H, Kunisue T, et al. Mechanical recycling of plastic waste as a point source of microplastic pollution. *Environ pollut* (2022) 303:119114. doi: 10.1016/j.envpol.2022.119114

47. Hartmann NB, Hüffer T, Thompson RC, Hassellöv M, Verschoor A, Daugaard AE, et al. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. *Environ Sci Technol* (2019) 53(3):1039–47. doi: 10.1021/acs.est.8b05297

48. Rochman CM, Brookson C, Bikker J, Djuric N, Earn A, Bucci K, et al. Rethinking microplastics as a diverse contaminant suite. *Environ Toxicol Chem* (2019) 38(4):703–11. doi: 10.1002/etc.4371

49. Bläsing M, Amelung W. Plastics in soil: analytical methods and possible sources. *Sci Total Environ* (2018) 612:422–35. doi: 10.1016/j.scitotenv.2017.08.086

50. Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A, et al. Marine pollution. Plastic waste inputs from land into the ocean. *Science* (2015) 347 (6223):768–71. doi: 10.1126/science.1260352

51. Waldschläger K, Lechthaler S, Stauch G, Schüttrumpf H. The way of microplastic through the environment - Application of the sourcepathway-receptor model (review). *Sci Total Environ* (2020) 713:136584. doi: 10.1016/j.scitotenv.2020.136584

52. Kukulka T, Proskurowski G, Morét-Ferguson S, Meyer DW, Law KL. The effect of wind mixing on the vertical distribution of buoyant plastic debris. *Geophys Res Lett* (2012) 39(7). doi: 10.1029/2012GL051116

53. Isobe A, Kubo K, Tamura Y, Kako S, Nakashima E, Fujii N. Selective transport of microplastics and mesoplastics by drifting in coastal waters. *Mar pollut Bull* (2014) 89 (1–2):324–30. doi: 10.1016/j.marpolbul.2014.09.041

54. Zhao S, Wang T, Zhu L, Xu P, Wang X, Gao L, et al. Analysis of suspended microplastics in the Changjiang Estuary: implications for riverine plastic load to the ocean. *Water Res* (2019) 161:560–9. doi: 10.1016/j.watres.2019.06.019

55. Napper IE, Baroth A, Barrett AC, Bhola S, Chowdhury GW, Davies BFR, et al. The abundance and characteristics of microplastics in surface water in the transboundary Ganges River. *Environ pollut* (2021) 274:116348. doi: 10.1016/j.envpol.2020.116348

56. Allen S, Allen D, Moss K, Le Roux G, Phoenix VR, Sonke JE. Examination of the ocean as a source for atmospheric microplastics. *PloS One* (2020) 15(5):e0232746. doi: 10.1371/journal.pone.0232746

57. Brahney J, Mahowald N, Prank M, Cornwell G, Klimont Z, Matsui H, et al. Constraining the atmospheric limb of the plastic cycle. *Proc Natl Acad Sci USA* (2021) 118(16):e2020719118. doi: 10.1073/pnas.2020719118

58. Coffin S, Dudley S, Taylor A, Wolf D, Wang J, Lee I, et al. Comparisons of analytical chemistry and biological activities of extracts from North Pacific gyre plastics with UV-treated and untreated plastics using *in vitro* and *in vivo* models. *Environ Int* (2018) 121(1):942–54. doi: 10.1016/j.envint.2018.10.012

59. Gruber MM, Hirschmugl B, Berger N, Holter M, Radulović S, Leitinger G, et al. Plasma proteins facilitates placental transfer of polystyrene particles. *J Nanobiotechnol* (2020) 18(1):128. doi: 10.1186/s12951-020-00676-5

60. Koelmans AA, Bakir A, Burton GA, Janssen CR. Microplastic as a vector for chemicals in the aquatic environment: critical review and model-supported reinterpretation of empirical studies. *Environ Sci Technol* (2016) 50(7):3315–26. doi: 10.1021/acs.est.5b06069

61. Zhang D, Ng EL, Hu W, Wang H, Galaviz P, Yang H, et al. Plastic pollution in croplands threatens long-term food security. *Glob Chang Biol* (2020) 26(6):3356–67. doi: 10.1111/gcb.15043

62. Wang J, Lv S, Zhang M, Chen G, Zhu T, Zhang S, et al. Effects of plastic film residues on occurrence of phthalates and microbial activity in soils. *Chemosphere* (2016) 151:171–7. doi: 10.1016/j.chemosphere.2016.02.076

63. Huang Y, Zhao Y, Wang J, Zhang M, Jia W, Qin X. LDPE microplastic films alter microbial community composition and enzymatic activities in soil. *Environ pollut* (2019) 254(A):112983. doi: 10.1016/j.envpol.2019.112983

64. Ng EL, Lin SY, Dungan AM, Colwell JM, Ede S, Huerta lwanga E, et al. Microplastic pollution alters forest soil microbiome. *J Hazard Mater* (2021) 409:124606. doi: 10.1016/j.jhazmat.2020.124606

65. Coyle R, Hardiman G, Driscoll KO. Microplastics in the marine environment: a review of their sources, distribution processes, uptake and exchange in ecosystems. *Case Stud Chem Environ Eng* (2020) 2. doi: 10.1016/j.cscee.2020.100010

66. Chen X, Chen X, Zhao Y, Zhou H, Xiong X, Wu C. Effects of microplastic biofilms on nutrient cycling in simulated freshwater systems. *Sci Total Environ* (2020) 719:137276. doi: 10.1016/j.scitotenv.2020.137276

67. Lamb JB, Willis BL, Fiorenza EA, Couch CS, Howard R, Rader DN, et al. Plastic waste associated with disease on coral reefs. *Science* (2018) 359(6374):460–2. doi: 10.1126/science.aar3320

68. Wilcox C, Puckridge M, SchuyleR QA, Townsend K, Hardesty BD. A quantitative analysis linking sea turtle mortality and plastic debris ingestion. *Sci Rep* (2018) 8(1):12536. doi: 10.1038/s41598-018-30038-z

69. Karbalaei S, Golieskardi A, Hamzah HB, Abdulwahid S, Hanachi P, Walker TR, et al. Abundance and characteristics of microplastics in commercial marine fish from Malaysia. *Mar pollut Bull* (2019) 148:5–15. doi: 10.1016/j.marpolbul.2019.07.072

70. Huang W, Song B, Liang J, Niu Q, Zeng G, Shen M, et al. Microplastics and associated contaminants in the aquatic environment: a review on their ecotoxicological effects, trophic transfer, and potential impacts to human health. *J Hazard Mater* (2021) 405:124187. doi: 10.1016/j.jhazmat.2020.124187

71. Wang Q, Adams CA, Wang F, Sun Y, Zhang S. Interactions between microplastics and soil fauna: A critical review. *Crit Rev Environ Sci Technol* (2022) 52(18):3211–43. doi: 10.1080/10643389.2021.1915035

72. Chae Y, An Y-J. Nanoplastic ingestion induces behavioral disorders in terrestrial snails: trophic transfer effectsviavascular plants. *Environ Sci Nano* (2020) 7(3):975–83. doi: 10.1039/C9EN01335K

73. Zeytin S, Wagner G, Mackay-Roberts N, Gerdts G, Schuirmann E, Klockmann S, et al. Quantifying microplastic translocation from feed to the fillet in European sea bass Dicentrarchus labrax. *Mar pollut Bull* (2020) 156:111210. doi: 10.1016/j.marpolbul.2020.111210

74. MacLeod M, Breitholtz M, Cousins IT, De Wit CA, Persson LM, Rudén C, et al. Identifying chemicals that are planetary boundary threats. *Environ Sci Technol* (2014) 48(19):11057–63. doi: 10.1021/es501893m

75. Jackson MC, Pawar S, Woodward G. The temporal dynamics of multiple stressor effects: from individuals to ecosystems. *Trends Ecol Evol* (2021) 36(5):402–10. doi: 10.1016/j.tree.2021.01.005

76. Rillig MC, Kim SW, Kim TY, Waldman WR. The global plastic toxicity debt. *Environ Sci Technol* (2021) 55(5):2717–9. doi: 10.1021/acs.est.0c07781

77. Bolan S, Padhye LP, Jasemizad T, Govarthanan M, Karmegam N, Wijesekara H, et al. Impacts of climate change on the fate of contaminants through extreme weather events. *Sci Total Environ* (2024) 909:168388. doi: 10.1016/j.scitotenv.2023.168388

78. Grause G, Chien M-F, Inoue C. Changes during the weathering of polyolefins. *Polym Degrad Stab* (2020) 181. doi: 10.1016/j.polymdegradstab.2020.109364

79. Wei XF, Yang W, Hedenqvist MS. Plastic pollution amplified by a warming climate. *Nat Commun* (2024) 15(1):2052. doi: 10.1038/s41467-024-46127-9

80. Chang M, Zhang C, Li M, Dong J, Li C, Liu J, et al. Warming, temperature fluctuations and thermal evolution change the effects of microplastics at an environmentally relevant concentration. *Environ pollut* (2022) 292(A):118363. doi: 10.1016/j.envpol.2021.118363

81. Masry M, Rossignol S, Gardette JL, TheriaS S, Bussière PO, Wong-Wah-Chung P. Characteristics, fate, and impact of marine plastic debris exposed to sunlight: a review. *Mar pollut Bull* (2021) 171:112701. doi: 10.1016/j.marpolbul.2021.112701

82. Singh B, Sharma N. Mechanistic implications of plastic degradation. *Polym Degrad Stab* (2008) 93(3):561–84. doi: 10.1016/j.polymdegradstab.2007.11.008

83. Andrady AL, Hamid HS, Torikai A. Effects of climate change and UVB on materials. *Photochem Photobiol Sci* (2003) 2(1):68–72. doi: 10.1039/b211085g

84. Nagai Y, Ogawa T, Yu Zhen L, Nishimoto Y, Ohishi F. Analysis of weathering of thermoplastic polyester elastomers-I. Polyether-polyester elastomers. *Polym Degrad Stab* (1997) 56(1):115–21. doi: 10.1016/S0141-3910(96)00189-9

85. Liu P, Zhan X, Wu X, Li J, Wand H, Gao S. Effect of weathering on environmental behavior of microplastics: properties, sorption and potential risks. *Chemosphere* (2020) 242:125193. doi: 10.1016/j.chemosphere.2019.125193

86. Cooper JE, Kendig EL, Belcher SM. Assessment of bisphenol A released from reusable plastic, aluminium and stainless steel water bottles. *Chemosphere* (2011) 85(6):943–7. doi: 10.1016/j.chemosphere.2011.06.060

87. Al-Malack MH. Migration of lead from unplasticized polyvinyl chloride pipes. *J Hazard Mater* (2001) 82(3):263–74. doi: 10.1016/s0304-3894(00)00366-6

88. Fasano E, Bono-Blay F, Cirillo T, Montuori P, Lacorte S. Migration of phthalates, alkylphenols, bisphenol A and di(2-ethylhexyl)adipate from food packaging. *Food Control* (2012) 27(1):132–8. doi: 10.1016/j.foodcont.2012.03.005

89. Loyo-Rosales JE, Rosales-Rivera GC, Lynch AM, Rice CP, Torrents A. Migration of nonylphenol from plastic containers to water and a milk surrogate. *J Agric Food Chem* (2004). 52(7):2016–20. doi: 10.1021/jf0345696

90. Nam SH, Seo YM, Kim MG. Bisphenol A migration from polycarbonate baby bottle with repeated use. *Chemosphere* (2010) 79(9):949–52. doi: 10.1016/j.chemosphere.2010.02.049

91. Walter RK, Lin PH, Edwards M, Richardson RE. Investigation of factors affecting the accumulation of vinyl chloride in polyvinyl chloride piping used in drinking water distribution systems. *Water Res* (2011) 45(8):2607–15. doi: 10.1016/j.watres.2011.02.016

92. Zhan F, Zhang H, Cao R, Fan Y, Xu P, Chen J. Release and transformation of BTBPE during the thermal treatment of flame retardant ABS plastics. *Environ Sci Technol* (2019) 53(1):185–93. doi: 10.1021/acs.est.8b05483

93. Hagen M, Kissling WD, Rasmussen C, De Aguiar MA, Brown LE, Carstensen DW, et al. Biodiversity, species interactions and ecological networks in a fragmented world. In: Jacob U, Woodward G, editors. *Advances in Ecological Research. Volume 46. Global Change in Multispecies Systems Part 1*. London: Academic Press 2012. 89–210.

94. Jones MW, Smith A, Betts R, Canadell JG, Prentice CI, Le Quéré C. Climate change increases the risk of wildfires. *Science Brief* (2020). Available at: https://tyndall.ac.uk/wp-content/uploads/2023/10/ScienceBrief_Review_WILDFIRES_Jan2020.pdf

95. Xu RB, Yu P, Abramson MJ, Johnston FH, Samet JM, Bell ML, et al. Wildfires, global climate change, and human health. *N Engl J Med* (2020) 383(22):2173–81. doi: 10.1056/NEJMsr2028985

96. United States National Academies of Sciences, Engineering, and Medicine. *The chemistry of fires at the wildland-urban interface*. Washington, DC: The National Academies Press (2022). doi: 10.17226/26460

97. Wang J, Lu L, Wang M, Jiang T, Liu X, Ru S. Typhoons increase the abundance of microplastics in the marine environment and cultured organisms: A case study in Sanggou Bay, China. *Sci Total Environ* (2019) 667:1–8. doi: 10.1016/j.scitotenv.2019.02.367

98. Alvarez-Zeferino JC, Ojeda-Benítez S, Cruz-Salas AA, Martínez-Salvador C, Vázquez-Morillas A. Microplastics in mexican beaches. *Resour Conserv Recy* (2020) 155. doi: 10.1016/j.resconrec.2019.104633

99. Gandhi KS, Pradhap D, Prabaharan G, Singh SH, Krishnakumar S. Distribution of plastic litter in beach sediments of Silver beach, Cuddalore, during Nivar Cyclone - A first report. *Mar pollut Bull* (2021) 172:112904. doi: 10.1016/j.marpolbul.2021.112904

100. Cheung CKH, Not C. Impacts of extreme weather events on microplastic distribution in coastal environments. *Sci Total Environ* (2023) 904:166723. doi: 10.1016/j.scitotenv.2023.166723

101. Cheung PK, Hung PL, Fok L. River microplastic contamination and dynamics upon a rainfall event in Hong Kong, China. *Environ Processes* (2018) 6:253–64 doi: 10.1007/s40710-018-0345-0

102. Hitchcock JN. Storm events as key moments of microplastic contamination in aquatic ecosystems. *Sci Total Environ* (2020) 734:139436. doi: 10.1016/j.scitotenv.2020.139436

103. Xia W, Rao Q, Deng X, Chen J, Xie P. Rainfall is a significant environmental factor of microplastic pollution in inland waters. *Sci Total Environ* (2020) 732:139065. doi: 10.1016/j.scitotenv.2020.139065

104. Andriolo U, Gonçalves G. Is coastal erosion a source of marine litter pollution? Evidence of coastal dunes being a reservoir of plastics. *Mar pollut Bull* (2022) 174:113307. doi: 10.1016/j.marpolbul.2021.113307

105. Welden NAC, Lusher AL. Impacts of changing ocean circulation on the distribution of marine microplastic litter. *Integr Environ Assess Manag* (2017) 13(3):483–7. doi: 10.1002/ieam.1911

106. Van Sebille E, Aliani S, Law KL, Maximenko N, Alsina JM, Bagaev A, et al. The physical oceanography of the transport of floating marine debris. *Environ Res Lett* (2020) 15(2):023003. doi: 10.1088/1748-9326/ab6d7d

107. Gündoğdu S, Çevik C, Ayat B, Aydoğan B, Karaca S. How microplastics quantities increase with flood events? An example from Mersin Bay NE Levantine coast of Turkey. *Environ pollut* (2018) 239:342–50. doi: 10.1016/j.envpol.2018.04.042

108. Thompson PR, Widlansky MJ, Hamlington BD, Merrifield MA, Marra JJ, Mitchum GT, et al. Rapid increases and extreme months in projections of United States high-tide flooding. *Nat Clim Change* (2021) 11(7):584–90. doi: 10.1038/s41558-021-01077-8

109. Ertel BM, Weinstein JE, Gray AD. Rising seas and roadway debris: microplastic and low-density tire wear particles in street-associated tidal floodwater. *Mar pollut Bull* (2023) 195:115502. doi: 10.1016/j.marpolbul.2023.115502

110. Hale RC, Seeley ME, La Guardia MJ, Mai L, Zeng EY. A global perspective on microplastics. *JGR Oceans* (2020) 125(1). doi: 10.1029/2018JC014719

111. Brand JH. *Assessing the risk of pollution from historic coastal landfills* [thesis]. London: Queen Mary University of London (2017). Available at: http://qmro.qmul.ac.uk/xmlui/handle/123456789/19486

112. Hurley R, Woodward J, Rothwell JJ. Microplastic contamination of river beds significantly reduced by catchment-wide flooding. *Nat Geosci* (2018) 11(4):251–7. doi: 10.1038/s41561-018-0080-1

113. Roebroek CTJ, Harrigan S, Van Emmerik THM, Baugh C, Eilander D, Prudhomme C, et al. Plastic in global rivers: are floods making it worse? *Environ Res Lett* (2021) 16(2):025003. doi: 10.1088/1748-9326/abd5df

114. Wang L, Bank MS, Rinklebe J, Hou D. Plastic-rock complexes as hotspots for microplastic generation. *Environ Sci Technol* (2023) 57(17):7009–17. doi: 10.1021/acs.est.3c00662

115. Huang Q, Cheng Z, Yang C, Wang H, Zhu N, Cao X, et al. Booming microplastics generation in landfill: an exponential evolution process under temporal pattern. *Water Res* (2022) 223:119035. doi: 10.1016/j.watres.2022.119035

116. Young IR, Ribal A. Multiplatform evaluation of global trends in wind speed and wave height. *Science* (2019) 364(6440):548–52. doi: 10.1126/science.aav9527

117. Yang H, Lohmann G, Wei W, Dima M, Ionita M, Liu J. Intensification and poleward shift of subtropical western boundary currents in a warming climate. *JGR Oceans* (2016) 121(7):4928–45. doi: 10.1002/2015JC011513

118. Harris PT, Westerveld L, Nyberg B, Maes T, Macmillan-Lawler M, Appelquist LR. Exposure of coastal environments to riversourced plastic pollution. *Sci Total Environ* (2021) 769:145222. doi: 10.1016/j.scitotenv.2021.145222

119. Reisser J, Slat B, Noble K, Du Plessis K, Epp M, Proietti M, et al. The vertical distribution of buoyant plastics at sea. *Biogeosci Discuss* (2014) 11:16207–26 doi: 10.5194/bgd-11-16207-2014

120. Floderus S, Pihl L. Resuspension in the Kattegat: impact of variation in wind climate and fishery. *Estuar Coast Shelf Sci* (1990) 31(4):487–98. doi: 10.1016/0272-7714(90)90039-T

121. Jong MC, Tong X, Li J, Xu Z, Chng SHQ, He Y, et al. Microplastics in equatorial coasts: pollution hotspots and spatiotemporal variations associated with tropical monsoons. *J Hazard Mater* (2022) 424(C):127626. doi: 10.1016/j.jhazmat.2021.127626

122. Cózar AEA, Martí E, Duarte CM, García-De-Lomas J, Van Sebille E, Ballatore TJ, et al. The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the thermohaline Circulation. *Sci Adv* (2017) 3(4):e1600582. doi: 10.1126/sciadv.1600582

123. Gregory JM, Stott PA, Cresswell DJ, Rayner NA, Gordon C, Sexton DMH. Recent and future changes in Arctic sea ice simulated by the HadCM3 AOGCM. *Geophys Res Lett* (2002) 29(24). doi: 10.1029/2001GL014575

124. Obbard RW, Sadri S, Wong YQ, Khitun AA, Baker I, Thompson RC. Global warming releases microplastic legacy frozen in Arctic Sea ice. *Earths Future* (2014) 2(6):315–20. doi: 10.1002/2014EF000240

125. Peeken I, Primpke S, Beyer B, Gütermann J, Katlein C, Krumpen T, et al. Arctic sea ice is an important temporal sink and means of transport for microplastic. *Nat Commun* (2018) 9(1):1505. doi: 10.1038/s41467-018-03825-5

126. Stroeve JC, Serreze MC, Holland MM, Kay JE, Malanik J, Barrett AP. The Arctic's rapidly shrinking sea ice cover: a research synthesis. *Clim Change* (2012) 110(3–4):1005–27. doi: 10.1007/s10584-011-0101-1

127. Laxon SW, Giles KA, Ridout AL, Wingham DJ, Willatt R, Cullen R, et al. CryoSat-2 estimates of Arctic sea ice thickness and volume. *Geophys Res Lett* (2013) 40(4):732–7. doi: 10.1002/grl.50193

128. Adams JK, Dean BY, Athey SN, Jantunen LM, Bernstein S, Stern G, et al. Anthropogenic particles (including microfibers and microplastics) in marine sediments of the Canadian Arctic. *Sci Total Environ* (2021) 784:147155. doi: 10.1016/j.scitotenv.2021.147155

129. Bergmann M, Wirzberger V, Krumpen T, Lorenz C, Primpke S, Tekman MB, et al. High quantities of microplastic in Arctic deep-sea sediments from the HAUSGARTEN observatory. *Environ Sci Technol* (2017) 51(19):11000–10. doi: 10.1021/acs.est.7b03331

130. Shen M, Huang W, Chen M, Song B, Zeng G, Zhang Y. (Micro)plastic crisis: un-ignorable contribution to global greenhouse gas emissions and climate change. *J Cleaner Prod* (2020) 254:120138. doi: 10.1016/j.jclepro.2020.120138

131. Chae Y, Hong SH, An YJ. Photosynthesis enhancement in four marine microalgal species exposed to expanded polystyrene leachate. *Ecotoxicol Environ Saf* (2020) 189:109936. doi: 10.1016/j.ecoenv.2019.109936

132. Focardi A, Moore LR, Raina JB, Seymour JR, Paulsen IT, Tetu SG. Plastic leachates impair picophytoplankton and dramatically reshape the marine microbiome. *Microbiome* (2022) 10(1):179. doi: 10.1186/s40168-022-01369-x

133. Galgani L, Tzempelikou E, Kalantzi I, Tsiola A, Tsapakis M, Pitta P, et al. Marine plastics alter the organic matter composition of the air-sea boundary layer, with influences on CO(2) exchange: a large-scale analysis method to explore future ocean scenarios. *Sci Total Environ* (2023) 857(3):159624. doi: 10.1016/j.scitotenv.2022.159624

134. Porter A, Lyons BP, Galloway TS, Lewis C. Role of marine snows in microplastic fate and bioavailability. *Environ Sci Technol* (2018) 52(12):7111–9. doi: 10.1021/acs.est.8b01000

135. Woodward G, Perkins DM, Brown LE. Climate change and freshwater ecosystems: impacts across multiple levels of organization. *Philos Trans R Soc Lond B Biol Sci* (2010) 365(1549):2093–106. doi: 10.1098/rstb.2010.0055

136. Daufresne M, Lengfellner K, Sommer U. Global warming benefits the small in aquatic ecosystems. *Proc Natl Acad Sci USA* (2009) 106(31):12788–93. doi: 10.1073/pnas.0902080106

137. Morris OF, Loewen CJG, Woodward G, Schäfer RB, Piggott JJ, Vinebrooke RD, et al. Local stressors mask the effects of warming in freshwater ecosystems. *Ecol Lett* (2022) 25(11):2540–51. doi: 10.1111/ele.14108

138. McCormick MI, Chivers DP, Ferrari MCO, Blandford MI, Nanninga GB, Richardson C, et al. Microplastic exposure interacts with habitat degradation to affect behaviour and survival of juvenile fish in the field. *Proc Biol Sci* (2020) 287 (1937):20201947. doi: 10.1098/rspb.2020.1947

139. Jagadish SV, Murty MV, Quick WP. Rice responses to rising temperatures–challenges, perspectives and future directions. *Plant Cell Environ* (2015) 38(9):1686–98. doi: 10.1111/pce.12430

140. Yang C, Gao X. Impact of microplastics from polyethylene and biodegradable mulch films on rice (Oryza sativa L.). *Sci Total Environ* (2022) 828:154579. doi: 10.1016/j.scitotenv.2022.154579

141. Guo S, Mu L, Sun S, Hou X, Yao M, Hu X. Concurrence of microplastics and heat waves reduces rice yields and disturbs the agroecosystem nitrogen cycle. *J Hazard Mater* (2023) 452:131340. doi: 10.1016/j.jhazmat.2023.131340

142. Xu M, Xu Q, Wang G, Du W, Zhu J, Yin Y, et al. Elevated CO(2) aggravated polystyrene microplastics effects on the ricesoil system under field conditions. *Environ pollut* (2023) 316(2):120603. doi: 10.1016/j.envpol.2022.120603

143. Liang Y, Lehmann A, Ballhausen MB, Muller L, Rillig MC. Increasing temperature and microplastic fibers jointly influence soil aggregation by saprobic fungi. *Front Microbiol* (2019) 10:2018. doi: 10.3389/fmicb.2019.02018

144. Nayab G, Zhou J, Jia R, Lv Y, Yang Y, Brown RW, et al. Climate warming masks the negative effect of microplastics on plant-soil health in a silt loam soil. *Geoderma* (2022) 425. doi: 10.1016/j.geoderma.2022.116083

145. Lozano YM, Rillig MC. Effects of microplastic fibers and drought on plant communities. *Environ Sci Technol* (2020) 54(10):6166–73. doi: 10.1021/acs.est.0c01051

146. Lehmann A, Leifheit EF, Feng L, Bergmann J, Wulf A, Rillig MC. Microplastic fiber and drought effects on plants and soil are only slightly modified by arbuscular mycorrhizal fungi. *Soil Ecol Lett* (2022) 4(1):32–44. doi: 10.1007/s42832-020-0060-4

147. Lozano YM, Aguilar-Trigueros CA, Onandia G, Maaß S, Zhao T, Rillig MC, et al. Effects of microplastics and drought on soil ecosystem functions and multifunctionality. *J Appl Ecol* (2021) 58(5):988–96. doi: 10.1111/1365-2664.13839

148. Zhang P, Zhang H, Wang S, Woodward G, O'Gorman EJ, Jackson MC, et al. Multiple stressors simplify freshwater food webs. *Glob Change Biol* (2025) 31(3): e70114. doi: 10.1111/gcb.70114

149. O'Brien AM, Lins TF, Yang Y, Frederickson ME, Sinton D, Rochman CM. Microplastics shift impacts of climate change on a plant-microbe mutualism: temperature, CO(2), and tire wear particles. *Environ Res* (2022) 203:111727. doi: 10.1016/j.envres.2021.111727

150. Yang Y, Guo Y, O'Brien AM, Lins TF, Rochman CM, Sinton D. Biological responses to climate change and nanoplastics are altered in concert: full-factor screening reveals effects of multiple stressors on primary producers. *Environ Sci Technol* (2020) 54(4):2401–10. doi: 10.1021/acs.est.9b07040

151. Sun S, Hu X, Kang W, Yao M. Combined effects of microplastics and warming enhance algal carbon and nitrogen storage. *Water Res* (2023) 233:119815. doi: 10.1016/j.watres.2023.119815

152. Martins A, Da Silva DD, Silva R, Carvalho F, Guilhermino L. Warmer water, high light intensity, lithium and microplastics: dangerous environmental combinations to zooplankton and Global Health? *Sci Total Environ* (2023) 854:158649. doi: 10.1016/j.scitotenv.2022.158649

153. Jaikumar G, Baas J, Brun NR, Vijver MG, Bosker T. Acute sensitivity of three Cladoceran species to different types of microplastics in combination with thermal stress. *Environ pollut* (2018) 239:733–40. doi: 10.1016/j.envpol.2018.04.069

154. Lyu K, Cao C, Li D, Akbar S, Yang Z. The thermal regime modifies the response of aquatic keystone species Daphnia. *Sci Total Environ* (2021) 783. doi: 10.1016/j.scitotenv.2021.147154

155. Guilhermino L, Martins A, Cunha S, Fernandes JO. Long-term adverse effects of microplastics on Daphnia magna reproduction and population growth rate at increased water temperature and light intensity: combined effects of stressors and interactions. *Sci Total Environ* (2021) 784:147082. doi: 10.1016/j.scitotenv.2021.147082

156. Chang M, Li M, Xu W, Li X, Liu J, Stoks R, et al. Microplastics increases the heat tolerance of Daphnia magna under global warming via hormetic effects. *Ecotoxicol Environ Saf* (2023) 249. doi: 10.1016/j.ecoenv.2022.114416

157. Hiltunen M, Vehniäinen E-R, Kukkonen JVK. Interacting effects of simulated eutrophication, temperature increase, and microplastic exposure on Daphnia. *Environ Res* (2021) 192:110304. doi: 10.1016/j.envres.2020.110304

158. Sadler DE, Brunner FS, Plaistow SJ. Temperature and clonedependent effects of microplastics on immunity and life history in Daphnia magna. *Environ pollut* (2019) 255(1):113178. doi: 10.1016/j.envpol.2019.113178

159. Kratina P, Watts TJ, Green DS, Kordas RL, O'Gorman EJ. Interactive effects of warming and microplastics on metabolism but not feeding rates of a key freshwater detritivore. *Environ pollut* (2019) 255(2):113259. doi: 10.1016/j.envpol.2019.113259

160. Silva CJM, MaChado AL, Campos D, Soares A MVM, Pestana JLT. Combined effects of polyethylene microplastics and natural stressors on Chironomus riparius life-history traits. *Environ Res* (2022) 213:113641. doi: 10.1016/j.envres.2022.113641

161. Wen B, Zhang N, Jin SR, Chen ZZ, Gao JZ, Liu Y, et al. Microplastics have a more profound impact than elevated temperatures on the predatory performance, digestion and energy metabolism of an Amazonian cichlid. *Aquat Toxicol* (2018) 195:67–76. doi: 10.1016/j.aquatox.2017.12.010

162. Şenol O, Sulukan E, Baran A, Bolat İ, Toraman E, Alak G, et al. Global warming and nanoplastic toxicity; small temperature increases can make gill and liver toxicity more dramatic, which affects fillet quality caused by polystyrene nanoplastics in the adult zebrafish model. *Sci Total Environ* (2023) 892:164682. doi: 10.1016/j.scitotenv.2023.164682

163. Sulukan E, Baran A, Şenol O, Yildirim S, Mavi A, Ceyhun HA, et al. The synergic toxicity of temperature increases and nanopolystrene on zebrafish brain implies that global warming may worsen the current risk based on plastic debris. *Sci Total Environ* (2022) 808:152092. doi: 10.1016/j.scitotenv.2021.152092

164. Hasan J, Siddik MA, Ghosh AK, Mesbah SB, Sadat MA, Shahjahan M, et al. Increase in temperature increases ingestion and toxicity of polyamide microplastics in Nile tilapia. *Chemosphere* (2023) 327:138502. doi: 10.1016/j.chemosphere.2023.138502

165. Woodward G, Ebenman B, Emmerson M, Montoya JM, Olesen JM, Valido A, et al. Body size in ecological networks. *Trends Ecol Evol* (2005) 20(7):402–9. doi: 10.1016/j.tree.2005.04.005

166. Woodward G, Blanchard J, Lauridsen RB, Edwards FK, Jones JI, Figueroa D, et al. Individual-based food webs: species identity, body size and sampling effects. In: Woodward G, editor. *Advances in ecological research Volume 43. Integrative ecology: from molecules to ecosystems*. London: Academic Press (2010). 211–66.

167. Plafcan MM, Stallings CD. Microplastics do not affect bleaching of Acropora cervicornis at ambient or elevated temperatures. *PeerJ* (2022) 10:e13578. doi: 10.7717/peerj.13578

168. Axworthy JB, Padilla-Gamiño JL. Microplastics ingestion and heterotrophy in thermally stressed corals. *Sci Rep* (2019) 9(1):18193. doi: 10.1038/s41598-019-54698-7

169. Mendrik FM, Henry TB, Burdett H, Hackney CR, Waller C, Parsons DR, et al. Species-specific impact of microplastics on coral physiology. *Environ pollut* (2021) 269:116238. doi: 10.1016/j.envpol.2020.116238

170. Reichert J, Tirpitz V, Anand R, Bach K, Knopp J, Schubert P, et al. Interactive effects of microplastic pollution and heat stress on reef-building corals. *Environ pollut* (2021) 290:118010. doi: 10.1016/j.envpol.2021.118010

171. Bove CB, Greene K, Sugierski S, Kriefall NG, Huzar AK, Hughes AM, et al. Exposure to global change and microplastics elicits an immune response in an endangered coral. *Front Mar Sci* (2023) 9. doi: 10.3389/fmars.2022.1037130

172. Romanó de Orte M, Clowez S, Caldeira K. Response of bleached and symbiotic sea anemones to plastic microfiber exposure. *Environ pollut* (2019) 249:512–7. doi: 10.1016/j.envpol.2019.02.100

173. Manno C, Sandrini S, Tositti L, Accornero A. First stages of degradation of Limacina helicina shells observed above the aragonite chemical lysocline in Terra Nova Bay (Antarctica). *J Mar Syst* (2007) 68(1–2):91–102. doi: 10.1016/j.jmarsys.2006.11.002

174. Manno C, Rumolo P, Barra M, D'Albero S, Basilone G, Genovese S, et al. Condition of pteropod shells near a volcanic CO(2) vent region. *Mar Environ Res* (2019) 143:39–48. doi: 10.1016/j.marenvres.2018.11.003

175. Manno C, Peck LV, Corsi I, Bergami E. Under pressure: nanoplastics as a further stressor for sub-Antarctic pteropods already tackling ocean acidification. *Mar pollut Bull* (2022) 174:113176. doi: 10.1016/j.marpolbul.2021.113176

176. Castro LC, Cetina-Heredia P, Roughan M, Dworjanyn S, Thibaut L, Chamberlain MA, et al. Combined mechanistic modelling predicts changes in species distribution and increased co-occurrence of a tropical urchin herbivore and a habitat-forming temperate kelp. *Divers Distrib* (2020) 26(9):1211–26. doi: 10.1111/ddi.13073

177. Ling SD, Barrett NS, Edgar GJ. Facilitation of Australia's southernmost reef-building coral by sea urchin herbivory. *Coral Reefs* (2018) 37(4):1053–73. doi: 10.1007/s00338-018-1728-4

178. Piccardo M, Provenza F, Grazioli E, Cavallo A, Terlizzi A, Renzi M. PET microplastics toxicity on marine key species is influenced by pH, particle size and food variations. *Sci Total Environ* (2020) 715:136947. doi: 10.1016/j.scitotenv.2020.136947

179. Bertucci JI, Bellas J. Combined effect of microplastics and global warming factors on early growth and development of the sea urchin (Paracentrotus lividus). *Sci Total Environ* (2021) 782:146888. doi: 10.1016/j.scitotenv.2021.146888

180. Cook LSJ, Briscoe AG, Fonseca VG, Boenigk J, Woodward G, Bass D. Microbial, holobiont, and Tree of Life eDNA/eRNA for enhanced ecological assessment. *Trends Microbiol* (2025) 33(1):48–65. doi: 10.1016/j.tim.2024.07.003

181. Beyer J, Green NW, Brooks S, Allan IJ, Ruus A, Gomes T, et al. Blue mussels (Mytilus edulis spp.) as sentinel organisms in coastal pollution monitoring: a review. *Mar Environ Res* (2017) 130:338–65. doi: 10.1016/j.marenvres.2017.07.024

182. Wang X, Huang W, Wei S, Shang Y, Gu H, Wu F, et al. Microplastics impair digestive performance but show little effects on antioxidant activity in mussels under low pH conditions. *Environ pollut* (2020) 258:113691. doi: 10.1016/j.envpol.2019.113691

183. Wang X, Zhang Q, Zhang T, Shao S, Wang Q, Dong Z, et al. Evaluation of antioxidant capacity and digestive enzyme activities in Mytilus galloprovincialis exposed to nanoplastics under different patterns of hypoxia. *Mar Environ Res* (2023) 183:105849. doi: 10.1016/j.marenvres.2022.105849

184. Wang X, Zhang T, Zhang Q, Xue R, Qu Y, Wang Q, et al. Different patterns of hypoxia aggravate the toxicity of polystyrene nanoplastics in the mussels Mytilus galloprovincialis: environmental risk assessment of plastics under global climate change. *Sci Total Environ* (2022) 818:151818. doi: 10.1016/j.scitotenv.2021.151818

185. Fonte E, Ferreira P, Guilhermino L. Temperature rise and microplastics interact with the toxicity of the antibiotic cefalexin to juveniles of the common goby (Pomatoschistus microps): post-exposure predatory behaviour, acetylcholinesterase activity and lipid peroxidation. *Aquat Toxicol* (2016) 180:173–85. doi: 10.1016/j.aquatox.2016.09.015

186. Walls LG, Reusch T, Clemmesen C, Ory NC. Effects of changing environmental conditions on plastic ingestion and feeding ecology of a benthopelagic fish (Gadus morhua) in the southwest Baltic Sea. *Mar pollut Bull* (2022) 182:114001. doi: 10.1016/j.marpolbul.2022.114001

187. Flindt MR, Pardal MÂ, Lillebø AI, Martins I, Marques JC. Nutrient cycling and plant dynamics in estuaries: a brief review. *Acta Oecol* (1999) 20(4):237–48. doi: 10.1016/S1146-609X(99)00142-3

188. Connolly RM, Gorman D, Guest MA. Movement of carbon among estuarine habitats and its assimilation by invertebrates. *Oecologia* (2005) 144(4):684–91. doi: 10.1007/s00442-005-0167-4

189. Thresher RE, Nichols PD, Gunn JS, Bruce BD, Furlani DM. Seagrass detritus as the basis of a coastal planktonic food chain. *Limnol Oceanogr* (1992) 37(8):1754–8. doi: 10.4319/lo.1992.37.8.1754

190. Kelaher BP, Bishop MJ, Potts J, Scanes P, Skilbeck G. Detrital diversity influences estuarine ecosystem performance. *Glob Chang Biol* (2013) 19(6):1909–18. doi: 10.1111/gcb.12162

191. Duggins DO, Simenstad CA, Estes JA. Magnification of secondary production by kelp detritus in coastal marine ecosystems. *Science* (1989) 245(4914):170–3. doi: 10.1126/science.245.4914.170

192. Litchfield SG, Schulz KG, Kelaher BP. The influence of plastic pollution and ocean change on detrital decomposition. *Mar pollut Bull* (2020) 158:111354. doi: 10.1016/j.marpolbul.2020.111354

193. Borrelle SB, Ringma J, Law KL, Monnahan CC, Lebreton L, McGivern A, et al. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science* (2020) 369(6510):1515–8. doi: 10.1126/science.aba3656

194. Napper IE, Thompson RC. Plastic debris in the marine environment: history and future challenges. *Global Chall* (2020) 4(6):1900081. doi: 10.1002/gch2.201900081

195. Plastic Free Foundation. Plastic free July [website]. Available at: https://www.plasticfreejuly.org/

196. Ellen MacArthur Foundation [website]. Available at: https://www.ellenmacarthurfoundation.org

197. United Kingdom Government. *Single-use plastics bans and restrictions* [online] (2024). Available at: https://www.gov.uk/guidance/single-use-plastics-bans-and-restrictions

198. United Nations Environment Programme. *Basel convention on the control of transboundary movements of hazardous wastes and their disposal*. Nairobi: UNEP (2020). Available at: https://www.unep.org/resources/report/basel-convention-control-transboundary-movements-hazardous-wastes

199. United Nations Environment Programme. *Draft report of the intergovernmental negotiating committee to develop an international legally binding instrument on plastic pollution, including in the marine environment, on the work of its resumed fifth session*. Nairobi: UNEP (2025). Available at: https://www.unep.org/inc-plastic-pollution/session-5.2

200. Ellen MacArthur Foundation. Plastics and the circular economy – deep dive [online] (2023). Available at: https://www.ellenmacarthurfoundation.org/plastics-and-the-circular-economy-deep-dive

201. Ecology Center. *The solution to plastic pollution: refuse, rethink, redesign* [online] (2025). Available at: https://www.ecocenter.org/solution-plastic-pollution-refuse-rethink-redesign

202. Lau WWY, Shiran Y, Bailey RM, Cook E, Stuchtey MR, Koskella J, et al. Evaluating scenarios toward zero plastic pollution. *Science* (2020) 369(6510):1455–61. doi: 10.1126/science.aba9475

203. Earthday.org. From fossil fuels to plastic addiction: unveiling the hidden link impacting our world [online] (2023). Available at: https://www.earthday.org/from-fossil-fuels-to-plastic-addiction-unveiling-the-hidden-link-impacting-our-world/

204. Thompson RC, Pahl S, Sembiring E. Plastics treaty – research must inform action. *Nature* (2022) 608(7923):472. doi: 10.1038/d41586-022-02201-0

205. Azoulay D, Villa P, Arellano Y, Gordon M, Moon D, Miller K, et al. *Plastics and health: the hidden costs of a plastic planet*. Center for International Environmental Law (2019). Available at: https://www.ciel.org/reports/plastic-health-the-hidden-costs-of-a-plastic-planet-february-2019/

206. Wiedinmyer C, Yokelson RJ, Gullett BK. Global emissions of trace gases, particulate matter, and hazardous air pollutants from open burning of domestic waste. *Environ Sci Technol* (2014) 48(16):9523–30. doi: 10.1021/es502250z

207. Napper IE, Thompson RC. Environmental deterioration of biodegradable, oxo-biodegradable, compostable, and conventional plastic carrier bags in the sea, soil, and open-air over a 3-year period. *Environ Sci Technol* (2019) 53(9):4775–83. doi: 10.1021/acs.est.8b06984

208. Leone G, Moulaert I, Devriese LI, Sandra M, Pauwels I, Goethals PLM, et al. A comprehensive assessment of plastic remediation technologies. *Environ Int* (2023) 173:107854. doi: 10.1016/j.envint.2023.107854

209. Schmaltz E, Melvin EC, Diana Z, Gunady EF, Rittschof D, Somarelli JA, et al. Plastic pollution solutions: emerging technologies to prevent and collectmarineplastic pollution. *Environ Int* (2020) 144:106067. doi: 10.1016/j.envint.2020.106067

210. Bellou N, Gambardella C, Karantzalos K, Monteiro JG, Canning-Clode J, Kemna S, et al. Global assessment of innovative solutions to tackle marine litter. *Nat Sustain* (2021) 4(6):516–24. doi: 10.1038/s41893-021-00726-2

211. Horton AA. Plastic pollution: when do we know enough?*J Hazard Mater* (2022) 422:126885. doi: 10.1016/j.jhazmat.2021.126885

212. Van Emmerik T, Mellink Y, Hauk R, Waldschläger K, Schreyers L. Rivers as plastic reservoirs. *Front Water* (2022) 3. doi: 10.3389/frwa.2021.786936

213. Spencer M, Culhane F, Chong F, Powell MO, Roland Holst RJ, Helm R. Estimating the impact of new high seas activities on the environment: the effects of ocean-surface macroplastic removal on sea surface ecosystems. *PeerJ* (2023) 11:e15021. doi: 10.7717/peerj.15021

214. Leone G, Catarino AI, Pauwels I, Mani T, Tishler M, Egger M, et al. Integrating Bayesian Belief Networks in a toolbox for decision support on plastic clean-up technologies in rivers and estuaries. *Environ pollut* (2022) 296:118721. doi: 10.1016/j.envpol.2021.118721

215. Ali N, Liu W, Zeb A, Shi R, Lian Y, Wang Q, et al. Environmental fate, aging, toxicity and potential remediation strategies of microplastics in soil environment: current progress and future perspectives. *Sci Total Environ* (2024) 906:167785. doi: 10.1016/j.scitotenv.2023.167785

216. Barone GD, Rodríguez-Seijo A, Parati M, Johnston B, Erdem E, Cernava T, et al. Harnessing photosynthetic microorganisms for enhanced bioremediation of microplastics: A comprehensive review. *Environ Sci Ecotechnol* (2024) 20:100407. doi: 10.1016/j.ese.2024.100407

217. Sheth MU, Kwartler SK, Schmaltz ER, Hoskinson SM, Martz EJ, Dunphy-Daly MM, et al. Bioengineering a future free of marine plastic waste. *Front Mar Sci* (2019) 6. doi: 10.3389/fmars.2019.00624

218. Rana AK, Thakur MK, Saini AK, Mokhta SK, Moradi O, Rydzkowski T, et al. Recent developments in microbial degradation of polypropylene: integrated approaches towards a sustainable environment. *Sci Total Environ* (2022) 826:154056. doi: 10.1016/j.scitotenv.2022.154056

219. Debroy A, George N, Mukherjee G. Role of biofilms in the degradation of microplastics in aquatic environments. *J Chem Technol Biotechnol* (2022) 97(12):3271–82. doi: 10.1002/jctb.6978

220. Yuan J, Ma J, Sun Y, Zhou T, Zhao Y, Yu F. Microbial degradation and other environmental aspects of microplastics/plastics. *Sci Total Environ* (2020) 715:136968. doi: 10.1016/j.scitotenv.2020.136968

221. Peller J, Nevers MB, Byappanahalli M, Nelson C, Ganesh Babu B, Evans MA, et al. Sequestration of microfibers and other microplastics by green algae, Cladophora, in the US Great Lakes. *Environ pollut* (2021) 276:116695. doi: 10.1016/j.envpol.2021.116695

222. Masiá P, Sol D, Ardura A, Laca A, Borrell YJ, Dopico E, et al. Bioremediation as a promising strategy for microplastics removal in wastewater treatment plants. *Mar pollut Bull* (2020) 156:111252. doi: 10.1016/j.marpolbul.2020.111252

223. Zhou Y, Kumar M, Sarsaiya S, Sirohi R, Awasthi SK, Sindhu R, et al. Challenges and opportunities in bioremediation of micro-nano plastics: a review. *Sci Total Environ* (2022) 802:149823. doi: 10.1016/j.scitotenv.2021.149823

224. Agarwal T, Atray N, Sharma JG. A critical examination of advanced approaches in green chemistry: microbial bioremediation strategies for sustainable mitigation of plastic pollution. *Future J Pharm Sci* (2024) 10(1). doi: 10.1186/s43094-024-00645-x

225. Thompson R. Microplastics in the marine environment: sources, consequences and solutions. In: Bergmann M, Gutow L, Klages M, editors. *Marine anthropogenic litter*. New York: Springer Open (2015). 185–200. doi: 10.1007/978-3-319-16510-3_7

226. Chamas A, Moon H, Zheng J, Qiu Y, Tabassum T, Jang JH, et al. Degradation rates of plastics in the environment. *ACS Sustain Chem Eng* (2020) 8(9):3494–511. doi: 10.1021/acssuschemeng.9b06635

227. Catarino AI, Asselman J, Niu Z, Everaert G. Micro- and nanoplastics effects in a multiple stressed marine environment. *J Hazard Mater Adv* (2022) 7. doi: 10.1016/j.hazadv.2022.100119

228. Soares J, Miguel I, Venâncio C, Lopes I, Oliveira M. Public views on plastic pollution: knowledge, perceived impacts, and pro-environmental behaviours. *J Hazard Mater* (2021) 412:125227. doi: 10.1016/j.jhazmat.2021.125227

229. Dilkes-Hoffman LS, Pratt S, Laycock B, Ashworth P, Lant PA. Public attitudes towards plastics. *Resour Conserv Recy* (2019) 147:227–35. doi: 10.1016/j.resconrec.2019.05.005

230. Pahl S, Wyles KJ, Thompson RC. Channelling passion for the ocean towards plastic pollution. *Nat Hum Behav* (2017) 1(10):697–9. doi: 10.1038/s41562-017-0204-4

231. Hartley BL, Pahl S, Veiga J, Vlachogianni T, Vasconcelos L, Maes T, et al. Exploring public views on marine litter in Europe: perceived causes, consequences and pathways to change. *Mar pollut Bull* (2018) 133:945–55. doi: 10.1016/j.marpolbul.2018.05.061

232. Wyles KJ, Pahl S, Thomas K, Thompson RC. Factors that can undermine the psychological benefits of coastal environments: exploring the effect of tidal state, presence, and type of litter. *Environ Behav* (2016) 48(9):1095–126. doi: 10.1177/0013916515592177

233. Jansen T, Claassen L, Van Kamp I, Timmermans DRM. 'All chemical substances are harmful.' public appraisal of uncertain risks of food additives and contaminants. *Food Chem Toxicol* (2020) 136:110959. doi: 10.1016/j.fct.2019.110959

234. Smithers R. Great British beach clean attracts record number of volunteers. *The Guardian* (2018). Available at: https://www.theguardian.com/environment/2018/nov/29/great-british-beach-clean-attracts-record-number-of-volunteers

235. Hartley BL, Thompson RC, Pahl S. Marine litter education boosts children's understanding and self-reported actions. *Mar pollut Bull* (2015) 90(1–2):209–17. doi: 10.1016/j.marpolbul.2014.10.049

236. Camins E, De Haan WP, Salvo VS, Canals M, Raffard A, Sanchez-Vidal A. Paddle surfing for science on microplastic pollution. *Sci Total Environ* (2020) 709:136178. doi: 10.1016/j.scitotenv.2019.136178