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Microplastics and Their Degradation Products in Surface Waters: A Missing Piece of the Global Carbon Cycle Puzzle

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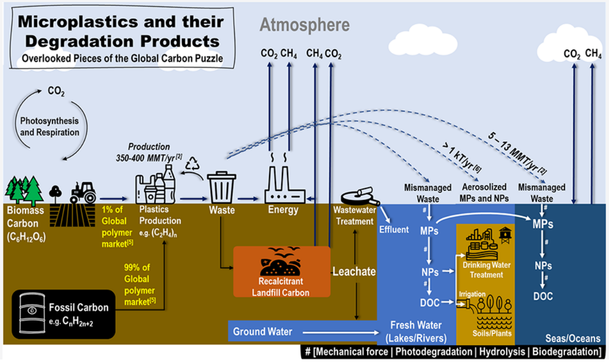

Since the mid-1950s, plastics have become an increasingly ubiquitous component in industrial and domestic products with an estimated 6300 million metric tons (MMT) of plastic waste generated by 2015.[1] At current rates of plastic production of 350−400 MMT per year, the volume of plastic waste could triple over current levels by 2050.[2] The magnitude of plastic waste generation presents a formidable challenge for waste management systems and a threat to ecosystems.[3] The impact of anthropogenic carbon from plastics and degradation byproducts on marine and terrestrial environments is particularly concerning. For a polymer carbon content of 80−90%, the current annual flow of plastic carbon into the global carbon cycle is roughly 280−360 MMT. These carbon amounts are enormous. For reference, this carbon flow from plastics is ∼10% of the magnitude of the 2.7 Gt of carbon added by the global combustion of coal for electricity.[4] Herein, we highlight this emerging biogeochemical cycle and the need for research to understand the degree to which anthropogenic carbon from plastic is impacting surface water ecosystems and, more broadly, the global carbon cycle.

Researchers now recognize plastic pollution beyond the effect of their bulk characteristics on aquatic and terrestrial environments. Due to the nature of terrestrial and aquatic interactions, it is not feasible to discuss either system in isolation. As shown in Figure 1, the flow of plastics and their degradation products through the environment is complex. The contribution of these flows to carbon stocks in aquatic and terrestrial systems is poorly understood. Roughly 99% of this carbon originates in fossil hydrocarbons, with a much smaller (but growing) 1% originating in the atmosphere in the form of biomass-based polymers.[5] This anthropogenic carbon enters the global carbon cycle as plastic products that can remain in use from days to decades. After a product's useful life, over the last ∼70 years, roughly 9% was recycled, 12% incinerated, and ∼79% was either managed in landfills or entered the natural environment.[1] Once in the environment, plastics degrade to smaller particles, nano- and microplastics (NMPs) under different conditions. Plastics also contain additives that may leech into the surrounding environment more readily that the parent polymer.

Although the current literature strongly supports the mobility of NMPs and the leached additives, the development of a framework to describe and quantify this complex and dynamic system is unrealized and is an urgent research need. Unmanaged plastic waste may degrade through physical or biological processes on land and in soils or find its way into groundwater or freshwater rivers and streams, and eventually the ocean. Thus, NMPs have been detected in air, soils, freshwater, oceans, and biota. Aerosolized particles may also be deposited on land and water via storms and air currents.[6] The plastic that reaches landfills may release some fraction of carbon to the atmosphere in the form of landfill emissions (CO_2 and methane). Carbonaceous degradation products also have high potential to escape the landfill and infiltrate

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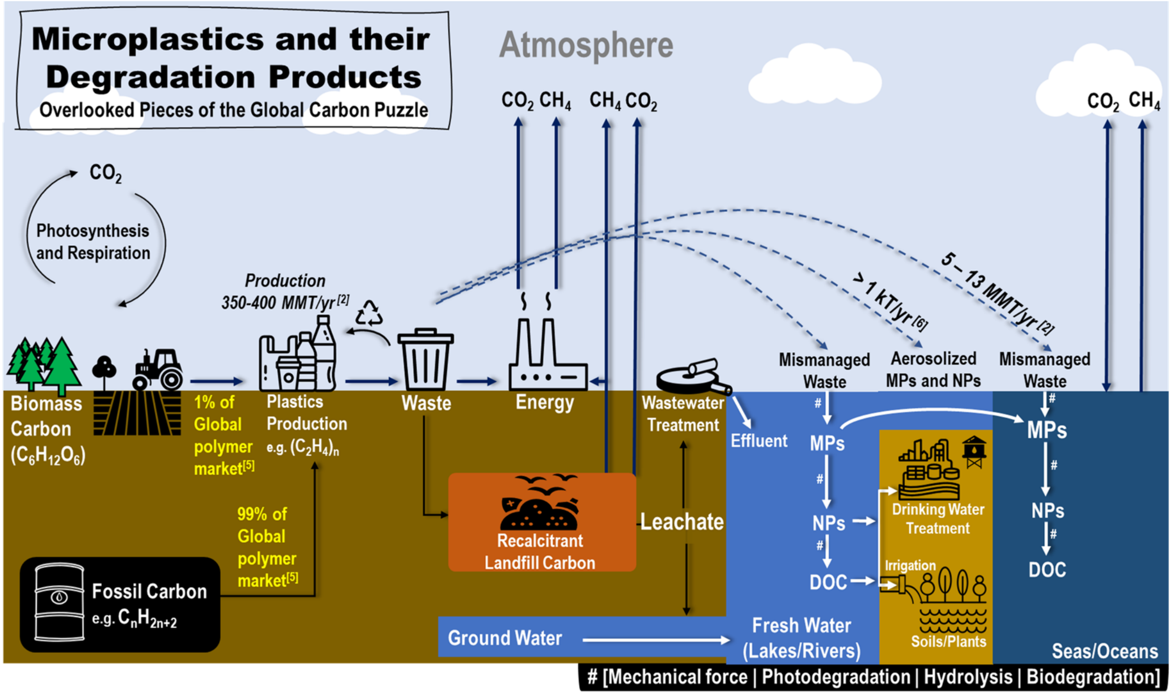

Figure 1. Plastics in the carbon cycle.

groundwater or directly pass into freshwater as leachate.[7] This pathway is particularly understudied. Once the carbon is in water, it is hard to distinguish the carbon coming from plastics and those of natural organic matter (NOM). Recent studies have shown similar reactivity of both carbon sources in forming of disinfection byproducts (DBPs). Finally, waterborne plastic may cycle back to land; e.g., NMPs can be transported in waste water treatment sludge applied as fertilizer.[8]

The lifetime of plastic in the environment and the stability of its carbon matrix are not well-understood. Much conventional wisdom assumes that plastics persist indefinitely, and there are very few data backing the degradation estimates that are available.[9] Laboratory experiments have shown complete photochemical oxidation of polystyrene to CO_2 on centennial time scales and partial photochemical oxidation to dissolved organic carbon on decadal time scales.[10] Other common consumer plastics such as polyethylene and polypropylene have shown similar photoreactivity under laboratory conditions.[11,12]

An estimated 13 MMT per year of NMPs is released to aquatic ecosystems,[2] where they undergo different degradation pathways: (1) biodegradation, (2) photodegradation by ultraviolet light, (3) thermooxidative degradation at low temperature, (4) thermal degradation at high temperature, and (5) hydrolysis in water. The resulting organic carbon will interact with biotic systems, and mineralized carbon will impact the magnitude of stocks and exchange among aqueous, terrestrial, and atmospheric carbon pools and have an effect on water chemistry (e.g., pH). To date, however, the impact of NMP and degradation product carbon on existing stocks is not well-quantified, but it is likely that carbon of plastic origin is showing up in measurements of total and dissolved organic carbon.[13,14] Moreover, recent research has asserted that plastics represent an important flux missing from the global carbon budget accounting.[15] Understanding the role of plastic degradation products in aquatic environments may have important implications for estimates of future biogeochemical feedback between the geosphere and the atmosphere, underscoring an urgent research need in the face of accelerating climate change.

Overall, the role of plastics in the global carbon cycle puzzle is not quantified or well-understood. Anthropogenic carbon from plastics may have important implications for scientists studying biogeochemical dynamics, climate science, life cycle assessment, and soil and agricultural sciences and for materials scientists and engineers. The emerging realization of the ubiquity of microplastics in all facets of the environment has led some researchers to describe a “microplastic cycle”,[16] but it is perhaps also correct to conceptualize plastics as an emerging anthropogenic component of the global carbon cycle. Research is needed to better characterize the fate of microplastics in surface waters and terrestrial systems and to characterize the dynamics between these flows of anthropogenic carbon and biogeochemical and ecological systems.

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Notes

The authors declare no competing financial interest.

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