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An estimation of the average residence times and onshore-offshore diffusivities of beached microplastics based on the population decay of tagged meso- and macrolitter

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ABSTRACT

Residence times of microplastics were estimated based on the dependence of meso- and macrolitter residence times on their upward terminal velocities (UTVs) in the ocean obtained by one- and two-year mark-recapture experiments conducted on Wadahama Beach, Nii-jima Island, Japan. A significant linear relationship between the residence time and UTV was found in the velocity range of about 0.3–0.9 $\mathrm{m\,s^{-1}}$, while there was no significant difference between the residence times obtained in the velocity range of about 0.9–1.4 $\mathrm{m\,s^{-1}}$. This dependence on the UTV would reflect the uprush-backwash response of the target items to swash waves on the beach. By extrapolating the linear relationship down to the velocity range of microplastics, the residence times of microplastics and the 1D onshore-offshore diffusion coefficients were inferred, and are one to two orders of magnitude greater than the coefficients of the macroplastics.

1. Introduction

A wide range of applications of plastics utilizing their unique properties, such as light weight, durability, excellent oxygen/moisture resistance and bioinertness, has resulted in the exponential growth of global plastic production from 5 million tons in the 1950s to 322 million tons in 2015 (Andrady, 2011; PlasticsEurope, 2016). Our lives have become highly dependent on plastics. As a result, 275 million tons of plastic waste was generated in 192 coastal countries in 2010, with 4.8 to 12.7 million tons of mismanaged plastics entering the ocean (Jambeck et al., 2015). When exposed to solar ultraviolet (UV) radiation with a higher oxygen concentration, marine plastics undergo photo-oxidative degradation and gradual fragmentation. These small plastic fragments have spread widely in the marine environment, namely the sea surface, water column, beaches, and bottom sediment (Thompson et al., 2004; Andrady, 2011; Cole et al., 2011; Hidalgo-Ruz et al., 2012). These fragments of plastics pick up persistent organic pollutants (POPs) in the sea water and develop high concentrations of POPs (Andrady, 2011; Cole et al., 2011), and, in addition, they are easily ingested by marine organisms (Shaw and Day, 1994; Derraik, 2002; Browne et al., 2008; Boerger et al., 2010; Murray and Cowie, 2011). Thus, plastic fragments are considered to be a transport vector of toxic chemicals and contaminants, affecting the ocean food web (Mato et al., 2001; Thompson et al., 2004; Andrady, 2011). The unique properties of plastics have made marine plastics pollution a worldwide, long-lasting problem.

Fragments smaller than 5 mm in size are generally defined as microplastics (Barnes et al., 2009). To understand the adverse effects of microplastics on marine biota, we have to evaluate the standing stock of micro- ($<$ 5 mm), meso- (5–25 mm), and macroplastics ($>$ 25 mm) (Lee et al., 2013; Romeo et al., 2015) in the reservoirs, namely, the sea water column, sea surface, coastal sediment, coastline, deep ocean floor, marine biota, and also the plastic fluxes between the reservoirs (Hardesty et al., 2017). However, the total budget of microplastics in the ocean environment remains unknown. When we consider the reservoir as a linear input/output system, the cohort population decay of remnant plastics in the reservoir, which is measured to calculate the residence time, describes the unit impulse response of the system. We can estimate the temporal variation of the standing stock by the convolution integral of the inflow flux and the unit impulse response. And, conversely, when a time series of the standing stock is obtained, the inflow flux can be estimated by applying the inverse Fourier transform to the time series and the unit impulse response (Kataoka et al., 2013). Therefore, measurement of the residence times of plastics in each reservoir is of crucial importance for a comprehensive understanding of the budget of microplastics.

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Beaches are considered to be a hotspot of microplastic generation (Andrady, 2011). The fragmentation rate of beached plastic per unit time would be closely related to the cumulative age of the plastic, that is, the cumulative duration that the plastic had spent washed ashore on beaches, which is estimated by its residence time on all the beaches. Thus, the total amount of fragmentation on the beach per unit time could be estimated from the total cumulative age of all the plastics remaining on the beach (Kataoka and Hinata, 2015). Mesoplastics and macroplastics wash ashore, deteriorate, and break into small pieces that are backwashed offshore by swash waves and wave-induced nearshore currents (Isobe et al., 2014; Kataoka et al., 2015). In the future, this process should be considered and implemented in the present oceanic transport models (e.g., Yoon et al., 2010; Law et al., 2010; Eriksen et al., 2013; Lebreton et al., 2012; Maximenko et al., 2012; Kako et al., 2014) to evaluate the standing stock of plastics in different size classes in each reservoir, the fluxes between the reservoirs, and the microplastics generation rate on beaches throughout the world.

Hinata and Kataoka (2016) proposed a simple model for calculating the flux of plastics in different size classes between a beach and offshore based on mark-recapture experiments on macroplastics. In addition to ocean and land cells, the model also includes beach cells, and the backwash flux of beached plastics ($F_{bw}(t)$) is calculated based on the 1D onshore-offshore diffusion coefficient ($\langle D_p \rangle$), the amount of beached plastics ($R(t)$) and the backshore width (B) as:

$$F_{bw} = \langle D_p \rangle \frac{R(t)}{B^2}. \tag{1}$$

The diffusion coefficient can be estimated by the residence time (τ) of the plastics on the beach:

$$\langle D_p \rangle \approx \frac{B^2}{\tau}. \tag{2}$$

The diffusion coefficient would be closely related to the diffusivity in the surf zone during storm events (Kataoka et al., 2015). In the model, the beaching flux of plastics from offshore to the beach might be calculated using, for example, the Stokes drift velocity, wind-driven current velocity and the amount of plastics in the ocean cells adjacent to the beach cell (Hinata and Kataoka, 2016).

The mark-recapture experiment (MRE) is the most common method used to evaluate the residence times of mesoplastics and macroplastics on a beach (e.g., Bowman et al., 1998; Garrity and Levings, 1993; Kataoka et al., 2013, 2015). However, due to the difficulty of recapturing all the marked or colored microplastics remaining on and in the sand, estimating the residence time of microplastics is practically impossible by conducting MREs in the same manner as in the previous studies. How can we estimate the residence time of microplastics on a beach?

Isobe et al. (2014) reported that the quantity of mesoplastics gradually increased close to the coast and microplastics were more dominant offshore in the coastal waters west of Shikoku Island. They successfully reproduced the near-shore trapping of mesoplastics by a numerical model considering the Stokes drift and size-dependent upward terminal velocity (UTV), which indicated that mesoplastics were selectively conveyed onshore by a combination of Stokes drift and their larger upward terminal velocities. They considered that mesoplastics washed ashore on beaches and degraded into microplastics, and that the microplastics, which are free from near-shore trapping, subsequently spread offshore in coastal waters. Based on a balance between a buoyant upward advection flux and a vertical turbulent flux of microplastics in a steady state, Kukulka et al. (2012) demonstrated that the larger microplastics with larger UTV were distributed in the shallower depths in the surface mixed layer, and that the smaller microplastics with smaller UTV were widely distributed from the deeper to the shallower depths in the layer.

Motivated by their works, we hypothesized that the residence time of macroplastics, mesoplastics and microplastics depends on their UTV in the ocean, or its equivalent, their size and specific gravity: the larger the velocity of the item, the longer its residence time, since beached plastics with a larger UTV are likely to drift on the water surface (not likely to sink by being trapped by eddies under breaking waves) and be pushed to the upper backshore by swash waves. If we find a significant relationship between the UTV and residence time for macroplastics and mesoplastics, we could infer the residence time of microplastics by extrapolating the relationship down to the UTV range of microplastics.

Here, we examined the dependency of the residence time of three types of plastic floats (macroplastic) and small pieces of wood (mesolitter) on their UTVs based on the results of one- and two-year MREs on Wadahama Beach, Nii-jima Island, Japan. Specifically, we plotted the estimated residence times with respect to their UTVs and inferred the residence times of microplastics on the beach by extrapolating the relationship obtained by regression analysis. This study is the first step toward gaining a comprehensive understanding of the "true" residence time of microplastics and conducting numerical simulations considering the backwash flux of microplastics from beaches to coastal oceans.

2. Data and method

To obtain the relationship between the UTV and residence time, we measured the residence times of beached litter in different size classes by conducting one- and two-year MREs. The residence times of three kinds of plastic floats (mesoplastics) were measured by the two-year MRE, and we estimated the residence time of small wood pieces (WPs, mesolitter) by combining the results of one- and two-year MREs. WPs were found to be buried in the sand, probably due to turbulent eddies of swash waves and, thus, we estimated the total amount of buried WPs by evaluating the ratio between the amount of WPs buried in the sand and the amount remaining on the sand by intensive surveys conducted in small sections. In addition, we measured the detection probabilities of WPs buried in and remaining on the sand by verification surveys. Details of the surveys are described in Sections 2.2 and 2.3. In this study, microplastics are defined as plastic particles in the size range of 0.3–5 mm (Collignon et al., 2012). For all statistical tests conducted in this study, significance was represented by $p < 0.05$.

2.1. Study site and target items

The study site is Wadahama Beach, Nii-jima Island, Japan (Fig. 1). For a detailed description of the location and topographic features of Wadahama Beach, readers are referred to Kataoka et al. (2015). We divided the beach into nine 100-m-wide belt transects (T1–T9) in the alongshore direction, as shown in Fig. 1b, to examine the temporal evolution of the alongshore distribution of target items.

The target items were three types of plastic floats (PF1, PF2, PF3) and colored wood pieces (WPR, WPB, WPG) (Fig. 2). The plastic floats (PFs) and wood pieces (WPs) are classified as macrolitter and mesolitter, respectively. The floats were backwashed offshore by swash waves and rip currents in the surf zone generated during storm events (Kataoka et al., 2015). There were large uncertainties in the attitude of items when trapped in the swash waves and drifting in the surf zone. For simplicity, here we calculated the radius of an equivalent sphere having the same volume as that of the target items to determine their UTV in the ocean. The UTVs were calculated by the following equation (Japan Society of Civil Engineers, 1999):

$$w = 1.82 \times \left\{ , \frac{(\rho - \rho')gr}{\rho} \right\}^{1/2} (R_e > 100), \tag{3}$$

where ρ (1.03 kg m^{-3}) is the density of the seawater, ρ′ the density of target items, g the gravitational acceleration, r the radius of an equivalent sphere, and R_e the Reynolds number.

Length (L), width (D), volume (V), radius of equivalent sphere (r), weight (W), specific gravity (d) and UTV (w) of the target items are