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A Call to Evaluate Plastic's Impacts on Ecosystem Interaction Networks in Nature

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Summary

Plastic pollution continues to seep into natural and pristine habitats. Emerging laboratory-based research has evoked concern regarding plastic's impact on ecosystem structure and function, the essence of the ecosystem services that supports our life, wellbeing, and economy. These impacts have yet to be observed in nature where complex ecosystem interaction networks are enveloped in environmental physical and chemical dynamics. Specifically, there is concern that environmental impacts of plastics reach beyond toxicity and into ecosystem processes such as primary production, respiration, carbon and nutrient cycling, filtration, bioturbation, and bioirrigation. Plastics are popularly regarded as recalcitrant carbon molecules, although they have not been fully assessed as such. We hypothesize that plastics can take on similar roles as natural recalcitrant carbon (i.e., lignin and humic substances) in carbon cycling and associated biogeochemistry. In this paper, we review the current knowledge of the impacts of plastic pollution on marine, benthic ecosystem function. We argue for research advancement through (1) employing field experiments, (2) evaluating ecological network disturbances by plastic, and (3) assessing the role of plastics (i.e., a carbon-based molecule) in carbon cycling at local and global scales.

Introduction

The disposable-product era (~1970s – present) has pushed plastic into nearly every environment [1]. Plastic's strong resistance to biodegradation and chemical attraction to toxic molecules causes a variety of environmental issues [2]. While we can now estimate the quantity and type of plastics accumulating in many different marine habitats including the seafloor [3,4], what is less clear is the effect on ecosystem functions. This is especially important because seafloor ecosystems provide humans with a multitude of services [5,6]. These services include the provision of oxygen and food, removal of contaminants, regulation of processes, and the allocation of natural places and recreational settings [7]. Recent laboratory-based research has revealed the potential impacts of microplastics (i.e., particles < 5 mm) on the ecosystem processes that collectively produce these services. These ecosystem processes include primary production and respiration [8,9], carbon and nutrient cycling [9,10,11,12,13,14,15,16], filtration [11], bioturbation [9,16], and bioirrigation [8] (Figure 1). Even low microplastic doses are capable of shifting ecosystem functions. For example, 1.5 % plastic by weight lowers sediment thermal diffusivity and temperature enough to influence sex-determination temperatures in sea turtles [17] and < 0.5 g/kg WW sediment shifts MPB communities, reduces MPB biomass, increases porewater NOx, increases organic matter, and decreases burrowing activity [16]. Research results such as these have strengthened the coherent societal awareness and agreement that plastics impact environmental and human health. However, there is no understanding on the exact extent to which microplastics change ecosystem functions. Herein, we explain how an ecosystem network view helps prioritization on critical processes. Without this advancement, society's management of plastic products will remain to inadequately protect our quality of life [18,19].

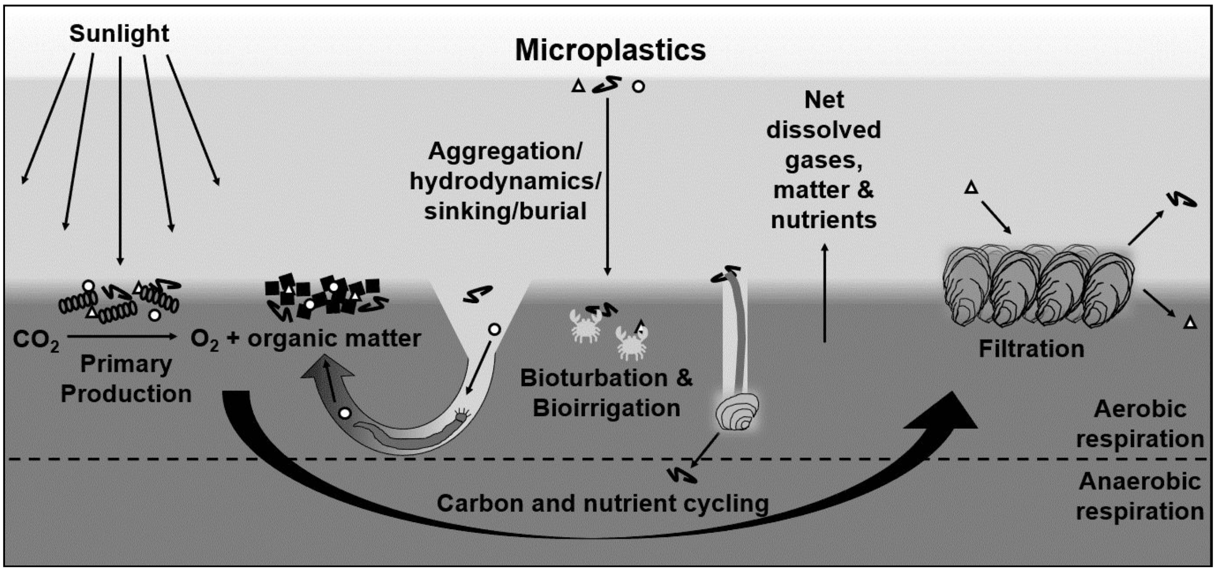

Figure 1: How microplastics affect ecosystem processes at the sediment-water interface [8,9,10,11,13,14,15,16].

We lack an environmentally relevant and holistic perspective that is necessary to understand ecosystem consequences and dynamical responses. Seafloor ecosystem responses involve the interactions between plants, animals, sedimentary characteristics, and hydrodynamics. Direct and indirect interactions between ecosystem components build networks that are capable of positive and negative feedbacks with important dynamical consequences [20,21]. For instance, Thrush et al. [20] showed that differences in benthic chlorophyll *a* concentration determined the existence, strength, and direction of component relationships linking nutrient processing in the sediment to percent sand/mud, large bioturbating fauna, and organic matter. Collectively, these changes reconstructed the network they were studying [20]. Changes to environmental characteristics like this generate context-dependent results that limit the applicability of universal guidelines or management thresholds. This effect can be exaggerated when literature biases skew our general understanding of the importance of specific processes and mechanisms associated with key ecosystem functions and global cycles [22]. An example being the strong bias towards laboratory-based studies in the microplastic ecosystem interaction literature. The very nature of ecosystem functions as emergent properties of network interactions creates two fundamental problems: 1) environmental conditions will influence both the presence of a specific environmental stressor (e.g. particular type of microplastic) and the magnitude of its effect on ecosystem processes; and 2) casual and correlative relationships shown in the current laboratory-based plastic literature unveil the potential for network disturbance in nature but require field verification. Thus, field studies that acknowledge heterogeneity and feedback loops are necessary to explore where and when plastic exposure is critical to ecosystem functionality and resilience in the real world.

Field evaluation of how microplastics affect key marine ecosystem processes are exceedingly rare [13,17], but the evidence to date supports our understanding through laboratory-based results. Adding microplastics to the field for even 1 m^2 plots in scientific experiments is unethical and any added microplastics are not easily removed from the field. Therefore, we recommend using an ecological approach by using natural environmental gradients [23] of plastic pollution to examine plastic as a stressor on key ecosystem component relationships and emergent processes. While laboratory experiments have focused on the impact of microplastics on nitrogen processing in marine sediments [9,10,11,15,16], it is important to focus experiments on carbon cycling networks. This is because plastics are made of chemically interactive carbon molecules that affect not only marine benthic biology, but also chemistry and sediment structural dynamics, which can collectively impact marine carbon sequestration. Thus, bridging the gap between the effects of plastic on biogeochemistry, ecology, and ecotoxicology will be critical.

Microplastic pollution targets marine, benthic carbon cycling

Microplastics affect marine, benthic ecosystem networks specific to carbon cycling (Figure 2). Faunal ingestion of microplastics impacts animal energy budgets and feeding rates and increases tissue inflammation, pseudofaeces production, and developmental defects [5,24]. These effects impact overall carbon uptake, storage, and release via the roles that the fauna plays in ecosystem functioning. Beyond microplastic ingestion, microplastics act as a carbon source to microbes through their fossilized carbon backbones, sorbed environmental chemicals, and production-line additives [12,14,25,26,27,28,29]. Therefore, each microplastic particle is a carbon package (MP-C) that carries its own potential to affect the surrounding environmental carbon quality and quantity [8,15,16,24,29,30,31].

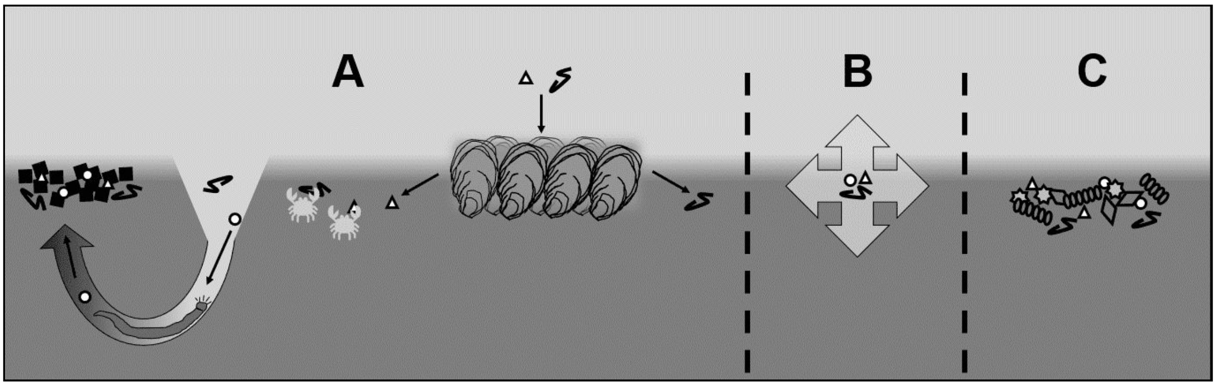

Figure 2: Direct effects of microplastics on marine, soft-sediment carbon cycling: (A) carbon uptake, storage, and release in fauna [5], (B) carbon additions (by leaching dissolved organic carbon [12,27], methane production [14,28], and ethylene production [28]) or (C) by acting as a substrate or energy source for microbes [12,15,25,26].

One potential avenue for examining how the MP-C package might interface with feedback loops and carbon cycling in natural systems is through priming effects. The notion of priming effects was first introduced by Bingemann et al. [32] in soils, and could generally be described as a short-term changes in turnover of organic matter due to the addition of organic matter that is relatively more or less reactive, resulting in positive or negative priming, respectively [33,34]. Other studies in priming followed suit in aquatic systems [35,36,37,38,39,40], with some having more emphasis on microbial dynamics (e.g., [41,42]).

MP-C are presumed to be recalcitrant, yet themselves and their escorted chemicals interact with microbial processes [12,15,26] including microbial enzyme activity [43,44]. We hypothesize the following two scenarios: (1) positive and (2) negative priming by MP-C (Figure 3). (1) Similar to traditional priming engagement [37], recalcitrant or labile carbon decomposers utilize a MP-C package as an energy source to produce environmental enzymes for carbon degradation. Their decomposition by-products then fuel one another (a syntrophic relationship), increasing decomposition, and consequently increasing CO_2 emission. This describes a positive priming effect. (2) Conversely, a MP-C package is toxic to recalcitrant or labile decomposers, inducing a negative priming effect by disabling decomposition activity, potentially deactivating environmental enzymes, and eventually loss of specific microbes. This will increase sediment organic matter concentrations, due to the lack of decomposition, and decrease CO_2 emissions. These concepts could be an explanation behind the sediment organic matter load increase in microplastic mesocosm experiments [9,15,16], especially since creating the experimental treatments involved a sudden dump of MP-C into the system. While pulses of microplastics into coastal waters occur regularly (i.e., nurdle spills, microplastic-filled wastewater outfall pipes, rain events where microplastics are flushed from the land to the sea, and macroplastic crumbling in their degradation into microplastics [45]), particles may disperse before aggregating and sinking to the seafloor. Therefore, experimental design details, such as MP-C introduced as a pulse or gradually over time, are important to consider when assessing research questions and interpreting experimental results. Such design details attribute to priming potentials and cascading priming effects, which ultimately guide carbon cycling dynamics.

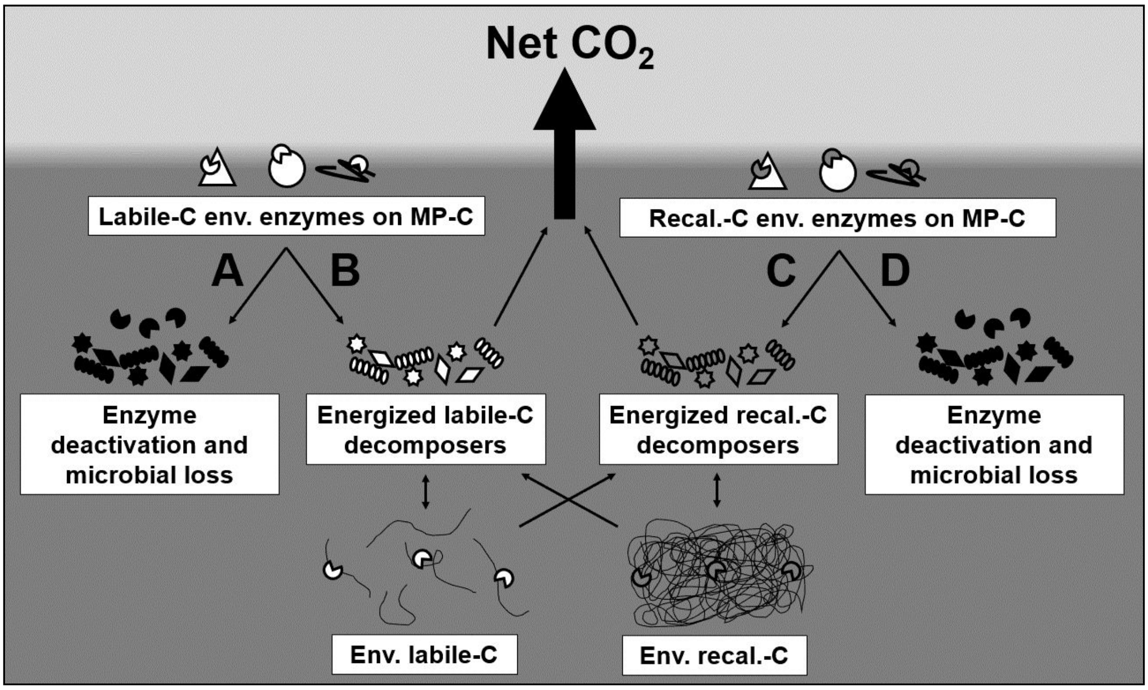

Figure 3: Theoretical mechanisms whereby MP-C packages influences organic matter priming dynamics in near surface sediments. MP-C packages can provide an energy source for sparking priming via routes (B) and (C), consequently increasing CO_2 emissions (aka positive priming). Conversely (A & D), they deactivate environmental enzymes, or kill priming decomposers, thus, increasing organic matter and decreasing CO_2 emissions (aka negative priming).

The convergence of natural refractory and labile carbon pools in marine sediment alters more than just carbon cycling. For example, Turnewitsch et al. [46] saw an increase of nitrogen flux from marine sediments to the overlying water in treatments with a 1:1 mixture of labile and refractory organic matter in comparison to treatments with either carbon type on its own. MP-C treatments to marine sediments have also reported changes to nitrogen processes in comparison to treatments without MP-C [9,10,11,15,16]. The direction and magnitude of effects are variable and link to Rochman et al. [31] argument that microplastic pollution be examined as a diverse contaminant suite: containing various polymers, additives, product types, sizes, morphologies, colors, and eco-toxins. Seeley et al. [15] and Hope et al. [16] propose that perhaps the MP-C caused a shift in the organic matter that originally fed nitrogen cycling bacteria via (1) hydrolytic cleavage of the plastic polymer's functional groups or (2) alteration of microphyte composition, respectively. These fine details are becoming more empirically supported today with hydrolytic cleavage of plastics in the marine environment [47 and references therein] and plastic specific microphyte colonizers [25] now detected. However, the net effects of environmental mechanisms like these require more exploration. Tightly woven relationships within and surrounding carbon cycling networks illustrate the ease of a carbon-based pollutant (i.e., MP-C particles) to impact feedback loops, making it clear that this is an important avenue of research to explore.

Plunging into the field

This paper aims to inspire a research movement that would propel the current popular research scope of microplastic distribution, organism impacts, and review papers [1] into advanced systematic, environmentally relevant assessments of MP-C and ecosystem interactions. Our oceans harbor trillions of plastic pieces and take on millions of metric tons more each year [48], thus we need to address where plastics fit into global carbon cycles. It is estimated that global marine plastics today leach 23,600 metric tons of dissolved organic carbon annually [12]. As plastics sink to marine sediments often associated with organic matter amalgams [49], do they affect traditional priming events? Can we afford additional atmospheric CO_2 inputs from plastic positive priming? Conversely, will we benefit from carbon storage maintenance implemented by negative plastic priming? These types of questions establish the urgency for field assessments regarding how the environment is currently handling plastic pollution. Specifically, we require field assessments on how MP-C packages are altering the relationships that mediate carbon sequestration and mineralization (i.e., C:N ratios and microbial activity [36]). Knowing what kinds of plastic and their additives cause ecosystem disruption, will allow careful selection of plastic products and chemical additives during manufacturing. Additionally, determining what ecosystems (i.e., high or low nutrient systems, muddy or sandy sediments, high or low sediment reactivity, etc.) are most at risk to ecological disruption by microplastics, will help select where to dedicate resources for bettering waste management protocols. We look forward to the day that our man-made innovations leave be our natural environments to function at mother nature's design.

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Author contributions

Conceptualization and Writing – Original Draft, S.M.L.; Writing – Review and Editing, T.S.B., G.C., J.A.H., and S.F.T.; Supervision, S.F.T.; Funding Acquisition – G.C., J.A.H., and S.F.T.

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