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# Evaluation of beach cleanup effects using linear system analysis

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ABSTRACT

We established a method for evaluating beach cleanup effects (BCEs) based on a linear system analysis, and investigated factors determining BCEs. Here we focus on two BCEs: decreasing the total mass of toxic metals that could leach into a beach from marine plastics and preventing the fragmentation of marine plastics on the beach. Both BCEs depend strongly on the average residence time of marine plastics on the beach ($\tau_r$) and the period of temporal variability of the input flux of marine plastics ($T$). Cleanups on the beach where $\tau_r$ is longer than $T$ are more effective than those where $\tau_r$ is shorter than $T$. In addition, both BCEs are the highest near the time when the remnants of plastics reach the local maximum (peak time). Therefore, it is crucial to understand the following three factors for effective cleanups: the average residence time, the plastic input period and the peak time.



## 1. Introduction

Beach cleanup is a key approach to reducing threats on marine and coastal environments, such as beach pollution from toxic metals contained in marine plastics (Nakashima et al., 2012) and fragmentation of marine plastics (Andrady, 2011). Ocean Conservancy, for instance, organizes international coastal cleanups (Ocean Conservancy, 2013), as well as waterway and ocean cleanups every year involving many volunteers. However, at present, it is impossible to identify how best to organize them, where and when to carry them out because the effects of these beach cleanups are not quantitatively well understood. Quantifying the effects of beach cleanups would enable us to strategically plan beach cleanups and to more effectively reduce the environmental risks caused by marine plastics.

Nakashima et al. (2012) recently suggested that toxic metals, which are widely used in additive agents during plastic production, leach into the beach via the water surrounding marine plastics (e.g., rainwater). They found high concentrations of lead stearate ($Pb(C_{18}H_{35}O_2)_2$), which is toxic to biota (Nordic Council of Ministers, 2003), in plastic fishery floats made from polyvinyl chloride (PVC) polymer (PVC floats). They computed the flux leaching into the surrounding water and the resultant concentration of Pb in the beach, and concluded that Pb leaching from PVC floats is a potential future risk of marine plastics on beaches.

When exposed to solar ultraviolet (UV) radiation, marine plastics undergo photo-oxidative degradation and gradual fragmentation. Marine plastics degrade much more quickly when lying on the beach compared to floating on the sea because of relatively higher temperatures and the higher oxygen concentration in air environments (Andrady, 2011). Thus, degradation on beaches is the predominant process in the fragmentation of marine plastics. On the other hand, fragments of marine plastic, referred to as microplastics, pick up persistent organic pollutants (POPs) in the sea and develop high concentrations of POPs (Andrady, 2011; Cole et al., 2011). Microplastics are defined as particle fragments smaller than 5 mm (Barnes et al., 2009) and are easily ingested by fish and seabirds in the ocean (e.g., Shaw and Day, 1994; Derraik, 2002; Boerger et al., 2010). Thus, plastic fragments may be important agents in the transport of toxic chemicals and contaminants, affecting the ocean food web (e.g., Mato et al., 2001; Thompson et al., 2004; Andrady, 2011).

These environmental risks would depend on the average residence time from washing ashore to backwashing offshore; thus, the average residence time is crucial for evaluating the beach cleanup effects (BCEs). Recently, Kataoka et al. (2013) found by mark-recapture experiments on Wadahama Beach, Niijima Island, Japan that remnants of plastic fishing floats exponentially decreased, and they successfully measured the average residence time of the floats. The exponential decay enables us to understand the beach characteristics as a linear input/output system for

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**Table 1**
Normalized amplification factor ($A$) and phase lag ($\theta$) in the case of $\xi = 10^1$, $10^0$ and $10^{-1}$.

| Dimensionless residence time $\xi$ | Normalized amplification factor $A$ | Phase lag $\theta$ [degrees] |
|---|---|---|
| $10^1$ | $1.59 \times 10^{-2}$ | −89.09 |
| $10^0$ | $1.57 \times 10^{-1}$ | −80.96 |
| $10^{-1}$ | $8.47 \times 10^{-1}$ | −32.14 |

marine plastics, i.e., amplitude and phase characteristics (Kataoka et al., 2013). Here we establish a method for evaluating BCEs based on linear system analysis, and investigate factors determining BCEs. In this study, we describe the quantification of two BCEs: (1) decreasing the total mass of toxic metals that could leach into the beach from marine plastics, and (2) preventing the fragmentation of marine plastics.

## 2. Materials and methods

### 2.1. Time-invariant linear input/output system for marine plastic

We assume that the beach is a time-invariant linear input/output system for marine plastic and the cohort population of remnants of marine plastics exponentially decreases as follows:

$$h(t) = \begin{cases} \exp(-t/\tau_r), & \text{for } t \geqslant 0 \\ 0, & \text{for } t < 0 \end{cases} \tag{1}$$

where $t$ and $\tau_r$ are the elapsed time and the average residence time, respectively (Kataoka et al., 2013). $h(t)$ denotes the unit impulse response (UIR) in the linear system analysis. The Fourier transformation of UIR represents the system function ($H(\omega)$):

$$H(\omega) = \frac{\tau_r}{1 + (\omega\tau_r)^2}(1 - i\omega\tau_r), \tag{2}$$

where $\omega$ (=$2\pi/T$) is the angular frequency and $T$ is the period of temporal variability of the input flux of marine plastics (hereafter "plastic input period"). Based on Eq. (2), the system characteristics can be expressed as a function of the residence time normalized by $T$ (i.e., $\xi = \tau_r/T$):

$$A(\xi) = \frac{|H(\xi)|}{\tau_r} = \frac{1}{\sqrt{1 + (2\pi\xi)^2}}, \tag{3}$$

$$\theta(\xi) = \tan^{-1}\frac{\mathrm{Im}(H(\xi))}{\mathrm{Re}(H(\xi))} = \tan^{-1}(-2\pi\xi), \tag{4}$$

where $A(\xi)$ and $\theta(\xi)$ mean the amplification factor normalized by $\tau_r$ and the phase lag of the output with respect to the input, respectively. Note that $\theta$ is a negative value (i.e., $\theta < 0$).

In principle, the system characteristics of UIR defined as an exponential function depend on $\xi$. If $T$ = 365 days, the system characteristics of a beach with one month, one year and ten years of $\tau_r$ are determined by $10^{-1}$, $10^0$ and $10^1$ of $\xi$, respectively. Table 1 shows $A$ and $\theta$ (degrees) for three values of $\xi$. The amplification factor $A$ (absolute value of phase lag $\theta$) of $\xi = 10^1$ is smaller (larger) than that of $\xi = 10^{-1}$ (Table 1).

### 2.2. Beach cleanup effect 1 (BCE1): decrease in total mass of toxic metals

Fig. 1 shows a schematic image of the beach cleanup effect in relation to toxic metals that could leach into the beach from marine plastics (BCE1). Based on Nakashima et al. (2012), we consider that toxic metals leach into the beach via surrounding water (e.g., rainwater). The beach cleanup can reduce total mass of toxic metals leached into the beach. BCE1 is evaluated based on the difference between the total mass with and without conducting beach cleanup.

Based on the time-invariant linear system, the leaching flux ($y_m(t)$) of toxic metals from marine plastics is evaluated as follows:

$$y_m(t) = \int_0^t v(t-\tau)x(\tau)h(t-\tau)d\tau, \tag{5}$$

where $t$–$\tau$ denotes the age from when marine plastics washed ashore ($\tau$) to time ($t$). $v(t)$ is the leaching rate of toxic metals per unit time from one plastic object. And, $x(t)$ and $h(t)$ are the input flux of marine plastics (hereafter "plastic input flux") and UIR (i.e.,

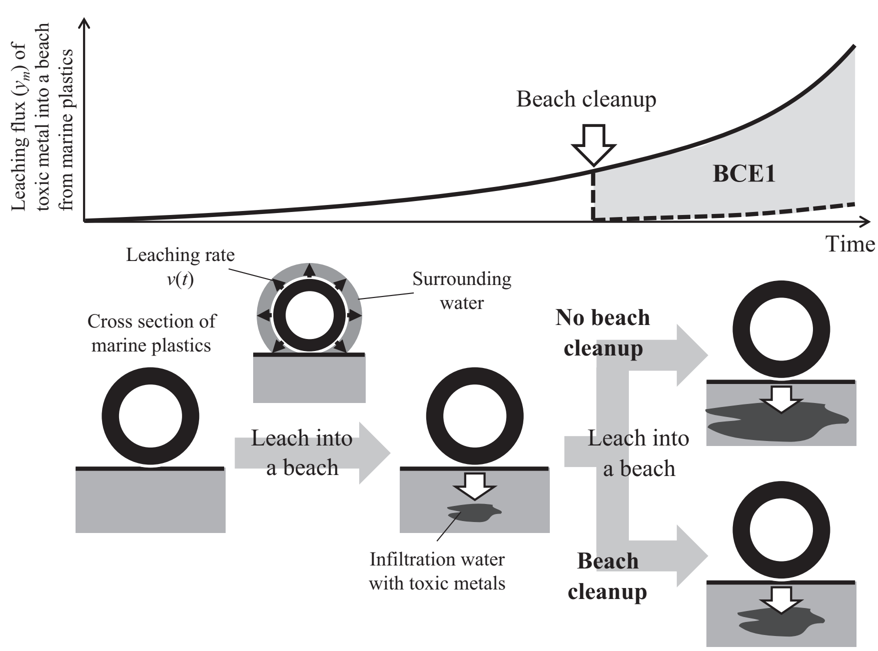


**Fig. 1.** Schematic image of a beach cleanup effect in relation to toxic metals that could leach into the beach from marine plastics (BCE1).

Eq. (1)), respectively. The total mass ($Y_m(t)$) of toxic metals leached into the beach is evaluated by the integral of Eq. (5):

$$Y_m(t) = \int_0^t y_m(t')dt' = \int_0^t \left( \int_0^{t'} v(t'-\tau)x(\tau)h(t'-\tau)d\tau \right) dt'. \quad (6)$$

### 2.3. Beach cleanup effect 2 (BCE2): prevention of plastic fragment generation

Fig. 2 shows a schematic image of the beach cleanup effect in relation to fragmentation of marine plastics (BCE2). Marine plastics could eventually break down due to exposure to solar UV radiation and beach temperature (Andrady, 2011). Portions of the plastic surface could exfoliate in the breakdown process as the result of a chemical change that drastically reduces the average molecular weight of the polymer (Andrady, 2011). We assume the generation of plastic fragments by the breakdown and exfoliation of marine plastics.

Based on the time-invariant linear system, the generating rate ($y_f(t)$) of plastic fragments is evaluated as follows:

$$y_f(t) = \int_0^t p(t-\tau)x(\tau)h(t-\tau)d\tau, \quad (7)$$

where $p(t)$ is the probability that plastic fragments are generated from the remnant per unit time (hereafter "generating probability"). The amount of plastic fragments on a beach ($Y_f(t)$) is evaluated by the integral of Eq. (7):

$$Y_f(t) = \int_0^t y_f(t')dt' = \int_0^t \left( \int_0^{t'} p(t'-\tau)x(\tau)h(t'-\tau)d\tau \right) dt'. \quad (8)$$

BCE2 is evaluated based on the difference between the amount of plastic fragments with and without conducting beach cleanup.

### 2.4. Simple models for plastic input flux, leaching rate and fragmentation probability

The plastic input flux often shows seasonal variation due to oceanic and/or weather conditions (e.g., Bowman et al., 1998; Kako et al., 2010; Kataoka et al., 2013). For example, immigration (i.e., plastic input to a beach) has local maximums on Wadahama Beach, Niijima Island in early summer when the Kuroshio Current approaches the island (Kataoka et al., 2013). Accordingly, the idealized plastic input flux ($x(t)$) is expressed as the combination of constant input and sinusoidal input:

$$x(t) = x_0 + a\sin(2\pi t/T), \quad (9)$$

where $x_0$, $T$ and $a$ are the constant flux, period and amplitude of the sinusoidal input flux, respectively. Basically, $x(t)$ has three cases of $x_0$ and $a$ (i.e., $x_0 > a$; $x_0 = a$; $x_0 < a$).

In this study, to simply investigate the dependence of BCEs on the average residence time, we assume that $x_0$ is equal to $a$ (i.e., $x_0 = a$), that the leaching rate of toxic metals from one plastic object is a constant value (i.e., $v(t) = v_0$), and that the generating probability $p(t)$ is proportional to the age of the remnants of marine plastics ($t-\tau$) (i.e., $p(t) = p_0(t-\tau)$). Assuming a constant leaching rate and proportional generating probability, $y_m(t)$ and $y_f(t)$ could be expressed using $y_r(t)$ and $y_a(t)$, respectively:

$$\begin{cases} y_m(t) = v_0 y_r(t) \\ y_f(t) = p_0 y_a(t) \end{cases} \quad (10)$$

where $y_r(t)$ and $y_a(t)$ denote the remnant and the total age of marine plastics on beaches, respectively:

$$y_r(t) = \int_0^t x(\tau)h(t-\tau)d\tau. \quad (11)$$

$$y_a(t) = \int_0^t (t-\tau)x(\tau)h(t-\tau)d\tau. \quad (12)$$

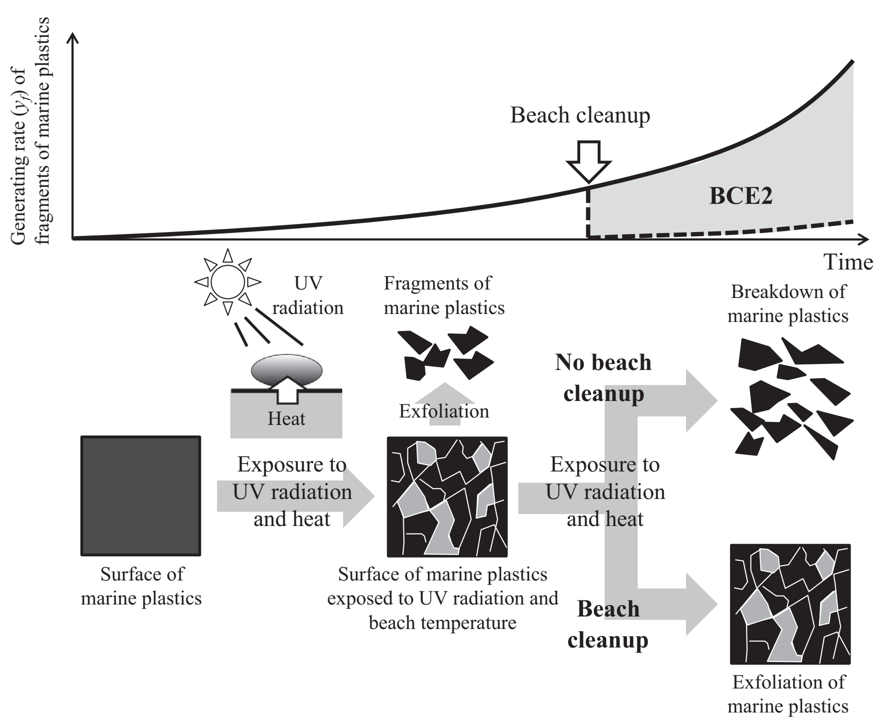


**Fig. 2.** Schematic image of a beach cleanup effect in relation to fragmentation of marine plastics (BCE2).

And also, $Y_m(t)$ and $Y_f(t)$ are obtained by the integral of Eqs. (11) and (12), respectively. Here, the integrals of $y_r(t)$ and $y_a(t)$ are defined as the cumulative remnant $Y_r(t)$ and age $Y_a(t)$, respectively:

$$Y_r(t) = \int_0^t y_r(t')dt' = \int_0^t \left( \int_0^{t'} x(\tau)h(t'-\tau)d\tau \right) dt'. \tag{13}$$

$$Y_a(t) = \int_0^t y_a(t')dt' = \int_0^t \left( \int_0^{t'} (t'-\tau)x(\tau)h(t'-\tau)d\tau \right) dt'. \tag{14}$$

Therefore, BCE1 is evaluated based on the difference between the cumulative remnant with and without conducting beach cleanup, and BCE2 is evaluated based on the difference between the cumulative age with and without beach cleanup.

## 3. Results

### 3.1. Dependence of temporal evolution of remnant and total age on the average residence time

Substituting UIR ($h(t)$: Eq. (1)) and the idealized input flux ($x(t)$: Eq. (9)) into the remnant ($y_r(t)$: Eq. (11)), and then normalizing $y_r(t)$ by $x_0\tau_r$, the dimensionless remnant ($y'_r$) is expressed as:

$$y'_r(\zeta,\xi) = \frac{y_r}{x_0}\tau_r = y'^{const}_r + y'^{sin}_r,$$
$$\begin{cases} y'^{const}_r = 1 - \exp(-\zeta/\xi) \\ y'^{sin}_r = \frac{a}{x_0}A[\sin(2\pi\zeta+\theta) - \sin\theta\exp(-\zeta/\xi)] \end{cases} \tag{15}$$

where $y'^{const}_r$ and $y'^{sin}_r$ are the terms of $y'_r$ derived from the constant and sinusoidal components of $x(t)$, respectively. $\zeta$ denotes the elapsed time normalized by the plastic input period ($T$) (i.e., $\zeta = t/T$), and $A$ and $\theta$ of Eq. (15) are defined by Eqs. (3) and (4), respectively. $a/x_0$ is determined to be 1 by assuming $x_0 = a$ (see Section 2.4).

As the same way with $y'_r$, the dimensionless total age ($y'_a$) is also expressed as a function of $\zeta$ and $\xi$:

$$y'_a(\zeta,\xi) = \frac{y_a}{x_0\tau_r^2} = y'^{const}_a + y'^{sin}_a,$$
$$\begin{cases} y'^{const}_a = 1-(1+\zeta/\xi)\exp(-\zeta/\xi) \\ y'^{sin}_a = \frac{a}{x_0}A^2[\sin(2\pi\zeta+2\theta) - \sin2\theta\exp(-\zeta/\xi)] - \frac{a}{x_0}A\sin\theta(\zeta/\xi)\exp(-\zeta/\xi) \end{cases} \tag{16}$$

where $y'^{const}_a$ and $y'^{sin}_a$ are the terms of $y'_a$ derived from the constant and sinusoidal components of $x(t)$, respectively. Note that $y'_a$ is normalized by $x_0{\tau_r}^2$.

Fig. 3c and d shows the dependence of $y'_r$ and $y'_a$ on $\xi$, respectively. Both $y'_r$ and $y'_a$ completely depend on $\xi$. If $\tau_r$ is shorter than $T$ (e.g., $\xi = 10^{-1}$), both $y'^{const}_r$ and $y'^{const}_a$ quickly increase (gray dash-dotted line in Fig. 3a and b). Conversely, if $\tau_r$ is longer than $T$ (e.g., $\xi = 10^1$), both $y'^{const}_r$ and $y'^{const}_a$ slowly increase (gray solid line in Fig. 3a and b). If $\zeta \to \infty$, $y'_r$ and $y'_a$ finally approach:

$$y'_r \to 1 + \frac{a}{x_0}A\sin(2\pi\zeta+\theta) \text{ and} \tag{17}$$

$$y'_a \to 1 + \frac{a}{x_0}A^2\sin(2\pi\zeta+2\theta) \tag{18}$$

as predicted by Eqs. (15) and (16), respectively. $y'_r$ ($y'_a$) fluctuates with the amplitude $A$ ($A^2$) at around $y'_r = y'_a = 1$, and has a phase delay of $\theta$ ($2\theta$) compared with the plastic input flux. The relaxation time until $y'_r$ and $y'_a$ reach 90% of $x_0\tau_r$ and $x_0{\tau_r}^2$ are respectively determined by $y'^{const}_r = 0.9$ and $y'^{const}_a = 0.9$, which are $2.3\xi$ and $3.9\xi$. Thus, the relaxation time is proportional to $\xi$.

$y'^{const}_r$ and $y'^{const}_a$ ($y'^{sin}_r$ and $y'^{sin}_a$) dominate the temporal evolution of $y'_r$ and $y'_a$ when $\xi > 10^0$ ($\xi < 10^0$). The contribution of $y'^{sin}_r$ and $y'^{sin}_a$ to the temporal evolution depends on the normalized amplification factor ($A$). For instance, $y'^{sin}_r$ and $y'^{sin}_a$ contribute more largely to the temporal evolution when $\xi = 10^{-1}$ compared with that when $\xi = 10^1$ because $A$ when $\xi = 10^{-1}$ is much larger than that when $\xi = 10^1$ (Table 1).

### 3.2. Dependence of temporal evolution of cumulative remnant and age on the average residence time

The dimensionless cumulative remnant ($Y'_r$) is expressed by substituting $h(t)$ (Eq. (1)) and $x(t)$ (Eq. (9)) into $Y_r(t)$ (Eq. (13)), and normalizing $Y_r(t)$ by $x_0{\tau_r}^2$ as follows:

$$Y'_r(\zeta,\xi) = \frac{Y_r}{x_0\tau_r^2} = Y'^{const}_r + Y'^{sin}_r,$$
$$\begin{cases} Y'^{const}_r = \zeta/\xi - 1 + \exp(-\zeta/\xi) \\ Y'^{sin}_r = \frac{a}{x_0}\frac{1}{2\pi\xi}[-A\cos(2\pi\zeta+\theta)+1] + \frac{a}{x_0}A\sin\theta\exp(-\zeta/\xi) \end{cases} \tag{19}$$

And, substituting $h(t)$ (Eq. (1)) and $x(t)$ (Eq. (9)) into $Y_a(t)$ (Eq. (14)), and normalizing $Y_a(t)$ by $x_0{\tau_r}^3$, the dimensionless cumulative age ($Y'_a$) is expressed as:

$$Y'_a(\zeta,\xi) = \frac{Y_a}{x_0}\tau_r^3 = Y'^{const}_a + Y'^{sin}_a,$$
$$\begin{cases} Y'^{const}_a = \zeta/\xi - 2 + (\zeta/\xi+2)\exp(-\zeta/\xi) \\ Y'^{sin}_a = \frac{a}{x_0}\frac{A^2}{2\pi\xi}[-\cos(2\pi\zeta+2\theta)+\cos2\theta] + \frac{a}{x_0}A\sin\theta[(\zeta/\xi+1)\exp(-\zeta/\xi)-1] \\ \quad + \frac{a}{x_0}A^2\sin2\theta[\exp(-\zeta/\xi)-1] \end{cases} \tag{20}$$

where $Y'^{const}_r$ and $Y'^{sin}_r$ ($Y'^{const}_a$ and $Y'^{sin}_a$) are the terms of $Y'_r$ ($Y'_a$) derived from the constant and sinusoidal components of $x(t)$, respectively.

Fig. 4c and d shows the dependence of $Y'_r$ and $Y'_a$ on $\xi$, respectively. Both $Y'_r$ and $Y'_a$ completely depend on $\xi$, namely, $Y'_r$ and $Y'_a$ become much smaller as $\xi$ becomes larger. If $\tau_r$ is shorter than $T$ (e.g., $\xi = 10^{-1}$), both $Y'^{const}_r$ and $Y'^{const}_a$ quickly increase corresponding to the temporal variation of $y'_r$ and $y'_a$ (gray dash-dotted line in Fig. 4a and b). Conversely, if $\tau_r$ is longer than $T$ (e.g., $\xi = 10^1$), $Y'^{const}_r$ and $Y'^{const}_a$ slowly increase (gray solid line in Fig. 4a and b). If $\zeta \to \infty$, $Y'_r$ and $Y'_a$ are proportional to $\zeta$ as predicted by Eqs. (19) and (20), respectively. Overall, $Y'^{const}_r$ and $Y'^{const}_a$ dominate the temporal evolution of $Y'_r$ and $Y'_a$ compared with $Y'^{sin}_r$ and $Y'^{sin}_a$. In addition, the contribution of $Y'^{sin}_r$ and $Y'^{sin}_a$ decreases as $\xi$ becomes longer because the amplitude of $Y'^{sin}_r$ and $Y'^{sin}_a$ ($A$ and $A^2$ in Eqs. (19) and (20)) is smaller (Table 1).

### 3.3. Effects of yearly and biyearly cleanups

Kataoka et al. (2013) revealed that the average residence time of plastic fishing floats on Wadahama Beach was 209 days, and immigration of fishing floats varied seasonally. Assuming the plastic input period ($T$) on Wadahama Beach is 365 days, the dimensionless residence time ($\xi$) becomes 0.57 (i.e., 209/365 = 0.57). Beach cleanup is usually conducted yearly, such as in the International Coastal Cleanups (Ocean Conservancy, 2013). Here, we show an example of the beach cleanup effects (hereafter "BCEs") on Wadahama Beach in a case where beach cleanup is conducted yearly or biyearly.

The temporal evolution of the cumulative remnant ($Y_r$) and age ($Y_a$) after a beach cleanup can be represented as follows:

$$Y_r(t) = Y_r(t_c) + \int_{t_c}^t y_r(t')dt'$$
$$= Y_r(t_c) + \int_{t_c}^t \left( \int_{t_c}^{t'} x(\tau)h(t'-\tau)d\tau \right) dt', \tag{21}$$

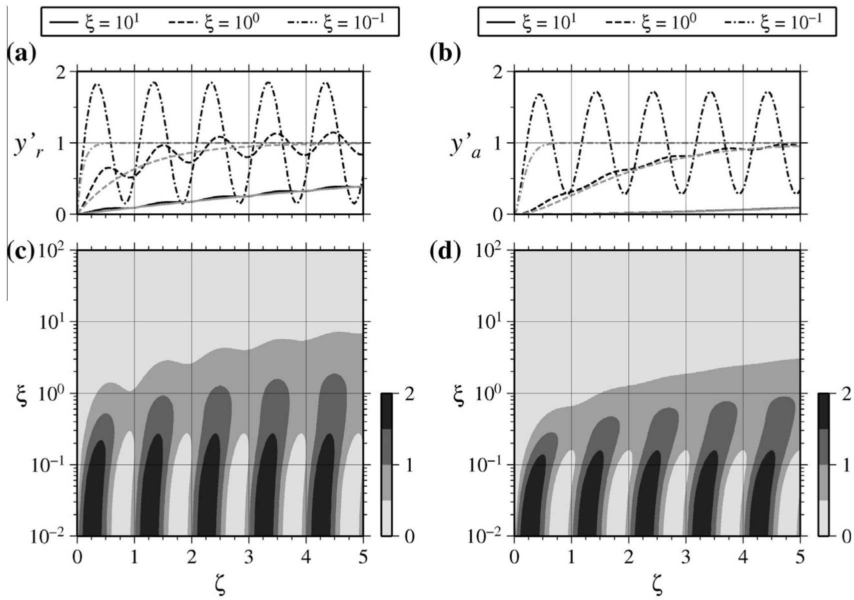


**Fig. 3.** Dependence of the temporal evolution of dimensionless remnant ($y'_r$) and total age ($y'_a$) on the dimensionless residence time ($\xi$). Panels (a) and (b) show the temporal evolution of $y'_r$ and $y'_a$ of $\xi = 10^1$ (solid line), $10^0$ (broken line) and $10^{-1}$ (dash-dotted line), respectively. In panels (a) and (b), the black line denotes $y'_r$ and $y'_a$, and the gray line denotes $y'^{const}_r$ and $y'^{const}_a$. Panels (c) and (d) show the temporal evolution of $y'_r$ and $y'_a$ in the range from $10^{-2}$ to $10^2$ of $\xi$, respectively. The white-black gradation of (c) and (d) denotes $y'_r$ and $y'_a$, respectively. The gradation scale is shown on the right side of (c) and (d).

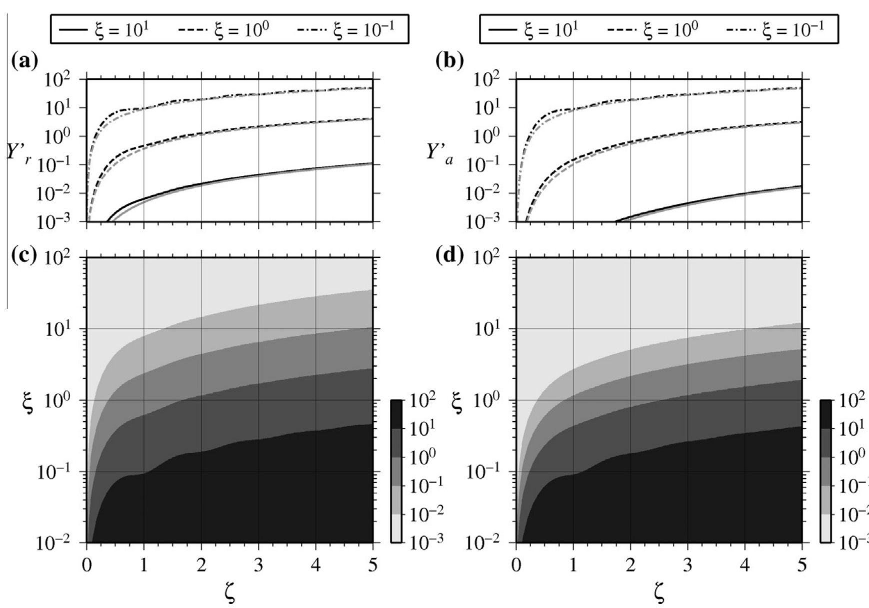


**Fig. 4.** Dependence of the temporal evolution of the dimensionless cumulative remnant ($Y'_r$) and age ($Y'_a$) on the dimensionless residence time ($\xi$). Note that the vertical axis of (a) and (b) and the gradation scale of (c) and (d) are logarithmic scales. The format is the same as that of Fig. 3.

$$
\begin{aligned}
Y_a(t) &= Y_a(t_c) + \int_{t_c}^{t} y_a(t')dt' \\
&= Y_a(t_c) + \int_{t_c}^{t} \left( \int_{t_c}^{t'} (t' - \tau)x(\tau)h(t' - \tau)d\tau \right) dt',
\end{aligned}
\tag{22}
$$

where $t_c$ means when a beach cleanup is conducted, which is referred as to "cleaning time". Thus, the BCEs are evaluated by dividing the difference between the cumulative responses (i.e., $Y_r$ and $Y_a$) with and without conducting beach cleanup by the cumulative responses without beach cleanup.

Fig. 5a and b shows the temporal evolution of $y'_r$ and $Y'_r$ in a case where beach cleanups are conducted yearly when the phase of the sinusoidal component of input flux (hereafter "cleaning phase $\theta_c$") is equal to $2\pi$, respectively (bold solid line: no cleanup; bold broken line: regular cleanup). Fig. 6a and b shows the temporal evolution of $y'_a$ and $Y'_a$ for the cleanup at the same cleaning phase (i.e., $\theta_c = 2\pi$). If the cleanups are conducted yearly at $\theta_c = 2\pi$ (Figs. 5a and 6a), the cumulative remnant (Fig. 5b) and age (Fig. 6b) can be reduced by 30% and 60%, respectively, compared with those without beach cleanups at $\zeta = 5$ (Table 2). On the other hand, regular cleanups conducted at $\theta_c = \pi$ (Figs. 5c and 6c) can greatly reduce the cumulative remnant (Fig. 5d) and age (Fig. 6d). The BCEs calculated from the cumulative remnant and age in this case are 54% and 82% at $\zeta = 5$, respectively (Table 2). Therefore, the BCEs depend on the timing of the regular cleanups

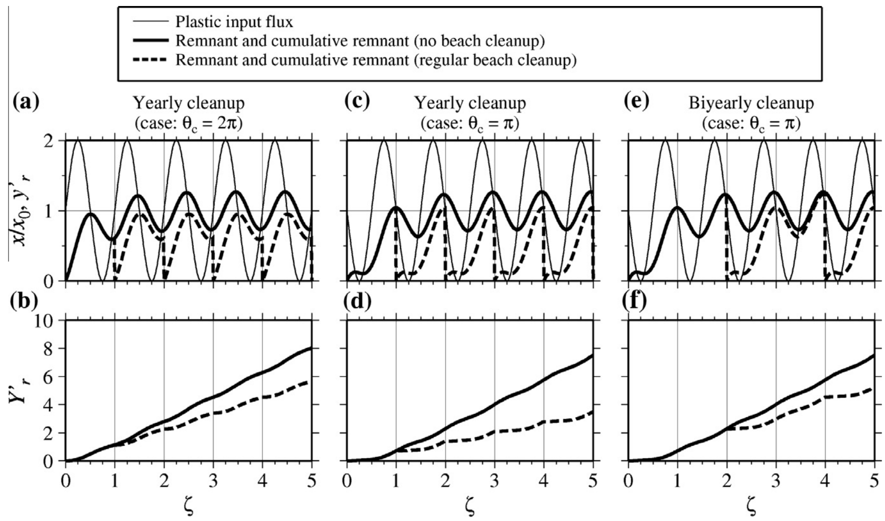


**Fig. 5.** Temporal evolution of the dimensionless remnant ($y'_r$) and dimensionless cumulative remnant ($Y'_r$) during the five input periods in the case of 0.57 of dimensionless residence time ($\xi$). Panels (a), (c) and (e) show the temporal evolution of $y'_r$ in the case of yearly cleanup at $\theta_c = 2\pi$, yearly cleanup at $\theta_c = \pi$ and biyearly cleanup at $\theta_c = \pi$, respectively. Panels (b), (d) and (f) show the temporal evolution of $Y'_r$ in these three patterns of regular cleanups. The meaning of lines is shown in the upper box.

(i.e., cleaning phase $\theta_c$). Regular cleanups at $\theta_c = \pi$ are more effective than those at $\theta_c = 2\pi$. On Wadahama Beach (or beaches having the characteristics of $\xi = 0.57$), the remnant at $\theta_c = \pi$ mostly corresponds to the local maximum of $y_r(t)$ (hereafter "remnant peak") because the phase lag $\theta$ is $-81°$ (Table 1) (i.e., $\pi/2-\theta \approx \pi$). This demonstrates that beach cleanup at the time of the remnant peak (hereafter "peak time") is the most effective.

Generally, beach cleanup involves high labor costs. If it is conducted every two years, it should be timed to coincide with the remnant peak. Even if beach cleanup is conducted only once every two years, it is as effective as yearly cleanup at $\theta_c = 2\pi$ (Figs. 5f, 6f and Table 2). This indicates that the cleaning phase ($\theta_c$) is an important factor for conducting effective beach cleanups.

### 3.4. Dependence of the effect of beach cleanup on the average residence time

Figs. 7a and 8a describe the dependence of BCEs for the remnant and total age by yearly cleanups during the five input periods (i.e., $\zeta = 0$–$5$) on both the dimensionless residence time ($\xi$) and the cleaning phase ($\theta_c$), respectively. The horizontal axes of Figs. 7a and 8a denote the phase difference ($d\theta$) between the phase of the input flux at the peak time determined by Eq. (4) (e.g., $\pi/2-\theta$ because the phase at the peak time is defined by $2\pi\zeta + \theta = \pi/2$; see Eq. (15)) and $\theta_c$: $d\theta = (\pi/2-\theta)-\theta_c$. Note that $\theta$ is a negative value (Eq. (4)). The vertical axes of Figs. 7a and 8a denote $\xi$. The white-black gradation of Figs. 7a and 8a represents the BCEs calculated from the cumulative remnant ($Y'_r$) and age ($Y'_a$), respectively (see Section 3.3). The BCEs clearly increase as $\xi$ becomes longer. Conversely, regular cleanup on a beach with shorter $\xi$ has little effect on the beach environment. Therefore, regular cleanups on a beach with longer $\xi$ are more effective than those with shorter $\xi$.

Figs. 7b and 8b show the dependence of BCEs of $\xi = 10^{-1}$, $10^0$ and $10^1$ on the phase difference ($d\theta$). At all levels of $\xi$, the BCEs for the remnant are fully maximized at $d\theta = 0$ (Fig. 7a and b). Thus, the most effective time for BCE1 matches the peak time (Fig. 7a and b). Furthermore, regular cleanups at around the peak time can also effectively reduce the cumulative age, although the maximum for BCE2 occurs shortly after the peak time (Fig. 8a and b). Therefore, beach cleanups conducted at around the peak time would become

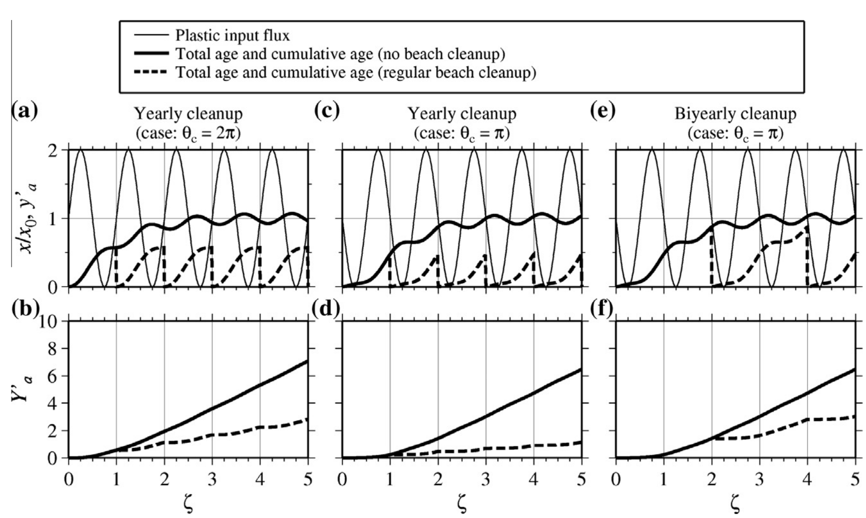


**Fig. 6.** Temporal evolution of the dimensionless total age ($y'_a$) and dimensionless cumulative age ($Y'_a$) during the five input periods in the case of 0.57 of dimensionless residence time ($\xi$). The format is the same as that of Fig. 5.

**Table 2**
Beach cleanup effects (BCEs) calculated from the dimensionless cumulative remnant ($Y'_r$) and age ($Y'_a$) after the five input periods in the case of 0.57 of dimensionless residence time ($\xi$).

| | Yearly cleanup (case: $\theta_c = 2\pi$) | Yearly cleanup (case: $\theta_c = \pi$) | Biyearly cleanup (case: $\theta_c = \pi$) |
|---|---|---|---|
| *Dimensionless cumulative remnant $Y'_r$* | | | |
| No cleanup | 8.03 | 7.51 | 7.51 |
| Cleanup | 5.65 | 3.47 | 5.25 |
| BCE (%) | 30 | 54 | 30 |
| *Dimensionless cumulative age $Y'_a$* | | | |
| No cleanup | 7.07 | 6.48 | 6.48 |
| Cleanup | 2.80 | 1.15 | 3.03 |
| BCE (%) | 60 | 82 | 53 |

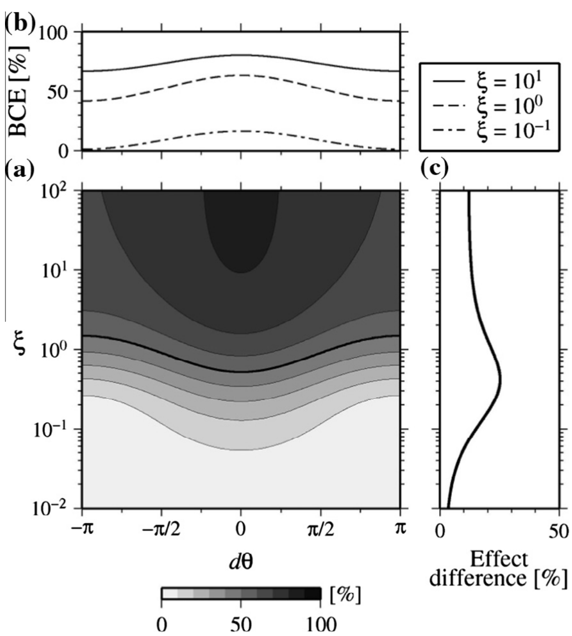


**Fig. 7.** (a) Dependence of the beach cleanup effect (BCE) for the remnant on the dimensionless residence time ($\xi$) and the cleaning phase ($\theta_c$). The horizontal axis represents the phase difference $d\theta$ between the phase of input flux at the remnant peak and $\theta_c$. The contour line and white-black gradation of (a) denotes the BCE; its scale is shown under panel (a). (b) Dependence of the BCE of $\xi = 10^1$ (solid line), $10^0$ (broken line) and $10^{-1}$ (dash-dotted line) on $\theta_c$. (c) Dependence of the effect difference (i.e., difference between maximum and minimum BCE) on $\xi$.

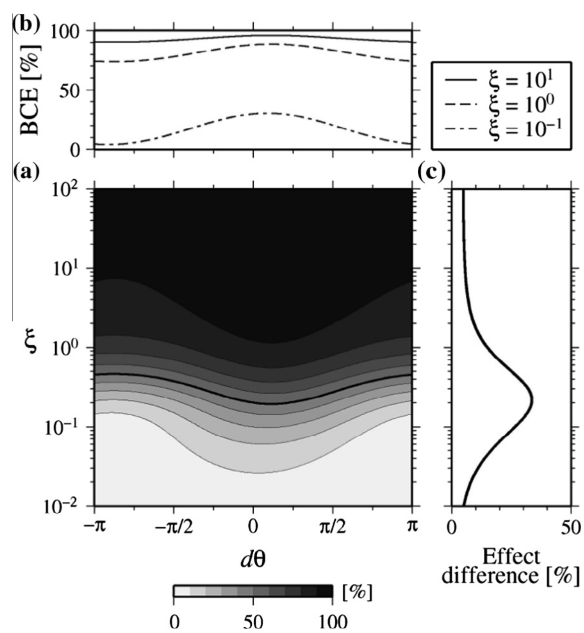


**Fig. 8.** (a) Dependence of the beach cleanup effect (BCE) for total age on the dimensionless residence time ($\xi$) and the cleaning phase ($\theta_c$). The format is the same as that of Fig. 7.

the most effective considering BCE1 (see Section 2.2) and BCE2 (see Section 2.3).

Figs. 7c and 8c show the effect difference in BCE1 and BCE2 calculated from the difference between the maximum and minimum BCEs. The effect difference also depends on $\xi$ (Figs. 7c and 8c). If $\xi$ is smaller than $10^{-1}$, the effect difference is small because the BCEs are very low for the all $d\theta$ (Figs. 7a and 8a). The effect difference when $\xi > 10^0$ is smaller than that when $10^{-1} < \xi < 10^0$ because the amplitude of $Y'^{sin}_r$ and $Y'^{sin}_a$ becomes smaller as $\xi$ becomes longer (see Section 3.2). The smaller effect difference means that the BCEs are dependent more weakly on the timing of beach cleanup.

## 4. Discussion

### 4.1. Efficacy of the time-invariant linear system in plastic pollution

To simply investigate the dependence of beach cleanup effects (BCEs) on the average residence time, several assumptions are employed for evaluating the total mass of toxic metals leached into the beach and the amount of plastic fragments: the leaching rate ($\nu(t)$) of toxic metals from marine plastics is a constant and the generating probability ($p(t)$) is proportional to the remnant age ($t-\tau$). In actuality, $\nu(t)$ and $p(t)$ would depend on the local precipitation and UV radiation (and/or temperature). Thus, these functions should be determined according to the local site. In any case, if these reasonable functions can be obtained, we could evaluate the total mass of toxic metals and the amount of plastic fragments by applying the concept of time-invariant linear system (e.g., Eqs. (6) and (8)).

For example, Nakashima et al. (2012) estimated the leaching rate of lead stearate ($Pb(C_{18}H_{35}O_2)_2$) from PVC floats by laboratory experiment. The Fickian diffusion process has been applied to the estimation of the leaching rate. If $\nu(t)$ follows the diffusion process as applied in Nakashima et al. (2012), it can be approximated as an exponential function:

$$\nu(t) = \nu_0 \exp(-t/\tau_m). \tag{23}$$

where $\nu_0$ and $\tau_m$ denote the initial leaching rate and average time of toxic metal until leaching into the beach (hereafter "leaching time"). Substituting Eqs. (1), (9) and (23) into Eq. (5), the leaching flux ($y_m(t)$) can be expressed as:

$$y_m(t) = y_m^{const} + y_m^{sin},$$
$$\begin{cases} y_m^{const} = v_0 x_0 \beta[1 - \exp(-t/\beta)] \\ y_m^{sin} = v_0 a \beta A'[\sin(2\pi t/T + \theta') - \sin\theta' \exp(-t/\beta)] \end{cases} \tag{24}$$

where $\beta$ denotes the coefficient determined by the average residence time ($\tau_r$) and the leaching time ($\tau_m$):

$$\beta = \frac{\tau_r \tau_m}{\tau_r + \tau_m}. \tag{25}$$

Also, $A'$ and $\theta'$ denote the normalized amplification factor and phase lag replacing $\tau_r$ of Eqs. (3) and (4) with $\beta$. Thus, the system characteristics of the leaching flux $y_m(t)$ (i.e., $A'$ and $\theta'$) fully depend on the ratio of $\beta$ to the plastic input period ($T$). Therefore, based on the exponential type of leaching rate, BCE1 is determined by the ratio of $\beta$ to $T$ corresponding to the dimensionless residence time ($\xi$). In actuality, in addition to the leaching time, $\upsilon(t)$ could vary as exfoliation and/or cracks develop on the surface of marine plastics. If we can determine $\upsilon(t)$ considering these factors, the BCEs could be evaluated relatively easily by the linear system analysis shown in this study.

### 4.2. Suggestion for effective beach cleanup

Considering a beach as the time-invariant linear system, we can devise a plan for effective beach cleanup. We demonstrated that beach cleanup is more effective at beaches with the average residence time longer than the plastic input period (i.e., $\xi > 10^0$) for two reasons: (1) the BCEs are very high, and (2) the BCEs are weakly dependent on the cleaning phase ($\theta_c$) (Figs. 7 and 8). Here, we discuss effective beach cleanup strategies based on the dependence of BCEs on the average residence time.

Our suggestion is to conduct cleanups on beaches with $\xi > 10^0$ because the BCEs are relatively high. For example, the amount of beach litter shows seasonal variation (e.g., at six beaches along the Mediterranean Sea in Israel: Bowman et al. (1998); New Jersey beach in the US: Ribic (1998); Ookushi Beach in Japan: Kako et al. (2010); Wadahama Beach in Japan: Kataoka et al. (2013)). The seasonal variation indicates that the predominant input period at these beaches is less than one year. If the amount of beach litter varies seasonally, then beach cleanup where the average residence time is longer than one year will be more effective.

Moreover, cleanup on these beaches ($\xi > 10^0$) has an advantage in terms of the weak dependence of the BCEs on the time for conducting beach cleanups. Generally, beach cleanup is most effective when conducted at the time of the remnant peak (hereafter "peak time") (Figs. 7 and 8). The time for conducting beach cleanups would be determined by various factors, such as weather conditions, availability of labor, and cost. In particular, the weather conditions are important for the safety of beach cleanups. If the remnant peak is during the stormy season, beach cleanup will be difficult. However, cleanup on beaches with longer dimensionless residence time will likely have a sufficient effect even if it cannot be conducted at the peak time.

To plan effective beach cleanup, it is necessary to understand the average residence time, input period and peak time. The average residence time can be measured by the mark-recapture experiments described in Kataoka et al. (2013). In addition, the plastic input period and the peak time can be understood by applying sequential monitoring for the remnant of beach litter using webcam (Kako et al., 2010; Kataoka et al., 2012). If the beach can be considered as the time-invariant linear system, the plastic input period is consistent with the remnant period (e.g., Eq. (15)). The predominant input period, for instance, can be calculated by applying Fourier transformation to the temporal variability of the remnant. Furthermore, the peak time can be statistically obtained as the time of the remnant peak through long-term webcam monitoring.

## 5. Conclusions

To strategically plan beach cleanups and to more effectively reduce the environmental risks caused by marine plastics, we established a method for evaluating beach cleanup effects (BCEs) based on a linear system analysis, and investigated factors determining BCEs. This study focused on two BCEs: decreasing the total mass of toxic metals that could leach into a beach from marine plastics (BCE1) and preventing the generation of fragments of marine plastics (BCE2).

In the time-invariant linear system, the exponential decay of the remnant corresponds to the unit impulse response (UIR), which enables us to understand the system characteristics. The system characteristics can be described as functions of the dimensionless residence time ($\xi$), which is defined as the ratio of the average residence time ($\tau_r$) to the periods of the input flux of marine plastics ($T$). BCE1 and BCE2 can be evaluated based on the remnant and the total age of marine plastics on the beach by making some assumptions: the leaching rate of toxic metals from marine plastics is a constant and the probability of generation is proportional to the remnant age ($t-\tau$), respectively.

When conducting regular beach cleanups, the BCEs depend on the dimensionless residence time ($\xi$) and the phase of the plastic input flux (cleaning phase; $\theta_c$). Overall, the BCEs increase clearly as $\xi$ becomes longer. Considering the two BCEs, beach cleanups around the time of the remnant peak (peak time) are most effective regardless of $\xi$. Therefore, to plan effective beach cleanups, we need to understand the average residence time ($\tau_r$), the plastic input period ($T$) and the peak time. Nevertheless, two BCEs on beaches of $\xi > 10^0$ are weakly dependent on the time at which beach cleanups are conducted. Our suggestion is to conduct cleanups on beaches of $\xi > 10^0$ (i.e., $\tau_r > T$) because high BCEs can be expected regardless of whether the cleanup is conducted at the peak time.

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