LIMNOLOGY and OCEANOGRAPHY LETTERS

ASLO

Open Access

Limnology and Oceanography Letters 10, 2025, 859–866

doi: 10.1002/lol2.70071

ESSAY

Rethinking plastic as a habitat modifier and a transport vector for organisms in aquatic environments

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Scientific Significance Statement

Plastic pollution is affecting freshwater and marine ecosystems. However, while increasing evidence highlights potential toxicological effects, broader ecosystem-level impacts remain largely overlooked. Recent findings suggest that plastic can undermine ecosystem functioning by altering fundamental fluxes of energy and matter at key interfaces within water environments. This view warrants urgent investigation, as rising plastic concentrations in aquatic ecosystems may disrupt their basic functioning, and current environmental concentrations in heavily polluted environments may already be altering ecosystem structure.

Plastic: A novel stressor in aquatic environments

Plastic is one of the most abundant manufactured materials, owing to its properties such as flexibility and durability. Inadequate waste management and degradation of plastic have resulted in widespread contamination, with estimates of 9–23 million metric tons of plastic reaching the oceans every year (Nava et al. 2023). Aquatic environments are then major recipients of plastics, with low flow systems (e.g., lake/ocean water, littoral and deep sediments) acting as accumulators. For example, monitoring of lakes and rivers reveals that up to 75,000 microplastic particles can be present in each kg of sediment (Onoja et al. 2022), while up to 10,000 particles per cubic meter are detected in oceans (Zhao et al. 2025). Plastic litter pollution is likely even more dramatic, with cases where sediments and water surfaces are entirely coated by plastics (Garaba and Park 2024). Even pristine areas are exhibiting notable concentrations of microplastics, indicating a global scale of pollution, due to widespread distribution and high mobility of plastic (Nava et al. 2023). Even in the unlikely

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Associate editor: Elise Granek

scenario of a complete cessation of plastic production, a reduction in plastic concentration in the environment is not expected in the foreseeable future (Geyer et al. 2017). This persistence results from the poor reversibility of plastic pollution and the temporary storage of plastic debris in soils, which can supply aquatic ecosystems (Koutnik et al. 2021). This will lead to further accumulation and deposition from several local and diffuse sources, including the urban environment and atmosphere (MacLeod et al. 2021). Replacing the currently used polymers with biodegradable materials is also concerning, since these are typically not designed to degrade in water and may accumulate in aquatic environments (Van Grinsven and Schubert 2023). The current environmental concentration of plastic and its predicted increase in the future put water bodies at extreme risk.

Canonical assessment of environmental risk for plastics and microplastics

Hazard assessments of plastics have been framed following traditional ecotoxicology approaches, whereby a direct relation is assumed to link exposure and effects (Koelmans et al. 2022). This approach may overlook the fundamental nature of organism-plastic interactions, where plastic fragments larger than a few microns do not penetrate the surface structures of organisms. This may cause non-linear responses of organisms to plastic exposure, as the effects are not mediated by the interaction of a toxicant with receptors inside the organism. Rather, plastics can impact the organisms in other ways besides toxic effects: this includes food dilution, entanglements and other adverse effects related to the properties of the habitat. Therefore, assessments by conventional ecotoxicological tests are unlikely to provide comprehensive responses, possibly leading to the underestimation of the actual hazard (Bank et al. 2022).

The changes induced by plastic on the habitat can have far-reaching implications for the functioning of aquatic ecosystems. They, in fact, do not require toxicological and prolonged interactions with the organisms, but affect the properties of the environment in which they live. Generally, fluxes of nutrients, organisms, and energy define the community structure, which in turn determines key ecological functions (Krause et al. 2017). Plastics can affect the rates of these fluxes by altering the substrate for the growth of microorganisms and the physicochemical structure of the habitat, owing to the peculiar properties of this material in comparison to other solids (MacLeod et al. 2021).

The accumulation of plastics in key ecosystem interfaces

Plastic polymers have distinct physicochemical properties (Koelmans et al. 2022) in comparison to other solid substrates that are commonly found in the environment (e.g., suspended solids, wood and stones). These specific properties have important implications:

1. Plastic surface is readily colonized by microorganisms, generating biofilm communities that may differ markedly from those found on natural substrates and in the surrounding water (Amaral-Zettler et al. 2020);
2. Roughly half of the plastics introduced in aquatic systems (especially the coarser grain size and composed of the lighter polymers) are capable of floating on the water surface due to their low density. Due to the higher density of seawater, plastic buoyancy is even more prevalent in marine systems (Thompson et al. 2024; Van Sebille et al. 2020);
3. While plastics, and especially particles below 100 μm, have slow settling rates and long residence times in the water column, the formation of a biofilm on plastics alters their physical properties and favors the sinking of fragments, ultimately leading to the accumulation of fragments at the sediment–water interface (Rogers et al. 2020). Since plastic is less dense than inorganic sediment components, hydraulic processes (e.g., resuspension and turbulence) can concentrate plastics at the sediment–water interface (Drummond et al. 2022; Martínez-Pérez et al. 2024).

These dynamics can favor the accumulation of plastic in key interfaces of aquatic ecosystems: the sediment–water and the water–air interface. These interfaces govern the transfer of energy and matter across habitats, and, in turn, define the structure of communities and the pool of resources. Sediments are capable to exchange organisms, nutrients, and energy with the water column through suspension and sedimentation processes. They are a bank of organisms and resources that contribute to controlling pelagic community structure and primary production (Krause et al. 2017).

The interface between the surface of the water and the atmosphere is another key component in water bodies: it controls influxes and effluxes of fundamental gases (e.g., CO_2 and O_2) between atmosphere and water, the inputs of depositions, and sunlight penetration, thereby mediating ecosystem production and community composition (Galgani et al. 2023). The accumulation of litter floating on the surface is well known, especially in seawater (Van Sebille et al. 2020): such an increase of an anthropogenic floating material may alter the natural water–air fluxes (e.g., gas exchanges), but the broader implications of this process are still unclear (Royer et al. 2018).

Alterations at the interfaces induced by plastic and potential ecosystemic impacts

Plastic, as a new widespread abiotic constituent of the ecosystem, may alter the exchanges of energy and matter between the aquatic ecosystem and other components, affecting the availability of nutrients, the dispersal of organisms, and the flow of mechanical and chemical energy. This may result in altered biodiversity patterns and ecological functions (Fig. 1). Here, the complex microbial community colonizing plastic fragments may play a pivotal role (Amaral-Zettler et al. 2020): this community, in fact, yields new patterns of resource utilization and exchange of nutrients and organisms, potentially further affecting the natural exchanges.

Exchanges at the water–air interface

In marine environments, plastic particles can accumulate in the surface microlayer of lakes and seas, owing to their low density (Van Sebille et al. 2020). Their amount can be substantially higher compared to the concentration in the water column. It has already been observed that floating plastic particles at the air-sea interface can also concentrate several microorganisms, notably (cyano)bacteria, diatoms and green algae (Amaral-Zettler et al. 2020; Yokota et al. 2017). Their metabolism can modify carbon dynamics and air-sea exchange of CO_2, likely due to an increased production of extracellular polymeric substances (EPS) that can concentrate in the surface microlayer. High concentrations of EPSs modify the physical composition of the air-sea interface, reducing exchanges of light, gases, and matter between the ocean and the atmosphere (Galgani et al. 2023). Plastic covered by autotrophs can also favor the efflux of several gases (e.g., nitrogen oxides and CO_2; Seeley et al. 2020; Zhang et al. 2022), while the degradation of its polymeric structure may also lead to further emissions of volatile compounds in the atmosphere (Huang and Xia 2024).

Preliminary evidence also suggests that floating plastics can impact the light influx in the water column, with potential implications for both primary productivity (Montoya et al. 2024) and heat transfer (VishnuRadhan et al. 2019). While this process is understudied, preliminary evidence from other compartments (e.g., atmosphere, Revell et al. 2021) warns about the likelihood of consequences for the water column. This can be even more marked if plastics are covered by biofilms, including autotrophs: the presence of plastics, in this case, can promote the spreading of epibenthic species with high growth rates, potentially inducing surface mats and algal blooms that might interfere with radiation influx (Binda et al. 2024).

Exchanges at the sediment–water interface

Plastic accumulated in sediment can affect this compartment's properties. For example, the hydrophobicity of plastic may decrease sediment permeability, impairing sediment–water interaction. Plastics have already been observed to alter sedimentation processes (Russell et al. 2023). Recent laboratory-scale analyses highlighted the changes in the cohesion and resistance to shear stress of sediment at increasing plastic concentration (Wu et al. 2024). Similarly, heat transfer in sediment is also observed to be affected (Carson et al. 2011). While these physical alterations of sediment have several important implications, further evidence is still very limited in the current literature. Studies from similar environmental compartments, such as soils, however, suggest that plastic affects water holding capacity and porosity, corroborating this preliminary evidence (Wang et al. 2022).

The colonization of plastics by a biofilm community can also have a central role in altering the natural exchanges at

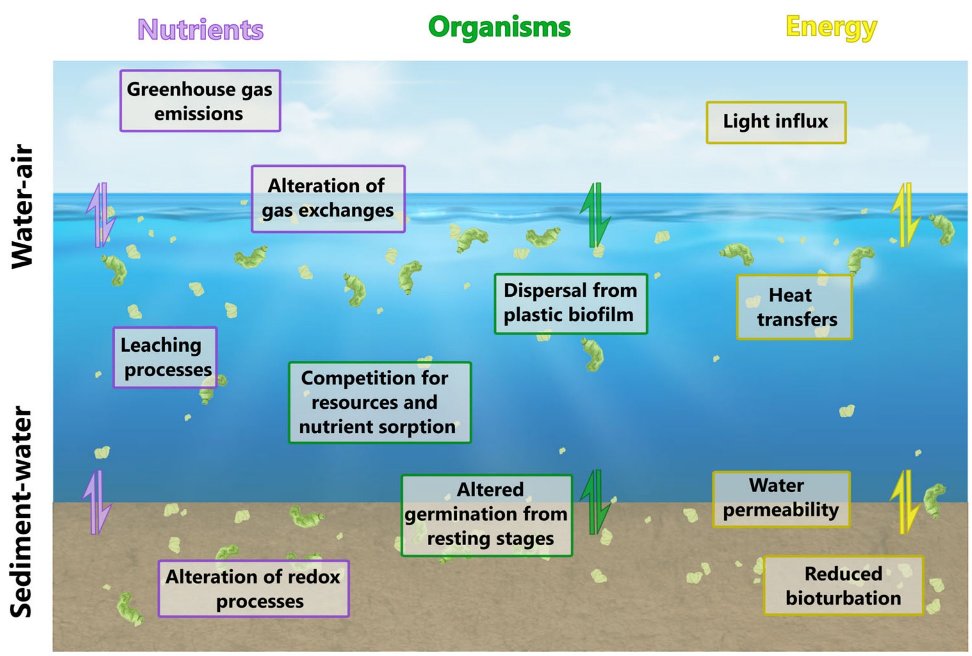

Fig. 1. Environmental processes impacted by the accumulation of plastic in the key interfaces of water bodies, affecting the exchanges of nutrients (purple), organisms (green), and energy (yellow).

the sediment–water interface. Biofouled plastics, in fact, have been observed to selectively sorb both major nutrients and trace metals, potentially altering their environmental fate (Huang and Xia 2024). As a further implication, recent studies highlighted the role of plastic fragments as substrates favoring the spreading of species that can compete with natural communities for resources (Binda et al. 2024; Nava et al. 2024). These processes can have far-reaching implications for ecosystem functioning.

Potential impacts on the pelagic ecosystem

The effects of plastic pollution on natural exchanges in key interfaces can affect the pelagic ecosystem too. Our understanding of how biofilms and plastics interfere with the availability of nutrients and biogeochemical cycling of elements is increasing, but important knowledge gaps remain. Potential impacts, in particular on carbon cycling, have been documented in an environmentally relevant scenario (Huang and Xia 2024; Rogers et al. 2020; Seeley et al. 2020). Virtually nothing is known about the likelihood of other potential consequences related to the dispersal of organisms and fluxes of energy, as these implications have been largely overlooked so far.

Several impacts on the pelagic ecosystem may be expected regarding community composition and ecosystem functioning. Here the presence of plastic biofilms specifically enriched in some species may play a pivotal role. For example, the presence of heterotrophs on biofilms leads to increased oxygen consumption and plastic can favor the dispersal of species typical of benthic communities through the pelagic domain (Ladewig et al. 2023; Nava et al. 2024). This can have further implications including: the blooming of invasive species and higher competition for resources, the production of cyanotoxins, and the enrichment of antibiotic-resistant genes in these biofilm communities. The likelihood of these ecosystem implications, however, is presently hard to assess.

Concerning the alteration of energy fluxes, changes in heat transfer and light influx may impact the germination of resting spores in sediments and phytoplankton community assembly in the water column. These effects are extremely likely to happen in the current environmental scenario, but the experimental evidence is still too limited to fully evaluate their relevance. Also, effects on gas and water exchange along the interfaces may alter the local redox conditions, altering solubility equilibria of (trace) elements. This may cause cascade effects for the community assembly, defining the available nutrients by resuspension and redox processes (Santschi et al. 1990).

Scaling the environmental relevance: Future work and key knowledge gaps

Research on the impact of plastic has primarily focused on several toxicological interactions with organisms, including humans (Thompson et al. 2024). However, recent and still fragmented evidence highlights the relevance of broader ecosystem effects. Addressing these more complex implications requires a comprehensive approach that not only considers plastic as a contaminant, but also as a habitat modifier and vector for microbial communities.

Table 1 summarizes the effects observed in experimental studies and the concentration at which they were observed. Environmental concentrations of plastic in sediments (Onoja et al. 2022) are likely to alter their chemical, biological, and hydraulic properties (Wazne et al. 2023; Wu et al. 2024), suggesting that ecosystem fluxes can already be affected. Preliminary evidence from in-situ experiments without plastic enrichments, for example, showed the alteration of oxygen and nitrogen fluxes (Ladewig et al. 2023).

Plastic concentrations highlighted in Table 1 in the water–air interface are up to two orders of magnitude higher than the average environmental concentrations (Thompson et al. 2024). It should be noted that most of these values are obtained through bulk sampling of water, which does not specifically consider floating plastic. Consequently, floating plastic hotspots with higher concentrations can occur. We would also highlight here that the concentration ranges mentioned in Table 1 are generally lower than concentrations showing (eco)toxicological effects in organisms through toxicity tests (Casabianca et al. 2021).

We recommend future research to assess the environmental relevance of plastic altering ecosystem fluxes and we encourage preliminary explorations of the potential effects in poorly investigated interfaces, such as the water–air interface in freshwater bodies and the sediment–water interface in marine ecosystems (Table 1). Multi-compartment assessments are needed to evaluate ecosystem-level implications and, primarily, the environmental relevance of these processes. Both lab-scale and mesocosm experiments are necessary to improve our understanding of the complex responses of biological communities to plastic pollution. Such studies are key to validate multiple endpoints of indirect effects mediating ecosystem exchanges (Bank et al. 2022).

Another key knowledge gap in understanding the ecological relevance of these effects is related to the residence time of plastic in such environments. Understanding degradation rates in different conditions along the water column will play a pivotal role in framing the environmental relevance of these processes to integrate the current knowledge on transport pathways and environmental fate (Van Sebille et al. 2020). In this context, the use of sediment traps would also help in understanding plastic floating-sinking dynamics in natural settings (Galgani et al. 2022).

We further propose that biofilms on plastic should be an important research focus, as they play a role in altering the biogeochemical cycling of elements and potentially spreading invasive organisms. Important knowledge gaps still remain in understanding the community dynamics of the biofilms formation on plastic fragments: several factors both related to

Table 1. Experimental evidence highlighting effects on the exchanges of nutrients, organisms and energy induced by plastic pollution. Research focused more on sediment–water interfaces, particularly in freshwater. Marine studies instead examined mostly the water–air interface, which remains unexplored in freshwater systems.

Interface	Ecosystem	Experimental setup	Plastic features	Concentration	Effect	References
Water–air	Marine ecosystem	In-situ mesocosm, floating nets of 50 m^3	Mixture of 5 polymers (polystyrene—PS, polyethylene—PE, polypropylene—PP, polyvinyl chloride—PVC, polyethylene terephthalate—PET) with size range 20–1000 μm	100 fragments/L	Light influx was reduced by plastic presence, enhancing phytoplankton productivity and altering microbial community structure	(Montoya et al. 2024)
Water–air	Marine ecosystem	Mesocosms, each with 3 m^3 of oligotrophic seawater	Standard PS beads of 30 μm diameter	430 particles/L	Reduced CO_2 concentration (about 3%) in the underlying water, increased production of organic carbon in the form of EPS and high accumulation of EPS in the sea-surface microlayer	(Galgani et al. 2023)
Sediment–water	Freshwater ecosystem	Microcosm including water, sediment and a benthic bioturbator	Mixture of PS and polyamide (PA) fragments with a variety of shapes and sizes (15–1500 μm)	700 particles/kg of sediment	Reduced bioturbation and oxygen exchanges, leading to more limited N and C mineralization	(Wazne et al. 2023)
Sediment–water	Freshwater ecosystem	Microcosm with natural water and sediment	PET analyzed for different grains size (varying from 5 μm to 2 mm)	0.5% by weight of sediment	Increased gas emissions (especially CO_2) with several grain sizes during the experiment	(Zhang et al. 2022)
Sediment–water	Freshwater ecosystem	Microcosm including lake sediment (300 g) with tap water (200 mL)	PET microplastics (diameter: 200 μm) irregular spherical structures.	0.5% by weight of sediment	Decrease in sediment viscosity over time and reduction of EPS	(Wu et al. 2024)
Sediment–water	Estuarine ecosystem	Microcosm including natural water (250 mL) and sediment (300 g)	53–300 μm fragments from consumer plastic, different polymer types (i.e., PE, PVC, polyurethane—PU, and polylactic acid—PLA)	0.5% by weight of sediment	Alteration of microbial community structure and denitrification rates, leading to altered nitrogen species concentration in the water	(Seeley et al. 2020)

polymer and environmental conditions can affect this process, but still knowledge is limited (Nava et al. 2024). Further investigations on the role of plastic as a specific substrate and other variables in defining biodiversity should be performed.

Summarizing, plastics can accumulate at key aquatic interfaces and can affect matter and energy exchanges. Biofilm formation on plastics may play a pivotal role in these processes: it can change plastic properties and favor the transfer of (micro)organisms. While research remains fragmented, evidence suggests significant ecological impacts, underscoring the need to focus on these interfaces and assess how the behavior of plastics shapes natural exchange processes in realistic conditions.

Author Contributions

Gilberto Binda: Funding acquisition, conceptualization, writing – original draft. Sudeep Chandra: Conceptualization, writing – review and editing. Margarida Costa: Conceptualization, writing – review and editing. Luisa Galgani: Investigation, writing – review and editing. Gabriela Kalčiková: Investigation, writing – review and editing. Eva Leu: Conceptualization, writing – review and editing. Steven Arthur Loiselle: Supervision, writing – review and editing. Luca Nizzetto: Conceptualization, supervision, writing – review and editing. Paula Noble: Conceptualization, writing – review and editing. Veronica Nava: Investigation, writing – review and editing. Daniel Roy Parsons: Supervision, writing – review and editing. Luka Šupraha: Conceptualization, writing – review and editing.

Acknowledgments

Authors disclose the use of Artificial Intelligence tools (specifically, ChatGPT 4.1, OpenAI) to correct grammatical errors and improve the clarity of the composed text and are responsible for all the content produced by these tools. This work was funded by the Research Council of Norway for the project "PATTERN—PlAsTic effecTs on the Exchanges of nutRienTs and biological information in aquatic ecosystems" (project number 345077). Gabriela Kalčiková acknowledge Slovenian Research and Innovation Agency (research program P2-0191 and *PLAStouch* [N2-0298] project) for financial support. This work was also supported by the Italian Ministry of University and Research, PNRR, Missione 4 Componente 2 funded by the European Union-Next Generation EU, project code CN_00000033, CUP 629 B63 C22000650007, project title "National Biodiversity Future Center-NBFC" to the University of Siena, funded by the (Luisa Galgani, Steven Arthur Loiselle). Open access publishing facilitated by Universita degli Studi dell'Insubria, as part of the Wiley - CRUI-CARE agreement.

Conflicts of Interest

None declared.

Data Availability Statement

No data have been generated in this manuscript.

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Submitted 03 June 2025
Revised 08 October 2025
Accepted 10 October 2025