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Risks of Plastic Debris: Unravelling Fact, Opinion, Perception, and Belief

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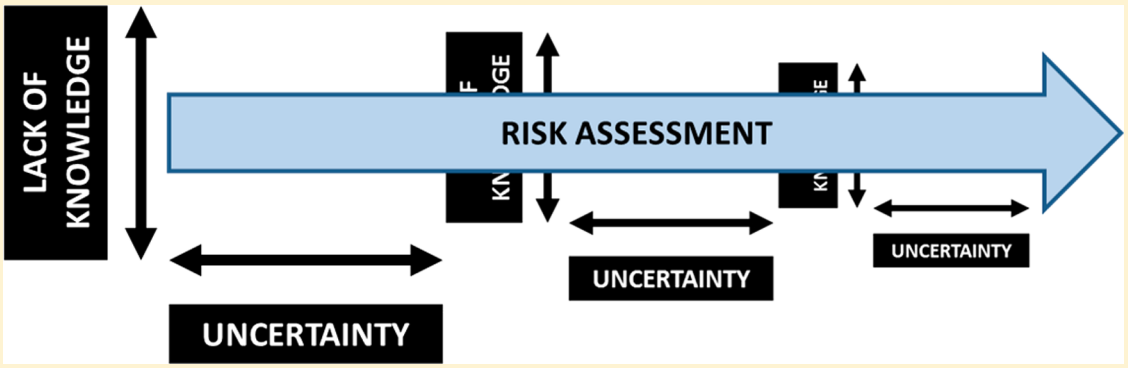

ABSTRACT: Researcher and media alarms have caused plastic debris to be perceived as a major threat to humans and animals. However, although the waste of plastic in the environment is clearly undesirable for aesthetic and economic reasons, the actual environmental risks of different plastics and their associated chemicals remain largely unknown. Here we show how a systematic assessment of adverse outcome pathways based on ecologically relevant metrics for exposure and effect can bring risk assessment within reach. Results of such an assessment will help to respond to the current public worry in a balanced way and allow policy makers to take measures for scientifically sound reasons.

■ INTRODUCTION

The potential risks of plastic debris for human health and the environment have received a growing amount of interest among the general public, media, policy community, and scientific community. Whereas for many chemical stressors established risk assessments have provided clarity about the likelihood of harm and impact, our understanding of plastic debris is still in the early stages.[1] There is no doubt that the presence of plastic debris in the biosphere is unwanted from an aesthetic, ethical, economic, and ecological point of view. However, the actual risks to human health and the environment remain highly uncertain. Some examples may illustrate that the presented data and strong views on plastic debris are frequently incomplete or contradictory.

Perceived impacts of plastic debris are mainly based on evidence of the presence of plastic, which often is framed as "huge" or "ubiquitous",[2,3] without taking into account the threshold concentration above which an effect occurs, or at least acknowledging that the actual risk is in fact indeterminate as long as environmentally realistic exposure concentrations are not compared to the effect thresholds.[4,5]

Adverse effects of natural materials or particles[6,7] may overwhelm or be similar to those of plastic debris,[8−10] which usually is not taken into account in the evaluation of hazards of plastic debris.

Plastic-associated chemicals are usually framed as an evident threat and inherently linked to the presence of plastic, even though recent research suggests that plastic ingestion does not necessarily affect the risks of such chemicals.[2,3,11−15]

As for the impact of plastic debris on human health, the ruling paradigm is that in the ocean environment zooplankton eat plastics, fish eat zooplankton, humans eat fish, and thus plastic is a threat to human health. Although at first sight this reasoning sounds plausible, it is arguable at the same time. The

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main uptake of microplastic (<5 mm particles) by fish is into the gastrointestinal tract, whereas, except for shellfish, it is mainly the fish filet that is consumed.[12,16]

As for inhalation risks, the presence of very small (i.e., <0.001 mm nanoplastic) plastic particles in air is likely, yet a balanced assessment may also require consideration of naturally occurring contaminated airborne particles, such as soot and black carbon.[17−19]

In the field of plastic research, the present proportion of nonstandardized preliminary results, gray literature, opinions, and even misperceptions seems relatively high.[5,8,14] Because in environmental chemistry and toxicology broadly accepted criteria[20,21] need to be met before toxicity claims are to be considered relevant, it is of particular importance to increase the quality of plastic research.

The mechanism of publication bias [i.e., the tendency of researchers and journal editors to prefer some outcomes rather than others (e.g., results showing a significant finding)] is well-documented in scientific research (e.g., ref 22), and this also plays a role in the young discipline of research on plastic debris. Journal editors have accepted conclusions about the environmental effects of plastic debris that are based on laboratory tests that used higher than realistic concentrations or unrealistic exposure scenarios,[5,11,14,23] mechanisms that both would artificially increase the number of reported effects.

Scientists differ in the way they convey their conclusions with respect to risks of plastic debris, due to their intrinsic motivations.[24] Scientists as policy advisors in an uncertain field like that of plastic debris can act as an issue advocate or as an honest broker.[25] The issue advocate seeks to reduce the range of policy options by promoting one specific view. The honest broker seeks only to expand or clarify the range of choices to the policy maker.

In their papers, scientists may have a reservation to definitively ascribe effects and therefore stress potential instead of actual risks of plastic debris. Although words like "potential", "maybe", or "could" are usually carefully reported in these papers, these subtle descriptions are often lost in the minds of policy makers and the public.

Finally, scientists may stress potential instead of actual risks of plastic debris to emphasize the relevance of the topic and enhance the availability of the research budget.

These points should not be taken as a plea for downscaling the attention to plastic debris in the environment. As the risks are uncertain and the concerns are considerable, plastics have rightly become an emerging political issue.[10] A common way to act upon the uncertainties and ignorance (i.e., lack of knowledge) regarding potential effects of plastic debris is to recognize it as a high-potential risk requiring urgent action.[26] As we will argue, this view is unbalanced. However, the other extreme position would be to take no action as long as any uncertainty about effects remains. Such an attitude delayed tobacco legislation for decades and still hampers control of greenhouse gas emissions.[27]

Clearly, contamination of our environment with plastic is a problem that is difficult to solve because there are many different ways to describe the problem, stakeholders view the problem differently, it is complicated by moral, political, or professional dimensions, and no efficient or optimal solutions exist (a so-called "wicked problem"[28,29]). The strong emotional involvement of the public as well as scientists makes it difficult to strike the right balance when addressing such problems. Microplastics are our newest contaminant of emerging concern[1,9] and require urgent attention. At the same time, the discussion has characteristics of a hype associated with unintended overreaction and exaggeration,[5,8] as illustrated in the examples listed above. This is a moral problem because research and mitigation efforts come at a cost and the resources for these are limited. Hence, research must focus on the most pertinent questions. Prioritizing efforts to control contamination with plastic debris is primarily the domain of policy, but there is an important role for scientists to provide the best possible information.

Here, we argue that it is high time to move away from the phase of framing effects, problems, hazards, threats, or concerns as "potential". We call for a more mature and rigorous approach in risk assessment with respect to plastic debris. Research should be prioritized in such a way that it is relevant for more rational risk assessments for plastic debris. We provide recommendations for a way to develop such a risk assessment framework for plastic debris of all sizes and in all habitats.

■ DEFINE THE ECOLOGICALLY RELEVANT METRICS (ERMS) FOR THE RISK ASSESSMENT OF PLASTIC DEBRIS

Developing a rational risk assessment framework for plastic debris comes with several challenges. For instance, the metric used to quantify the effect should be ecologically relevant and should be the same as the one used to quantify exposure.[30] For conventional chemicals, this "ecologically relevant metric" (ERM) is "concentration". Defining an ERM for plastic debris, however, is not a trivial issue because the material comes in numerous types, shapes, and sizes, with or without associated chemicals. The current inconsistent use of units, exposure media, and habitats makes it difficult to combine exposure and effect data in a meaningful characterization of the risk.[12] A way out of this ambiguity is to recognize that plastic debris comes with multiple ERMs. They can be characterized on the basis of known particle- and species-specific effect mechanisms [e.g., adverse outcome pathways (AOPs)[31,32]] for exposure and effects (Figure 1 and examples in Figure 2).[30,33] We suggest that an unbiased and relatively fast way of defining these AOPs and ERMs is by expert panel consultation [expert knowledge elicitation (EKE)[34]].

Another challenge is to account for the combined effects of all particles and chemicals in the mixture on organisms in a community.[35] Such approaches are available, such as response addition models[36] or dynamic energy budget models[37] (the technical explanation of which, however, is beyond the scope of this work).

■ EXPOSURE ASSESSMENT

Progress is quickly being made with respect to measuring plastic debris in the environment,[38] but present measurement methods are far from fully developed or standardized among laboratories.[38,39] Most significantly, present methods are not yet capable of measuring all plastics in a given sample (i.e., these methods have limited recovery), nor can they measure all sizes in a sample with sufficient accuracy;[40] no methods that can detect nanosized plastic particles in environmental samples exist.[41]

Furthermore, plastic debris abundances are expressed as number concentrations (e.g., one particle per liter). Especially at low concentrations, finding a particle in a volume is a matter of chance. Whereas for conventional chemicals a concept of

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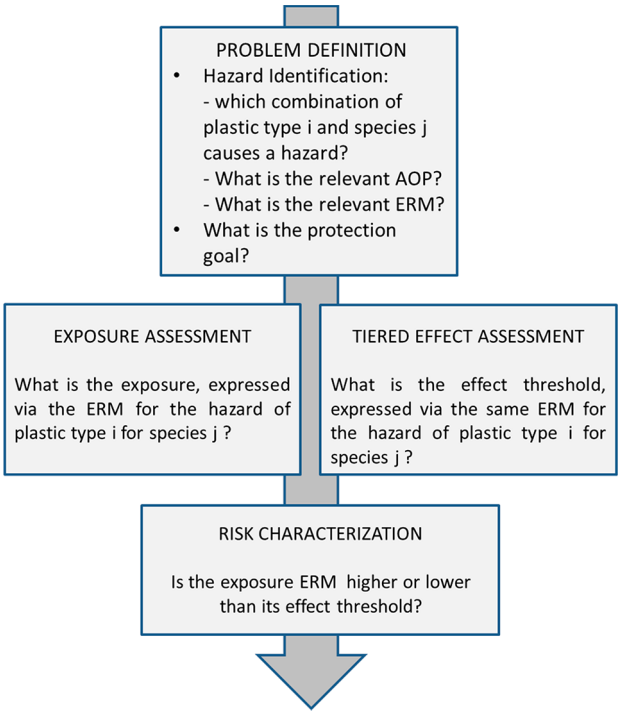

Figure 1. Generic ecological risk assessment framework for plastic debris linking protection goals, problem definition, exposure assessment, effect assessment, and risk characterization. "ERM" is the ecologically relevant metric for a specific adverse outcome pathway (AOP) concerning the interaction of a particular plastic particle type (i) with a particular species or species age group of interest (j). For an explanation of the tiers used within the effect assessment, see the text.

uniform concentration can be used, this is not adequate for plastic debris of all sizes. At sufficiently high concentrations, nano- or microplastic can be considered widely dispersed so that their risk assessment can use concentration-based ERMs. It has been reported, however, that >80% of the mass of marine plastic debris is macroplastic (i.e., >5 mm),[42] with a (very) low number count per unit of surface or unit of volume. Hence, research groups are developing model frameworks that use encounter frequencies between plastic items and biota to relate number concentrations in aquatic media with ingestion rate data.

Although monitoring is important, it will always remain fragmentary in time and space. Given the present uncertainties with respect to microplastic behavior in nature, assessing future trends from monitoring data is difficult. Given the fact that the environmental analysis of plastic debris is very laborious, the concept of defining ERMs is particularly useful because only those particle types that make it to an ERM may need to be assessed (see Figure 2). From a risk assessment perspective, there is no need to characterize plastic debris with accuracy higher than what is defined to be the ERM for a given habitat and protection goal. For example, nanoplastic concentrations are likely to be low in marine waters because of retention already occurring in source freshwaters and water treatments plants, due to simple dilution or due to fast aggregation,[43−45] fouling and/or sinking,[45,46] which inherently causes the nanoplastics to lose their nanoparticle characteristics. If this were the case, characterizing the risk of nanoplastics in marine habitats would be a lower priority.

Besides the determination of ERMs for exposure through measurement, they can be estimated by modeling. Fate and exposure models optimized to simulate ERMs for microplastics provide opportunities for geographical interpolation, for spatiotemporally explicit assessments in freshwater catchments and in the oceans, and for future scenario analysis.[44,45,47]

■ MEASURE EFFECT THRESHOLDS

Recent publications have sparked the debate about what microplastic concentrations are relevant to test.[5,23] As noted above, studies often find effects at unrealistically high exposure concentrations, which has prompted calls for testing environmentally realistic concentrations. Given the present data on concentrations at which adverse effects are to be expected, testing current realistic concentrations is likely to result in finding "no effect".[4,5] However, the realistic concentrations of today are not the realistic concentrations of tomorrow. In an assessment of future risk, where increased plastic production and progressive fragmentation of plastic particles would be accounted for, higher than present concentrations are relevant. Furthermore, the higher concentrations often tested in the current literature may very well be relevant occasionally, for instance, for a site-specific risk assessment. Instead of addressing just low or high concentrations, effect tests should use a range of concentrations that maximizes the chance of detecting the effect thresholds with statistical rigor. This implies that microplastic ecotoxicology research should adhere to the standard common practice in chemical risk assessment:[48] using a sufficient number of doses and sufficient replication to allow fitting of dose effect models that produce the traditional end points of ecotoxicology (i.e., LC_{50} or EC_{50}). To date, studies that follow such a rational approach are difficult to find in the literature about the adverse effects of plastic debris.[5,8]

■ APPLY TIERED EFFECT ASSESSMENT

For time and cost efficiency, tiered approaches are used routinely in chemical risk assessment,[49] and such approaches are also feasible for the risk assessment of plastic debris (Figure 1). For at least some of the relevant AOPs and ERMs, relatively simple "back of the envelope" effect assessments can be formalized, after which they can be included in a first tier of the effect assessment, and they rule out many of the present concerns regarding microplastics claimed in the literature. For instance, zooplankton will never suffer from the physical AOP "entanglement by fishing ropes", whereas it is unlikely that fin whales are physically impacted by the ingestion of microplastic. As for chemicals associated with plastic debris, they can affect species, including humans. However, it is relatively simple to assess that this would not be the case if (a) toxicity due to these chemicals is negligible compared to that of other chemicals in the total mixture of chemicals, (b) exposure to these chemicals is negligible compared to that via other exposure pathways like water, air, or regular food,[11,12] or (c) an increase in exposure to these chemicals due to ingestion of plastic debris would still not cause the level to exceed a toxicity threshold.[11]

However, for future emissions scenarios, for occasional "hot spots" of pollution with plastic debris, or for other unforeseen cases, the outcome of such a first tier may indicate a risk, and a trigger for higher-tier testing may be passed. Higher-tier approaches to demonstrate effects of plastic debris on wildlife should include dedicated assays and long-term field experiments.[9] Modeling approaches may be especially important to

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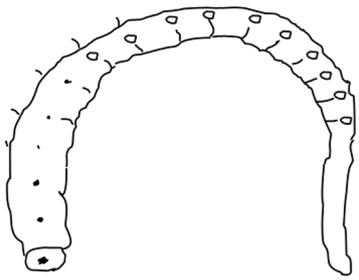
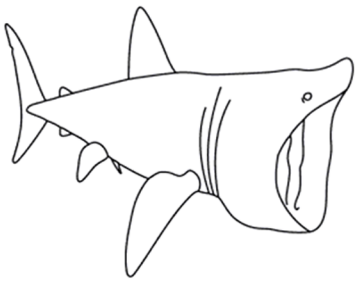
Lugworm



Plastic type	ERM nr	Suggested ERM	Potentially Relevant (Y/N)
Nanoplastic	1	#	Y
Highly contaminated microplastic	2	C	Y
'Clean' microplastic	3	#	Y
Rugby ball sized plastic item	4	#	N
Fishing net	5	#	N

Assess combined stressor effects

Basking shark



Plastic type	ERM nr	Suggested ERM	Potentially Relevant (Y/N)
Nanoplastic	1	#	Y
Highly contaminated microplastic	2	C	Y
'Clean' microplastic	3	#	N
Rugby ball sized plastic item	4	#	Y
Fishing net	5	#	Y

Assess combined stressor effects

Humans

Plastic type	ERM nr	Suggested ERM	Potentially Relevant (Y/N)
Nanoplastic	1	#	Y
Highly contaminated microplastic	2	C	Y
'Clean' microplastic	3	#	Y
Rugby ball sized plastic item	4	#	N
Fishing net	5	#	N

Assess combined stressor effects

Figure 2. Examples of ecologically relevant metrics (ERMs). A risk assessment for plastic debris could systematically distinguish among different species (here, lugworms, sharks, and humans), plastic types (here, nanoplastic, contaminated microplastic, clean microplastic, and two types of macroplastic), and ERMs [here, number concentration (#) or mass concentration (C)]. For the three species, example plastic types and their ERMs are provided with a provisional likeliness of effect indicated. Nanoplastic, which can penetrate cell membranes, could be available for all species with the number concentration as a useful ERM. Chemically contaminated microplastic would be available for all species with a chemical mass concentration as a useful ERM. "Clean" microplastics, that is, with chemical concentrations (far) below effect thresholds, would imply a physical risk for worms and for humans, but probably much less risk for a basking shark, and would cause a chemical risk for none of the species. Large plastic debris would be irrelevant for ingestion risks to species like worms or humans but might be relevant for the shark. Per species, the combined stressor effects need to be assessed, for instance, using approaches as described in the text.

support the risk assessment of ocean habitats,[50] as the complexity and scale of real life marine food webs are hard to capture in the laboratory. A higher-tier tool that can be applied to plastic debris could be the species sensitivity distribution (SSD) approach.[35] SSDs are useful tools for deriving effect thresholds on the level of communities. SSDs have been used most frequently for dissolved chemicals, but also for particles such as clay[6,7] and nanoparticles.[51] SSDs for microplastic ERMs would show the variation in sensitivity of species across microplastic doses and types and would calculate the proportion of species affected as a function of dose.

SEPARATE RISK OF PLASTIC DEBRIS FROM THAT OF ASSOCIATED CHEMICALS

Plastic debris is a hydrophobic material with a charged surface and/or a charged biofilm, which implies that this material will be contaminated with chemicals like persistent organic pollutants (POPs), pesticides, and heavy metals. These chemicals adsorb to and desorb from the plastic, depending on environmental conditions. Therefore, the chemical state and ecological risks of contaminated plastic will differ across time and space during the life cycle of a plastic particle.

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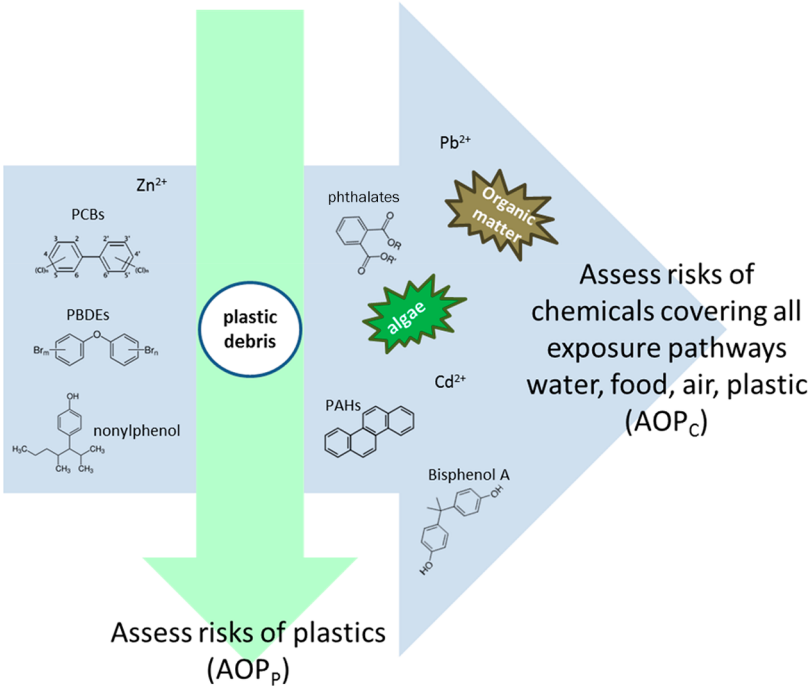

Figure 3. Separating the chemical component (horizontal arrow) from the physical component (vertical arrow) of the risk of plastic debris. If a certain type of plastic particle causes an adverse effect on an organism different from that of another type of particle, then it needs another ERM. Risk assessment of the plastic particle proceeds following adapted versions of existing frameworks for chemicals and/or particles.

Consequently, it is difficult to assess the risk of "contaminated plastic" in one go because its associated chemicals are not known unless a detailed and time-consuming characterization is performed. Therefore, we argue that risk assessment of plastic debris should separate the risk component of the plastic-associated chemicals from the risk component of the plastic material itself (Figure 3). Existing risk assessment approaches for mixtures of chemicals like the toxic unit (TU) or multispecies potentially affected fraction of species (msPAF) approach[35,52,53] first assess ecological effects for the individual components in the mixture, and then effect thresholds for the separate components in the mixture are used to normalize and combine the effects. This would mean that AOP effect thresholds for ERMs for the pure plastic material [physical AOPs (AOP_P in Figure 3)] need to be known and then considered together with those thresholds for both the chemicals associated with the plastic and those present in the ambient environment [chemical AOPs (AOP_C in Figure 3)]. Here, AOP_Ps could relate to the physical problems associated with plastic debris, like entanglement, starvation, suffocation, and blockage of the gastrointestinal tract, or to particle toxicity like inflammation. AOP_Cs would relate to chemical toxicity end points and can be characterized by direct effects, for example, those caused by interaction of chemicals with DNA, enzymes, or membranes, or by changing the osmotic pressure in cells.

Risks of plastic-associated chemicals can be accommodated through the existing regulatory approaches addressing chemical risks, e.g., the food safety regulations, REACH, Pesticide Directive, Toxic Substances Control Act, Industrial Chemicals Act, or the Stockholm Convention on POPs. These assess risk based on exposure through all relevant pathways for organisms, including humans, which in an environment contaminated with plastic are (drinking) water, food ingestion, absorption through the skin, and air inhalation.[16] For a region or location of interest, the chemical distribution among the plastic, the biofilm on the plastic, water, and food can easily be assessed, which provides a basis for assessing the relative importance of these exposure pathways.[11] Thus, this automatically assures that all exposure pathways (and not just chemical exposure via plastic ingestion, which would result in an underestimation of risk) are considered. After all, it is not very relevant to assess only the risk of a chemical associated with plastic. If an organism is exposed to a chemical through both ingestion of plastic and other pathways and experiences toxic responses, the risk assessment should take into account all responses, to protect the organism. Similarly, the risk assessment should address all compounds in the mixture, both those absorbed by the plastic and those in ambient water and food.

■ PROSPECT

The best basis for reducing plastic waste in the environment is a balanced assessment of costs and benefits.[10] Compelling and unambiguous evidence of the actual environmental risks will be helpful in this process.[9] To achieve this, we present a vision for the development of a rational framework for the risk assessment of plastic debris. Such a framework can follow the principles of traditional risk assessment approaches but needs to be tuned to the peculiarities of the material plastic. This is similar to the recent development of risk assessment frameworks for engineered nanomaterials, which feature similar differences from the framework for soluble chemicals.[30] A high-priority issue to address when developing such a framework for plastic debris is the many AOPs expected, which follows from the wide variety of potential harm mechanisms that plastics may cause. We provide a way forward by arguing how the use of ERMs and AOPs may facilitate risk assessment and by framing how the potential risks of plastic-associated chemicals best can be separated from those of the material itself. These concepts can be further developed toward technical guidance documents, and then actual risk assessments for plastic debris of all sizes

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will be within reach. Results of such an assessment inform policy makers and will reduce the present ignorance and uncertainty about ecological and human health risks.[1,54] This may bring the debate to rest, guide legislative processes, and help to balance worries about plastic debris relative to the many other environmental issues that require our attention.

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Notes

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