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Review

Sources and sinks of plastic debris in estuaries: A conceptual model integrating biological, physical and chemical distribution mechanisms

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A B S T R A C T

Micro- and macroplastic accumulation threatens estuaries worldwide because of the often dense human populations, diverse plastic inputs and high potential for plastic degradation and storage in these ecosystems. Nonetheless, our understanding of plastic sources and sinks remains limited. We designed conceptual models of the local and estuary-wide transport of plastics. We identify processes affecting the position of plastics in the water column; processes related to the mixing of fresh and salt water; and processes resulting from the influences of wind, topography, and organism–plastic interactions. The models identify gaps in the spatial context of plastic–organisms interactions, the chemical behavior of plastics in estuaries, effects of wind on plastic suspension–deposition cycles, and the relative importance of processes affecting the position in the water column. When interpreted in the context of current understanding, sinks with high management potential can be identified. However, source–sink patterns vary among estuary types and with local scale processes.

Contents

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1. Introduction

Accumulation of synthetic organic polymers, known as plastics, threatens ecosystems worldwide. Plastic production has grown continuously from 1.5 million tonnes in the 1950s when commercial production took off to approximately 311 million tonnes in 2015 (PlasticsEurope, 2015; Thompson et al., 2009). Because of their unique properties including their use at a wide range of temperatures, chemical and light resistance, strength, toughness, ease of manipulation and low cost, plastics have become widely integrated in our everyday life (Andrady and Neal, 2009). Plastics have applications in diverse fields such as transport, telecommunications, clothing, footwear, packaging, storage, medical devices and energy savings and production, all of which have resulted in great benefits to society (Andrady and Neal, 2009). However, the durability and mobility of plastics, coupled with unsustainable use and inappropriate waste management have presented a global problem. Indeed, plastics are accumulating in terrestrial and marine environments from the equator to the poles (Barnes et al., 2009; Moore, 2008).

Early studies in the 1970s reported marine pollution of large visible plastic debris (named “macroplastics”, see the following sections) but drew limited attention (Andrady, 2011; Derraik, 2002). However, in the early 1990s, an increasing number of reports on the effects of macroplastics, via their ingestion and entanglement of charismatic marine fauna such as dolphins, whales, turtles and seabirds, spurred interest among the scientific community and general public (Andrady, 2011; Derraik, 2002). Subsequent research demonstrated multiple health problems related to the ingestion of macroplastics (Gall and Thompson, 2015; Gregory, 2009; Laist, 1997). For example, macroplastics can trigger abrasions and ulcers and cause blockages of the digestive tract, all of which can result in starvation and physical deterioration. Moreover, macroplastics can lead to a reduction of reproductive fitness, drowning, lowered predator avoidance, impairment of feeding ability, increased uptake of toxicants from seawater and death (Gregory, 2009).

Recently, the presence of large amounts of smaller plastics referred to as microplastics (<5 mm along its longest axis) in the environment has caused growing concern. These microplastics were previously overlooked, but have likely been in the marine environment since at least the 1960's (Thompson et al., 2004). Primary microplastics can originate as direct inputs into the environment. These include resin powders and pellets used as feedstock in plastic production, in air blasting, and in cleaning and cosmetic products (Cole et al., 2011; Gregory, 1996). Alternatively, secondary microplastics can result from fragmentation of macroplastics under influence of moisture, temperature, UV and oxygen, or via biotic interactions (Andrady, 2011; Cole et al., 2011). Fragmentation in the environment is mainly driven by photo-oxidative degradation, followed by thermal- and biodegradation. The rate and mechanism of fragmentation, however, varies among polymer types. For example, polyethylene (PE) is more readily fragmented by weathering events, while polypropylene (PP) fragments slower and is more subject to mechanical degradation (Cooper and Corcoran, 2010). Because of the diverse origins of microplastics, a variety of point and non-point sources can contribute to their pollution in the environment. For example, wastewater treatment, sewage sludge, fisheries, cargo shipping and ports, industrial plastic production sites and runoff from urban, agricultural and industrial areas have been identified as microplastic pollution sources (Wagner et al., 2014).

Authors use different size categories for plastics and other anthropogenic debris, including terminology such as micro-, meso-, macro- and megaplastics; but also small, medium and large (Hidalgo-Ruz et al., 2012; Ivar do Sul and Costa, 2013). The size limits of these categories often vary relative to the aims of the study. For example, Donohue et al. (2001) classify items larger than 25 m^2 as megadebris, while Ribic et al. (1992) classify items 2 to 3 cm in size as megadebris. Similarly, microplastics are frequently defined as smaller than 1 mm (Costa et al., 2010) or smaller than 5 mm (Arthur et al., 2009), with some authors making a distinction between small (<1 mm) and large (1–5 mm) microplastics (Imhof et al., 2012). Lower size limits of microplastics are similarly variable and often not clearly reported (Costa et al., 2010). The lack of agreement in terminology leads to difficulties in interpreting and comparing results from the literature. This is further augmented by the fact that sampling designs, including mesh sizes and sampling areas and volumes, follow the varying size-class definitions. The lack of an agreed definition is one of the most crucial limitations in advancing towards a common understanding of plastic pollution. We will use 5 mm along its longest axis as the upper size limit form microplastics following a trend by the main publications in the field and the proceedings of a NOAA research workshop on the topic (Arthur et al., 2009). All plastics above 5 mm will be referred to as macroplastics, unless explicitly mentioned.

Microplastics overlap in size range with sediments and plankton. Consequently, they become available for uptake to a diversity of organisms (Wright et al., 2013). Additionally, microplastics can transfer throughout the food web (Farrell and Nelson, 2013). Consequently, a wide range of organisms going from zooplankton, invertebrates, fish and birds to whales have been found to contain microplastics in their guts and tissues (Wright et al., 2013). Potential impacts of microplastics on wildlife are numerous, including: blockages of the digestive system, abrasions of organs, inhibition of enzyme production, lowered feeding rates, growth rates and hormone levels, delayed ovulation and reproductive failure (Galgani et al., 2010). These effects are augmented as microplastics are also vectors for chemical additives, heavy metals and persistent organic pollutants (POPs), and substrates for non-native and pathogenic communities (Engler, 2012; Zettler et al., 2013).

Estuaries are among the most valuable ecosystems of the world, providing a variety of goods and services such as food, medicines, wood, coastal erosion defence, storm surge protection, nurseries for commercially important fish species and traps for pollutants (Costanza et al., 1997; Ronnback, 1999). Consequently, the proliferation of plastics in these ecosystems could pose a threat to human livelihoods, economic activities and human health. Plastic pollution is likely to increase dramatically in estuaries because urban and economic centres thrive there and concentrations of plastics are correlated with population size (Browne et al., 2011; Seto, 2011; Yonkos et al., 2014). Estuaries are traditionally seen as a sink for pollutants (Costanza et al., 1997) and are likely to also accumulate plastics (Browne et al., 2010). For example, over a period of just 9 years until 2012, microplastic concentrations increased from 0–16 to 12–63 particles per kg dry sediment in a Singapore estuary (Nor and Obbard, 2014). In terms of abundance, microplastics accounted for 65% of debris recorded within the Tamar Estuary, UK (Browne et al., 2010). In a Brazilian estuary, the amount of microplastic in the water column at times surpassed the abundance of planktonic fish eggs and larvae (Lima et al., 2014). Due to the dynamic nature of estuaries, micro- and macroplastics can potentially remain in large estuarine ecosystems for extended periods and undergo significant degradation (Ivar do Sul et al., 2014). Moreover, burial is a major sink for plastics on beaches (Kusui and Noda, 2003) and could also be a mechanism for long term storage in estuaries. Indeed, the anoxic conditions that often prevail in estuarine sediments limit further fragmentation and degradation of plastic debris (Andrady, 2011; Williams and Simmons, 1996). However, whether estuaries act primarily as a source or a sink for plastics and which locations within estuaries are more prone to plastics accumulation is currently unclear.

A number of reviews, mainly focussing on the marine environment, have emerged regarding plastic pollution. These reviews address a range of topics including methodological issues (Hidalgo-Ruz et al., 2012; Rocha-Santos and Duarte, 2015), degradation mechanisms (Andrady, 2011), sources, distribution patterns and impacts on the environment (Barnes et al., 2009; Cole et al., 2011), interactions with toxic chemicals (Engler, 2012), effects on organism and human health (Thompson et al., 2009; Wright et al., 2013), future research directions

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