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Perspective

Invasion of the biosphere by synthetic polymers: What our current knowledge may mean for our future

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In 1974, a member of the Council of the British Plastics Federation and a fellow of the Plastics Institute, stated that "Plastics litter is a very small proportion of all litter and causes no harm to the environment except as an eyesore"(Derraik, 2002). It has taken less than fifty years for that opinion to be completely discredited, indeed, that opinion was already in doubt the moment it was stated. Nevertheless, it was the strong denial by the plastic industry that plastics could cause harm that delayed the study of plastic's environmental effects for decades. Not until Moore et al. (2001) found six times as much plastic as zooplankton by weight in the surface waters of the North Pacific Subtropical Gyre (NPSG), did plastic environmental pollution begin to receive increasing attention by scientists, policy makers, regulators, and the media, who began referring to the area as "The Great Pacific Garbage Patch", a term coined by an oceanographer, Curtis Ebbesmeyer (Ebbesmeyer and Scigliano, 2009). Today it is widely acknowledged that vagrant plastic waste is polluting oceans, rivers, soil, food, the water we consume, and even the air we breathe. The invasion of this synthetic waste into organisms is facilitated by the fact that with surface ablation and disintegration mechanisms over time, micro- and nano-sized synthetic polymers are created that can be readily assimilated into living organisms. Recent studies reveal that these micro- and nano- scale polymers, which sorb and desorb pollutants, can pass through the intestinal wall and from the lungs to the circulatory system and in contact with human cells produce reactive oxygen species (ROS), which are implicated in many pathologies (Schirinzi et al., 2017). As primarily a marine scientist, I focus on the threats to marine ecosystems, but the topic of plastic pollution has grown to global proportions affecting not only the biosphere, but geological formations as well. Here I present a summary of the work done to date to understand our situation and discuss briefly the future of plastic pollution.

Use of plastic in construction of natural structures:

(1) As early as 1973, Kartar et al. (1973) reported polychaetes in the Severn estuary incorporating plastic pellets into their dwelling tubes.

(2) I have observed nests of birds and rodents with plastic as a nest building material.

(3) MacIvor and Moore (2013) found bees constructing brood cells with bits of plastic bags and polyurethane sealant.

(4) Reichert et al. (2018) found that reef building corals built their bodies around adhering plastic particles.

(5) Corcoran et al. (2014) identified in Hawaii "...the appearance of a new 'stone' formed through intermingling of melted plastic, beach sediment, basaltic lava fragments, and organic debris...which could be preserved by burying in marine sediments and signals...the occurrence of the informal Anthropocene epoch".

(6) Beach sands are increasing the percentage of microplastics incorporated and the speculation by Gregory (1977) that mankind will sunbathe on plastic sand beaches is becoming a reality.

Use of plastic as an aid in reproduction and range extension for organisms:

(1) Gregory (2009) called out "alien invasions" on plastic: "Dispersal of aggressive alien and invasive species...could endanger sensitive, or at-risk coastal environments (both marine and terrestrial) far from their native habitats."

(2) Zettler et al. (2013) found that these invaders were composed of unique communities that: "...are distinct from surrounding surface water, implying that plastic serves as a novel ecological habitat in the open ocean".

(3) Goldstein et al. (2012) found that floating plastic in the NPSG... "released the pelagic insect *Halobates sericeus* from substrate limitation for oviposition. High concentrations of microplastic in the NPSG resulted in a positive correlation between *H. sericeus* and microplastic, and an overall increase in *H. sericeus* egg densities."

(4) In a survey of benthic plastic, Gündoğdu et al. (2017) stated: "plastic debris as a substrate can contain a very high diversity of life just like natural substrates". And for organisms on surface plastics, Goldstein et al. (2014) observed that: "diversity patterns on plastic debris are compatible with the concept of island biogeography".

Given these findings, it seems logical to conclude that an increase in plastic "islands" would correspond to an increase in associated populations of organisms adapted to the introduced plastic habitat, and if in an area of limited food resources, that there would be a decrease of certain members of the indigenous population. As in any major ecosystem disruption, there will be winners and losers. In the marine environment of the depauperate gyres, where floating plastics accumulate, winners are likely to be epibionts and losers true pelagics. In the area where I work, the NPSG, I have noticed fewer salps as the number of barnacles on marine debris increases.

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Ingestion of plastic by organisms:

(1) Plastic ingestion by marine megafauna (Germanov et al., 2018), fishes (Boerger et al., 2010; Lusher et al., 2013; Rochman et al., 2015), birds (Robards, 1993; Moser and Lee, 1992; van Franeker et al., 2011), jellyfish (Macali et al., 2018), marine worms (Browne et al., 2013), bivalves, corals (that have been said to find the plastic "tasty"), and zooplankton, point to the ability of synthetic polymers to mimic natural food throughout the entire food web, even in terrestrial soils, where Zhu et al. (2018) found that a common soil arthropod consumed plastic, which perturbed their gut microbiota. Plastic "food" does not provide nutrients, or decompose in the digestive tract. Rather it blocks passages, delivers pollutants and damages the epithelial lining.

(2) Plastic in its most insidious form is micro and nano sized; whether formed purposely for commerce or through the wearing and weathering of larger objects. At these size classes it has been shown to enter the brain of fishes and the physical features of the particles themselves cause more damage than the associated pollutants (Mattsson et al., 2017). The authors noted physiological and behavioral changes in the fish: less water than normal in the brain, less time feeding and less distance covered looking for food.

(3) Small plastic fibers and fragments are being ingested by humans in salt from different countries (Karami et al., 2017), in all types of water tested (Schymanski et al., 2018), and through respiration by humans, causing an inflammatory response and lesions in human cells (Prata, 2018). Catarino et al. (2018) stated that: "Our predictions of microplastics ingestion by humans via consumption of mussels is 123 particles every year for each person in the UK and can go up to 4 620 particles every year for each person in countries with a higher shellfish consumption. By comparison, the risk of plastic ingestion via mussel consumption is minimal when compared to fibre exposure during a meal via dust fallout in a household (13 731–68 415 particles every year for each person)."

Physiologists are beginning to assess the health impacts to humans and other animals caused by ingestion of micro- and nano-plastics, their two major lines of inquiry may be categorized as:

(1) Kinetics—how does the plastic get into organisms and where will it go?

(2) Effects—what will the plastic and associated toxicants do once assimilated into an organism?

These criteria are used in a request for proposals by the Dutch government, which has put up a million Euros to study human health impacts of plastics.

In Greek mythology, Zeus, king of the gods, created the first woman on earth, Pandora, in order to deliver a punishment to the first men for having obtained fire stolen from the gods. Pandora was made to be beautiful so that her delivery of the god's punishment to mankind in a sealed earthen jar would not raise an alarm. Pandora did not know there was anything dangerous in the jar, and though she had been warned to never open it, her curiosity overcame her, and when all around her were asleep, she opened it. Out flew "the thousand natural shocks that flesh is heir to" (Hamlet, Act III, Scene 1). When she saw what she had done and felt the stings of bugs she released, she attempted to put the troubles back in the jar without success. Plastics, like fire, confer innumerable opportunities for mankind, but mankind has not kept shut the jar containing plastic waste, and it is now impossible to retrieve it. The set of troubles caused by plastic waste is of a magnitude to affect essential planetary systems such as water, air and soil.

Dust and marine sediments were formerly of mineral origin and settled out of air and water or were removed through the action of natural barriers and other mechanisms. Plastic has characteristics that vary widely depending on type of polymer, but many plastics become neutrally buoyant, yet sediment-like and proliferate at different levels in the water column in complex ways, and their similarity to natural fibers allows them to occupy environmental niches formerly occupied by natural, biodegradable materials. The dictum that "in ecosystems, nothing is wasted" is challenged by synthetic polymers. Plastic waste accumulates and becomes more than ecosystems can process. This situation has been conceived of as the crossing of a "planetary boundary". Three criteria are used to determine if plastic pollution is a planetary boundary threat: Is it poorly reversible? Are there effects only visible at a planetary scale? Is there a disruptive effect on Earth-system processes?

Criteria 1 has clearly been met. It will be impossible to remove plastic waste from most niches of the environment.

Criteria 2: Villarrubia-Gómez et al. (2017) state: "...despite the fragmented state of current evidence, the mismanagement of discarded plastic is already implicated in globally systemic alteration to food webs, habitats, and biogeochemical flows". If it is not clear that criteria 2 has already been met, it shortly will be. In my own research, I have identified large areas of the ocean where surface plastics outweigh and in some cases outnumber the associated zooplankton (Moore et al., 2001).

Criteria 3: While most investigators believe that this question remains to be answered, and their focus is mainly on how ocean plastics retard carbon sequestration (Villarrubia-Gómez et al., 2017), I believe there is enough evidence from widely diverse sources to make the claim that the fitness of earth's biology as a whole is negatively affected by plastics and their associated chemicals. I believe that there are only negative consequences of plastic ingestion, that it is occurring on a planetary scale, and that it is rapidly increasing. Curtis Ebbesmeyer has termed ocean plastic pollution, "the greatest infection of the sea", and plastic pollution of air and fresh water threatens the circular loop of the water cycle as a clean source for drinking.

Over a decade ago, it was recognized at a conference where I presented, held by the World Federation of Scientists in Erice, Sicily, that the pollution of water by plastic was a planetary emergency. During that conference, I was able to enlist an editor of the Philosophical Transactions of the Royal Society to devote an issue to the problem. I was one of the editors of "Our Plastic Age", along with Richard Thompson, Fred vom Saal and Shanna Swan (Thompson et al., 2009). We were able to publish the first connection between chemicals sorbed to plastics and their transmission to wildlife (Teuten et al., 2009). Vagrant plastics may not be the main link in the transfer of manmade toxicants to biological systems, but their role is ever increasing.

The timid response to this planetary emergency caused by misuse of what I term "the solid phase of petroleum" is in part due to the adoption of petroleum industry tactics by the plastics industry. In papers quantifying plastic entering the environment, "leakage" is a term often used. Although plastic is a solid, it can spill (Webster definition: to cause or allow accidentally or unintentionally to fall, flow, or run out so as to be lost or wasted). Industries' modus operandi is to *spill*, *study and stall*. Compared to the petroleum industry, the plastic industry has done little to study the problem of plastic waste, preferring to put the blame on consumers for irresponsible disposal, and the cost of research and cleanup is borne by both governmental and non-governmental institutions and society at large. Industry lobbyists have spent millions of dollars to stall proposed remedies such as carrier bag bans. Industry has not, however, resisted the regulating of plastic pellet loss from factories in the State of California, acknowledging the loss of virgin polymer feedstock as their "personal responsibility problem". Thus, based on my research funded by the California Water Resources Control Board to find how much of this plastic industry feedstock was lost to the aquatic environment; we were able to pass legislation to make their discharge illegal in California. As with most regulations, enforcement lags behind legislation.

Natural disasters such as floods, hurricanes and tsunamis also release millions of tons of plastic into the environment. If plastic were liquid petroleum, technologies would be deployed to retrieve the material after a disaster, but no laws or regulations mandate such a response for plastic, even though plastic will persist far longer in the environment than petroleum, and potentially cause more harm over time.

Part of the problem with our response to the plastic pollution crisis is the unrealistic assessment of possibilities by researchers themselves. In a paper titled "Global research priorities to mitigate plastic pollution impacts on marine wildlife", Vegter et al. (2014) concludes by saying: "Although there are still many questions surrounding the issue, the numerous negative impacts of plastic pollution make it clear that we must strive to reduce the amount of plastics reaching our oceans. If the methods for doing so are attainable (e.g., reducing plastic use, improvements in waste management, better access to recycling) and the costs are non-prohibitive, it would be feasible to deal with what is ultimately an entirely avoidable problem." It seems that at just this point, the scientists stop being objective and revert to fantasy. On a global scale, there is no evidence that the methods enumerated for reducing the amount of plastics entering the ocean are attainable. Plastic use will surge with 3-D printing of everything imaginable, recycling costs are prohibitive and the fraction of plastic waste recycled globally remains under 10%. Waste management is focused globally on incineration and landfilling, both of which create greenhouse gasses and waste the billions of dollars spent on the fabrication of valuable commodities from plastic feedstocks. Given the difficulty of capturing ubiquitous plastic of all types and sizes from earth orbit to the ocean depths, I ask: In what fantasy universe is plastic pollution "an entirely avoidable problem"?

In the Greek myth, Pandora, after releasing the world's torments, tried to put the lid back on the jar where they were once contained, but she failed. As she sat crying, one last creature flew out. Zeus had sent *Hope* to compensate mankind for its perpetual struggle. While there may be no hope of cleaning plastic from the environment in the foreseeable future, there is hope that mankind can respect and fear plastic enough to treat it with great care, by designing products and creating take-back infrastructure that makes plastic benign. It is difficult to imagine this, however, in a world where plastic is the omnipresent facilitator of global trade by packaging commodities in a vapor and moisture barrier, preserving "newness". But when the wrapper is ripped off, it becomes useless, and for many of the products it contains, the newness quickly fades, and they are replaced sooner rather than later. Hope seems a weak ally in the fight against the plastic plague overtaking our precious ocean, our land, our air, our water, and even the space around us with millions of waste plastics in earth orbit. The only ally powerful enough to push back against the "Plastic Attack", is us, all of us, and it will require that we fear plastic sufficiently to demand reduction in its use drastically. That fear will only come when plastic's dangers are widely exposed. Scientists are helping in this effort, as nature herself begins to spew plastic vomit worldwide. A world economy dependent on making and reproducing persistent, destructive and unrecoverable waste en masse is in no sense, sustainable.

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