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Article

Why Cleanups Do Not Work: Accumulation and Reaccumulation of Cigarette Butts on Runoff-Contributing Surfaces near Storm Water Inlets

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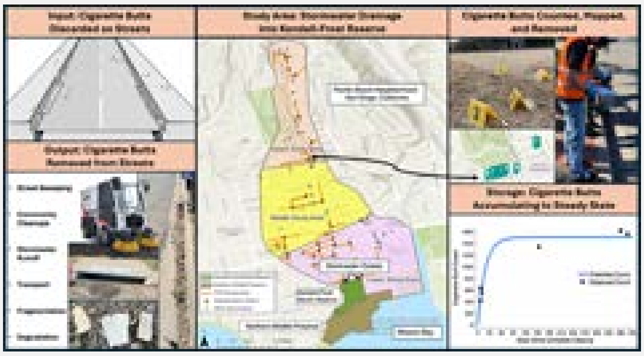
ABSTRACT: Cigarette butts (CBs) are the most common form of litter worldwide and a persistent source of plastic and chemical pollution in aquatic environments. Despite their potential environmental burden, the accumulation dynamics of CBs as aquatic biome pollution are poorly described. We conducted a longitudinal field study of runoff-contributing surfaces near stormwater inlets that flow into the Kendall-Frost Marsh Reserve (San Diego, California) to characterize CB accumulation dynamics. Using a stratified random sample of 29 inlets, CBs were counted and removed in six rounds from January to August 2025. We analyzed counts using mixed-effects negative binomial regression and a first-order accumulation model. Surveys yielded 355−1406 CBs per round, with strong temporal correlations ($r = 0.77–0.95$, $p < 0.001$). The accumulation model fit well (adjusted $R^2 = 0.988$), estimating a daily input rate of 79.7 CBs, an annual input of 29,073 CBs ($0.44/m^2$), and a steady-state observable storage of 1503 CBs ($0.02/m^2$). Results indicate the accumulation of countable CBs near storm drains rapidly establishes an equilibrium following removal, with an unknown number of uncountable CBs and fragments remaining in the environment. Effective mitigation of CB contamination of aquatic biomes must involve source reduction.



KEYWORDS: *cigarette butts, tobacco product waste, stormwater runoff, urban drainage systems, first-order accumulation model, plastic pollution, aquatic ecosystems*

■ INTRODUCTION

Waste from discarded commercial tobacco products is increasingly recognized as an environmental and public health hazard from local to global levels.[1−7] Generated in vast quantities and habitually tossed into the environment, cigarette butts (CBs) and other forms of tobacco product waste (TPW) contribute significant plastic and hazardous chemical pollution to the environment. In the United States, more than 99% of all cigarettes have cellulose acetate filters, each consisting of 12,000 to 15,000 individual fibers that can break down into microplastics.[4,8−13] The filter and the attached charred tobacco have been shown to leach toxic chemicals into soil and water environments. Globally, an estimated 4.5 trillion CBs are discarded annually, adding about 280,000 tons of microfibers to the environment each year, and an additional 1.5 trillion CBs enter managed waste streams.[9] Although waste from electronic tobacco products currently accounts for less than 10% of the total discarded TPW, this is a growing concern because these products generate additional hazardous waste (e.g., batteries, electronic components).[7]

The most common approach to dealing with TPW discarded in the environment, and CBs in particular, has been street sweeping and cleanups by municipal governments, businesses, volunteer groups, and individuals. The actual and potential effectiveness of these efforts has been increasingly questioned, considering the enormous amount of TPW generated annually, its heterogeneous distribution, and the economic costs of these cleanup measures.[3,14,15] For example, the Ocean Conservancy's International Coastal Cleanups in recent years have gathered 1−2 million CBs annually, or 0.00002%−0.00004% of the previously estimated 4.5 trillion discarded annually.[16] Even if cleanup efforts increased by a factor of 100 to 100−200 million butts per year, this would still leave 99.996%−99.998% discarded in the environment.

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Despite growing research on the number of discarded CBs and their environmental impact, little is known about how quickly they reaccumulate after complete cleanup and their fate if left in the environment. A recent field study of TPW in a random sample of 60 census blocks in San Diego County removed 28,296 CBs among 29,981 discarded tobacco, electronic, and cannabis waste items in publicly accessible areas.[7] When the same areas were surveyed a second time, 27,924 CBs had reaccumulated. Surprisingly, there was no association between the reaccumulation counts and the number of days since the last complete removal. Because the shortest interval between removal and the follow-up survey was two months, the authors concluded that CBs reestablished an equilibrium between accumulation (input or influx) and removal (output, efflux) within that two-month period.

Once discarded in the environment, the fate of CBs can take different pathways. While some fraction of discarded CBs is removed through regular street sweeping or special community cleanups, the remainder undergoes variable fragmentation and degradation, and much of this waste remains in the environment. Through chemical (e.g., photochemistry, oxidation, hydrolysis), physical (e.g., mechanical abrasion, thermal cycling), and biological processes (e.g., limited microbial action), CBs degrade into fragments and microfibers over months to years.[17−19] Eventually, the small pieces are no longer recognizable as a cigarette filter and therefore are not countable as CBs. CBs counted on surface areas represent only the visible, recognizable fraction of the CBs that have been discarded into the environment. While fragmentation and degradation processes have been studied in laboratory and field settings, there has been no research to estimate the fraction of discarded CBs that enter the municipal waste stream, the visible (i.e., countable) fraction on surfaces near storm drains, and the invisible fraction that may remain stored in the environment and is not countable.

The observed pattern of rapid CB reaccumulation can be described using a simple first-order accumulation model (formula 1) introduced by Olson to explain the decomposition and buildup of leaf litter in forests.[20] Briefly, this model describes the change in the mass accumulation over time, M(t), as a function of a constant input rate (I) and a constant removal rate (k) proportional to the accumulated mass. In addition to leaf litter, such models have been successfully applied to study indoor air pollution, pesticides,[21] and pharmacokinetics.[22−24]

$$\frac{dM}{dt} = I - kM(t) \tag{1}$$

Solving this linear equation yields a nonlinear exponential model describing the relationship between total mass accumulation and accumulation time (t) as a function of input (I) and removal (k) rate.

$$M(t) = \frac{I}{k}(1 - e^{-kt}) \tag{2}$$

Applied to the accumulation of CBs, this model assumes that smokers discard butts in a defined area at a constant rate (e.g., I = 50 CBs per day), while the removal through street sweeping, clean-ups, runoff, displacement, and degradation is proportional to the accumulated count (e.g., k = 0.10 or 10% of the accumulated total). This input−output system asymptotically approaches a steady-state value where input equals output at a value of I/k (e.g., 50/0.10 = 500).

To investigate the accumulation dynamics of CBs, we studied an urban neighborhood from which stormwater drains into a coastal saltmarsh. Previous research in that setting demonstrated chemical markers for TPW in water and sediment samples (e.g., nicotine: up to 50 μg/L in water and up to 6 μg/g in sediment).[25] In the present study, we repeatedly observed and removed CBs from runoff-contributing areas near storm drain inlets into this protected aquatic biome. We then calculated the input (accumulation) and output (removal) parameters of a first-order accumulation model to address the following questions: First, what is the rate at which CBs are discarded and accumulate in runoff-contributing surfaces near storm drain inlets (i.e., input rate)? Second, what is the rate at which CBs are removed from the runoff-contributing surfaces (i.e., output rate)? Third, what is the steady-state level at which CBs accumulate (i.e., are stored) on runoff-contributing surfaces under existing removal processes? Fourth, how often would a complete cleanup need to be performed to significantly lower CB counts from current levels?

METHODS

Study Site

The Kendall-Frost Mission Bay Marsh Reserve is a 16-acre coastal saltmarsh located in the northeast corner of Mission Bay, San Diego. Its proximity to San Diego's Pacific Beach neighborhood and the presence of two stormwater outlets into the Reserve make it a particularly relevant site for studying the impact of urban runoff discharged into a protected aquatic environment. Using San Diego City maps of the municipal storm drain system and ArcGIS Pro, we mapped the drainage area (3.584 km^2) above the two outlets and identified all storm drain inlets.[26] See Figure S1 in the Supporting Information for a map of the drainage area, location of stormwater inlets, and runoff-contributing street surfaces surveyed for this study.

Sample Selection

We enumerated all inlets connecting to the storm drain system along residential streets and alleys in the Kendall Frost drainage area (i.e., study area) that direct rainwater runoff into the Reserve. Out of 162 storm drains maintained by the City of San Diego, 138 qualified as inlets receiving stormwater. We excluded those on private land or with limited access, resulting in 84 eligible storm drains for selection. Next, we divided the drainage area into three subareas based on types of land-use and major roads: Sub-Area 1 (lower study area) is located near the stormwater outlets at Noyes Street and Olney Street and includes high-density mixed-use businesses, large parking lots, single and multiunit housing, and two busy streets (total eligible inlets N_1 = 41, of which n_1 = 13 were randomly selected). Sub-Area 2 (middle study area) consists of mainly single- and multiunit residences (N_2 = 22, n_2 = 8). Sub-Area 3 (upper study area) is comprised mainly of single-family homes (N_3 = 21, n_3 = 8). We randomly sampled proportionally from these subareas (i.e., stratified proportional random sampling) approximately one-third of the eligible inlets for a total sample size of N = 29 storm drain inlets. A map of the drainage area, the city-maintained storm drains, and the selected inlets can be found in Figure S1 of the Supporting Information. Detailed demographic information for the population residing in the drainage area is provided in Table S1 of the Supporting Information.

Defining Survey Areas Near Storm Drains at Risk of Runoff

For each of the 29 selected storm drain inlets, we defined a runoff-contributing surface area on both sides of the inlet on the street from which TPW is likely to be carried into the storm drain system during a major rain or other significant runoff event (e.g., irrigation). Cross streets were used to set the boundaries of the survey area to the left and right of the inlet. Between the cross streets, the survey area included surfaces from the center of the street to the gutter, the gutter

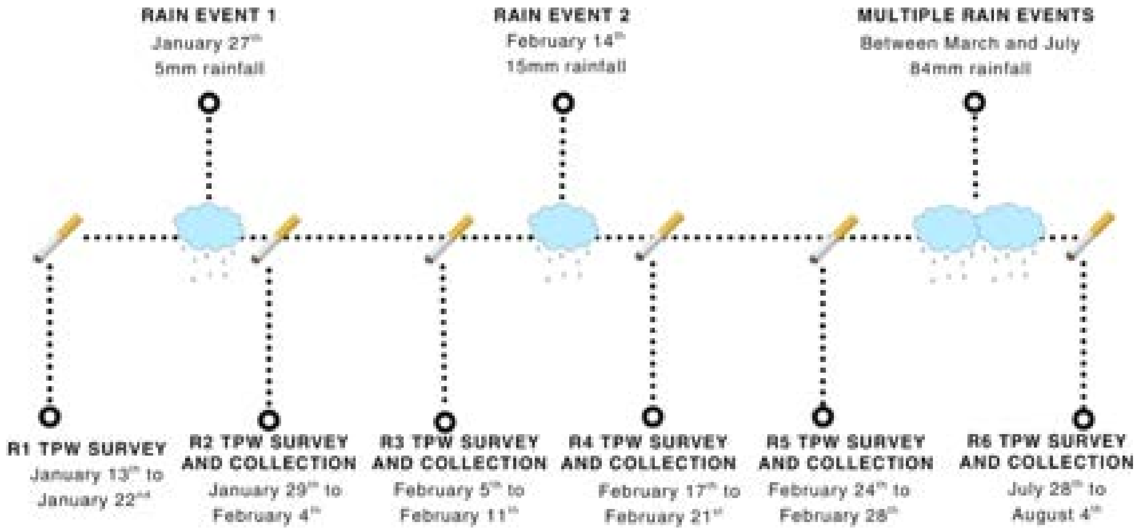

Figure 1. Schedule of tobacco product waste (TPW) surveys, cleanups, and rain events.

Table 1. Count Totals, Arithmetic Means, Standard Deviations, and Tukey's Five-Number Summaries Cigarette Butt Counts in Survey Rounds 1 to 6 (N = 29 Runoff-Contributing Areas)[a]

Survey Round	Days since last Survey	Total Count	Density CB/m^2	Arithmetic Mean	SD	Min	P25	Mdn	P75	Max
1	-	1393	0.0212	48.0	40.4	0	15	41	72	165
2	17.1	1406	0.0214	48.5	45.1	0	11	37	72	181
3	7.9	570	0.0087	19.7	17.5	0	5	16	31	57
4	10.1	477	0.0073	16.5	13.5	0	7	14	22	51
5	7.0	355	0.0054	12.2	9.9	0	6	10	20	31
6	154.3	1124	0.0171	38.8	33.0	1	8	37	59	139

[a]Note: SD: Standard deviation. Min: lowest count. P25 and P75 refer to the 25th and 75th percentiles, respectively. Mdn: Median or 50th percentile. Max: highest count.

itself, and the vertical and horizontal surfaces of the curb. For curbs cut to access a driveway, we included the driveway's sloped area from the curb to the property line, including the sidewalk, to account for materials likely to be washed into the street during a rain event. For alleys, the surface area covered the entire width of the alley from the edge of the sidewalk at either end (i.e., the upper and lower boundaries). Boundaries were marked in the field and documented in ArcGIS Pro, showing a total runoff-contributing area that was to be surveyed of 65,650m^2,[26] Figure S2 in the Supporting Information shows a schematic of the defined runoff-contributing areas surveyed near stormwater inlets. Figure S3 of the Supporting Information shows a map of one of the stormwater inlets in the drainage area and the runoff-contributing areas on either side of the inlet.

Identifying, Classifying, and Geo-Locating TPW

The data collection protocol, described in detail elsewhere, was adapted from an earlier study.[7] Per protocol, all surfaces within each street's boundaries were assessed for different types of TPW. Research assistants worked in teams of 3−4 using the "snowplow" or "lawnmower" method to ensure the entire area was inspected.[7] Loose debris, such as leaves or trash, was raked and inspected for hidden TPW. On streets with high traffic, surfaces were visually inspected from a safe distance. TPW items were photographed and geocoded at their location, and the type and number of items in each photo were recorded in ArcGIS using Quick Capture. In Round 1, all TPW items were left undisturbed; in subsequent rounds, all items were collected for disposal. Items were left undisturbed in Round 1 so that we could observe changes in CB accumulation under "natural conditions" and without our complete manual removal. Therefore, Rounds 1 and 2 counts reflect the CB accumulation under existing deposition and removal processes.

Repeated TPW Surveys and Removal

Figure 1 shows the timing of six TPW surveys, pickups, and rain events between January and August 2025. San Diego city street sweeping takes place weekly on busy streets (e.g., Garnet and Grand Avenue), monthly on side streets, and bimonthly on upper residential streets, with no sweeping in alleys. Round 1 TPW surveys started on 1/13/25, 50 days after the last rainfall on 11/24/24. After recording, all TPW items were left where they were counted. Round 2 surveys occurred after the first rain event of the season (5 mm of precipitation), on average 17.1 days (SD = 3.2) after Round 1, with all TPW items collected and disposed of. Round 3 surveys took place an average of 7.9 days (SD = 2.4) after Round 2, and all TPW was again removed. No rain had fallen since the previous survey. Round 4 took place an average of 10.1 days (SD = 3.5) after Round 3, following the next rain event (15 mm of precipitation); all TPW was removed. Round 5 occurred exactly 7 days after Round 4, with no rain since the last survey, and all TPW was removed. Round 6 was conducted in late July and early August 2025, an average of 154.3 days (SD = 0.9) after Round 5, with all TPW removed. Multiple rain events totaling 84mm of precipitation occurred between the end of Round 5 on 2/28/25 and the start of Round 6 on 7/28/25.

TPW-Related Characteristics

The municipal street-sweeping schedule, posted on the city Web site, was used to determine the days between street sweeping and data collection. Whenever possible, data collection was scheduled to maximize the days after street sweeping. To identify rain events, daily precipitation was monitored using Weather Underground forecasts at the Pacific Beach station and verified with NOAA observed precipitation data.[27,28] A rain event was defined as 6 mm, or a quarter of an inch, of predicted precipitation over 24 h in the study area.

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Statistical Analyses

We present univariate statistical analyses to describe the distribution of cigarette butt counts. A logarithmic transformation (i.e., log10(x +1)) was applied when examining correlations between repeated observations of CB counts because of the positive skew and heterogeneous variances of the count distributions. To examine changes in CB counts over time, data were analyzed using a mixed-effects negative binomial regression model that accounted for overdispersion and used robust variance estimates. To estimate the parameters of the first-order loss model, nonlinear least-squares estimation was employed. All analyses were conducted using Stata 19, with a Type I error rate of 5%.[29]

■ RESULTS

Cigarette Butt Accumulation Near Storm Drains

Table 1 presents the total counts and distributions of CBs collected across six TPW surveys. In the runoff-contributing areas surrounding the 29 stormwater inlets, we recorded between 355 and 1406 CBs (0.0054−0.0214 CB/m^2), with averages ranging from 12.2 to 48.5 butts per inlet. Rounds 1 and 2 show the CB counts under typical city street-sweeping, community cleanup, natural degradation, and weather conditions, without any known prior special cleanup efforts. Rounds 3 through 6 reflect counts after a complete cleanup conducted between 7 and 154 days earlier. This means that after a previous cleanup, between 355 and 1124 butts (0.0054−0.01712 CB/m^2) had reaccumulated by the time of the next survey. The Rounds 2 and 4 counts may have also been influenced by rain events (3.1 mm and 5.8 mm, respectively) that occurred since the last survey.

Table 2 displays the Pearson product−moment correlations for the log-transformed cigarette butt counts. Repeated CB counts between 7 and 154 days apart show strong linear relationships, ranging from 0.77 to 0.95 (all $p < 0.001$). Because we left CBs undisturbed in Round 1, the correlation between the counts in Rounds 1 and 2 ($r_{12} = 0.95$) indicates the high stability of CB over a 17 day interval under the existing removal practices. Because all CBs were removed in Rounds 2−6, the correlations between Rounds 2−6 counts reflect the stability of CB reaccumulation.

Table 2. Pearson Product−Moment Correlations of log10-Transformed Cigarette Butt Counts in Survey Rounds 1 to 6 (N = 29)[a]

	Round 1	Round 2	Round 3	Round 4	Round 5	Round 6
round 1	1.00					
round 2	0.95	1.00				
round 3	0.91	0.89	1.00			
round 4	0.88	0.85	0.91	1.00		
round 5	0.77	0.78	0.85	0.88	1.00	
round 6	0.86	0.84	0.84	0.84	0.81	1.00

[a]All *P*-values <0.001.

Short-Term and Long-Term Impact of Cigarette Butt Accumulation after Cleanups

Figure 2 displays the actual counts and mean estimates from the mixed-effects negative binomial model for the repeated CB counts. This model demonstrated excellent overall fit ($\chi^2(7) = 199.9$, $p < 0.001$) with significant main effects for the repeated measures ($\chi^2(5) = 163.7$, $p < 0.001$) and subareas ($\chi^2(2) = 25.5$, $p < 0.001$).

We tested specific contrasts to examine hypotheses about the effects of cleanup on subsequent counts. First, we compared counts from Rounds 1, 2, and 6 that were preceded by extended periods without cleanups. The estimated mean counts of 55.7, 53.7, and 46.1 did not significantly differ from each other (Round 1 vs 2: $\chi^2(1) = 0.21$, p = 0.64; Round 1 vs 6: $\chi^2(1) = 2.78$, p = 0.10; Round 2 vs 6: $\chi^2(1) = 1.60$, p = 0.62). Next, we compared counts from Rounds 3, 4, and 5 that were preceded by cleanups 7.9, 10.1, and 7.0 days earlier. The differences between Rounds 2 and 3 (53.7 vs 21.8, $\chi^2(1) = 70.9$, $p < 0.001$) and between Rounds 4 and 5 (19.2 vs 14.4; $\chi^2(1) = 7.45$, p = 0.0063) revealed statistically significant reductions. The mean counts in Rounds 3 and 4 were not significantly different (21.8 vs 19.2, $\chi^2(1) = 1.86$, p = 0.17).

Daily Accumulation and Removal Rates

Figure 3 displays the total number of CBs on surfaces near the 29 storm drains across the six surveys, plotted against the number of days since the last cleanup. Because there was no organized cleanup before Round 2, we arbitrarily assigned 360 days to Round 1 and 377 days (360 + 17) to Round 2. The first-order accumulation model fit the data well (adj. R^2 = 0.988, RMSE = 124.1), with an estimated asymptote of Y_{Max} = M(t→infinity) = 1503.5 (95% CI: [1304.3; 1702.6]) and daily removal rate of k = 0.05298 (95% CI: [0.02662; 0.07934]). The estimated asymptote of 1503.5 represented the persistent visible storage of CBs on surfaces near the inlets. Sensitivity analyses revealed that model estimates remained virtually unchanged assuming that prior cleanups for Rounds 1 and 2 occurred from 120 and 137 to 720 and 737 days earlier, respectively (see Table S2 of the Supporting Information).

Based on these estimates, the daily accumulation is I = 79.7 butts, resulting in an annual total of 29,073 butts deposited in surface areas around the 29 storm drains (i.e., 79.7*365; the projected total CB count for all 84 inlets is 84,211). Of the 29,073 discarded butts, 27,570 (i.e., 29,073−1503) were removed from the surveyed surfaces through multiple processes, including street sweeping, community pickups, or by entering the stormwater system through one of the inlets. In addition, "removal" also occurred because CBs were no longer countable as they degraded into fragments that were no longer recognizable or too small to be identified as part of a CB.

How often would a cleanup have to be conducted to significantly reduce TPW?

Solving the first-order accumulation model for t (accumulation time; see Supporting Information Part D), we determined the number of days after a complete cleanup when the CB count is predicted to reaccumulate to levels ranging from 10% to 90% of the steady-state level. Table 3 shows that, based on the observed input and removal rates in the study area, a community would need to perform a cleanup every other day to reduce the accumulation to 10% of the steady-state total of 1503 (i.e., 150 butts). Cleanups every 6−7 days are necessary to keep the total accumulation to 30% (i.e., 451 butts), approximately 2 weeks are required to limit reaccumulation to 50% (i.e., 752 butts), and about 7 weeks are needed for 90% reaccumulation (1588 butts).

■ DISCUSSION

Overview of Findings

This study reports the dynamics of CB reaccumulation, focusing specifically on CBs discarded on streets near storm

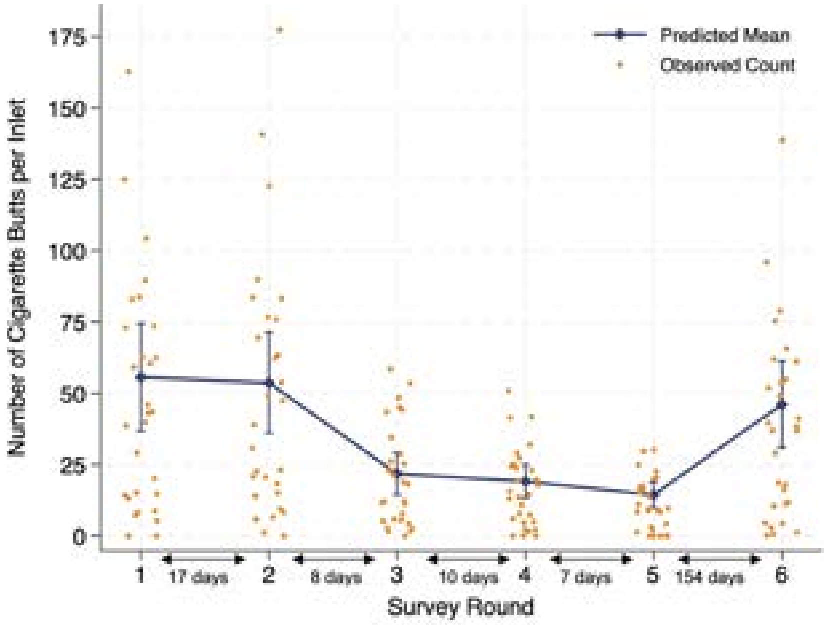

Figure 2. Observed counts (orange dots) and estimated mean cigarette butts (blue dots) per storm drain inlet with 95% confidence interval based on six surveys. CBs were removed in survey rounds 2 to 6. Rain events occurred between Round 1 and 2, 3 and 4, and 5 and 6.

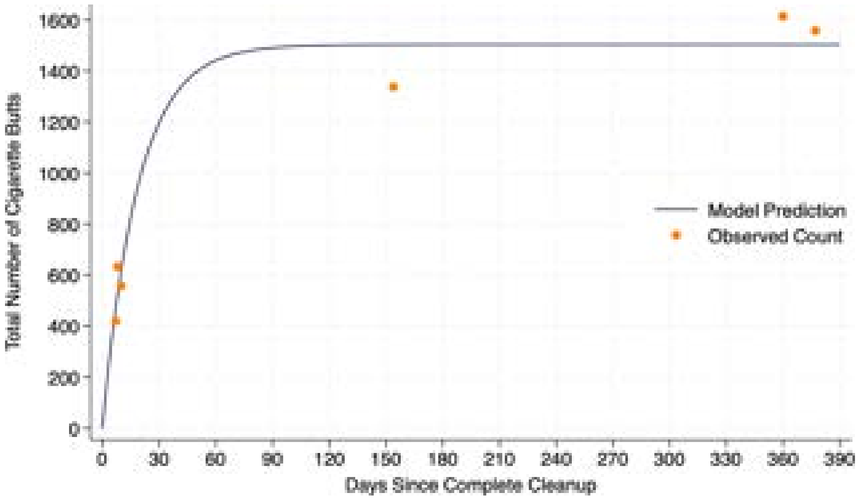

Figure 3. Total number of cigarette butts observed (orange dots) and estimated to accumulate (blue line) near the 29 storm drains as a function of the number of days since the last cleanup.

Table 3. Predicted Number of Days after Complete Removal for the Total Number of Cigarette Butts to Accumulate at Various Percentages of the Steady State Value (i.e., 1503) Along the 29 Storm Drains

total accumulation % of steady State	cigarette butts	cleanup interval (days)	95% CI
10%	150	2.0	[1.8;2.2]
20%	301	4.2	[3.8;4.6]
30%	451	6.7	[6.1;7.4]
40%	601	9.6	[8.7;10.6]
50%	752	13.1	[11.8;14.4]
60%	902	17.3	[15.6;19.0]
70%	1052	22.7	[20.5;25.0]
80%	1203	30.4	[27.4;33.4]
90%	1353	43.5	[39.2;47.7]

drain inlets in an urban neighborhood adjacent to a sensitive coastal ecosystem. Over six repeated surveys conducted between January 2025 and August 2025, we documented both the rapid reaccumulation of CBs after cleanups and the longer−term equilibrium state that developed under typical municipal maintenance and environmental conditions. A first-order accumulation model showed that approximately 80 CBs accumulated per day and 5% were "removed" per day, approaching a steady-state count of about 1500 CBs across the runoff-contributing surfaces near 29 storm drain inlets.

The findings have three main implications. First, the accumulation of visible CBs near storm drain inlets was highly predictable based on their daily accumulation and removal rates. Even after complete cleanups, CB waste quickly returned to previous levels within a few weeks, with half of the steady-state level reappearing in less than 2 weeks. Second, based on the steady-state count of 1503 CBs, we estimated that 94.8% of

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the 29,073 CBs discarded near the 29 inlets annually were "removed" from the streets. It is unclear, however, what fraction of CBs had actually been physically removed and were no longer stored near the inlets, and what fraction was no longer countable because chemical, physical, and biological processes degraded the discarded CBs to the point that fragments were no longer recognizable as CBs.[19] Third, to further reduce the amount of CBs remaining near inlets, municipal street sweeping and community cleanups would need to be increased to levels that most communities cannot afford or manage logistically. To reduce surface accumulation to 150 CBs (i.e., a 90% reduction), complete cleanups would have to be conducted every 2 days.

Dynamics of Cigarette Butt Accumulation

The strong correlations between repeated counts (ranging from 0.77 to 0.95, all $p < 0.001$) suggest that accumulation near storm drains is the result of a robust, predictable pattern of CB discarding. Certain inlets consistently registered higher counts, pointing to persistent behavioral and environmental factors, such as smoking hotspots near businesses, high foot traffic, and parking lots, that cause increased butt accumulation in particular microenvironments.

The finding that rain events did not substantially disrupt accumulation patterns is notable. However, it is important to recognize that the two rain events during the study period yielded only 15 mm and 5 mm of precipitation, respectively, amounts that may have been insufficient to carry CBs into the stormwater system. The persistence of strong correlations across wet and dry periods suggested that the rainfall may have primarily redistributed rather than removed CBs. Considering that San Diego receives, on average, only about 250 mm of rainfall in a year, our findings suggest that the transport of CBs from street-level surfaces to aquatic ecosystems occurs over multiple rain events and longer periods of time. It also suggests that during dry periods, TPW accumulates at higher rates, and thus removal through the stormwater system may be minimal.

The fitted first-order accumulation model performed exceptionally well (adj. $R^2 = 0.988$), supporting the utility of this framework for describing TPW dynamics. The input–output structure of the model captures the fact that CB accumulation is a balance between deposition (i.e., input: smoker discard behaviors) and removal (i.e., output: sweeping, runoff, degradation, displacement). The estimated daily input rate of nearly 80 butts across 29 inlets, the stability of CB counts when left undisturbed (Rounds 1 and 2), and the high correlations between repeated counts are consistent with stable behavioral patterns across the different inlet locations. Extrapolated annually, the nearly 29,000 discarded butts in this relatively small drainage area illustrate the potential environmental downstream burden of CB pollution in the Kendall-Frost Reserve. For example, with an estimated 1.5–3.5 mg of nicotine released per CB, this could mean as much as 101 g of nicotine is potentially released into the environment in runoff-contributing areas surrounding 29 storm drains.[30]

Implications for Cleanup and Mitigation Strategies

Residential streets are typically swept once a month in the Pacific Beach neighborhood of San Diego, where the study area was conducted, while commercial streets are swept once per week. Our findings show that existing mitigation efforts cannot remove all CBs on a weekly or monthly basis. If this were the case, the observed accumulation counts would be expected to be at about 30% or 50% of the steady-state levels of 1503. The immediate impact of complete removals is evident in the counts for Rounds 3, 4, and 5, when we picked up and discarded all TPW between 7 and 10 days earlier and observed a two-thirds reduction to approximately 500 butts, compared with the steady-state level of 1503 under the usual municipal street-sweeping schedule.

The practical implications of our findings are noteworthy. Our predictions show that to maintain CB counts near storm drains at just 10% of steady-state levels, complete cleanups would be required every other day in this specific urban setting. Such a cleanup frequency is unrealistic for municipal governments, businesses, or volunteer organizations in our study area, given the labor and financial costs involved. This is particularly true considering that, in addition to increasing the frequency, the effectiveness of existing cleanup methods would have to be significantly improved. Our data also indicate that persistent behavioral and environmental factors, such as smoking areas near businesses, high foot traffic, and parking lots, are associated with increased butt accumulation in particular microenvironments. Mapping these relatively stable "hot spots" could inform local planning to remove TPW more efficiently. The extent to which targeted clean-ups at persistent hotspots can reduce the overall environmental burden will depend on the relative contribution of these hotspots to the overall accumulation.

The accumulation dynamics documented here call into question the reliance on cleanups as a primary strategy to address TPW. Instead, we suggest that upstream interventions are needed to reduce the input rate, rather than attempting to increase the output rate through frequent and more intensive cleanups. Such upstream efforts should involve the elimination of cigarette filters, greater restrictions on where tobacco use is allowed outdoors, and stronger educational and behavioral interventions to reduce CB littering. Overall, our findings confirm what coastal cleanup reports have long suggested: organized cleanups, while symbolically important, are ineffective in preventing the continuous environmental pollution caused by TPW.

Policy and Regulatory Implications for Lowering the Input Rate

Product Redesign. The adoption of novel filter materials that biodegrade at a faster rate has been suggested to lower the environmental impact of CBs.[31,32] While such a design change would potentially reduce plastic pollution caused by CBs, this change would not address the leaching of toxicants. The cellulose acetate filter, the primary component of CBs, has been shown to serve no meaningful health purpose but is the major contributor to the plastic waste burden and chemical leaching of tobacco smoke toxicants.[2,33] Local or state-wide sales bans on filtered cigarettes would dramatically reduce the accumulation of plastic filters in the environment and may lower smoking prevalence due to changes in perception and product palatability. The County of Santa Cruz, California, has adopted such a policy for its unincorporated areas and has been joined by the cities of Santa Cruz and Capitola.[34−36]

Extended Producer Responsibility. The predictable and persistent accumulation of CBs near storm drains and elsewhere suggests that manufacturers and retailers should be held accountable for the waste generated by their products. Such policies have been successfully implemented for beverage containers, e-waste, paint, motor oil, pharmaceuticals, fluorescent lighting, and batteries.[37,38] Policies requiring tobacco

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companies to educate and warn consumers about the adverse environmental impacts of TPW and to fund cleanup and disposal infrastructure could help local governments address TPW waste at the local level.

Local Ordinances Restricting Tobacco Use. As has already been done in some municipalities,[39] local policies could restrict smoking in outdoor environments near storm drains, waterways, or sensitive ecological areas. Given the predictability of CB accumulation demonstrated in this study, targeted education, monitoring, and enforcement of no-smoking zones could potentially reduce CB pollution in high-risk, geographically limited areas. For such policies to be impactful, compliance must be monitored and consistently enforced. Such policies may also serve to denormalize tobacco use in general.

Deposit-Return or Litter Fees. Similar to bottle deposits, a fee on the sale of cigarettes earmarked for mitigation could provide funding for cleanup and public education campaigns. Such a policy has been in effect in San Francisco, California, starting in 2009 with a $0.20/pack fee that was increased to $1.75/pack in 2025.[40,41] Because such a fee is likely to increase the purchase price, there would also be an expected decrease in sales, tobacco consumption, and youth initiation. It should be noted that the effectiveness of litter fees to reduce TPW in general or CB pollution in particular has not been investigated.

Environmental and Public Health Implications

The environmental implications of CB accumulation at storm drains are particularly notable. Stormwater outlets at the Kendall-Frost Mission Bay Marsh Reserve discharge directly into a protected coastal wetland. The continuous deposition of CBs in the drainage area documented here likely contributes to chronic microplastic and chemical pollution in the Reserve. Cigarette filters release nicotine, heavy metals, and other toxicants into aquatic environments, with demonstrated lethal and sublethal effects on fish, invertebrates, and microbial communities.[1−3,42,43] The input−output equilibrium observed in our study suggests that these pollutants present a persistent hazard in the drainage area throughout the year. Based on a study of nicotine and cotinine levels in water and soil samples collected near the outlets into the reserve,[25] increases in the pollutant flow into the Reserve are particularly noticeable during the November to April rainy season.

Limitations

Several limitations must be acknowledged. First, the study focused on a single urban drainage area adjacent to a coastal wetland in Southern California, limiting the generalizability to other geographic and sociodemographic contexts. Compared with urban settings elsewhere, the study area has a relatively low population density, a high per capita income, and well-established municipal street-cleaning practices. Different climate conditions, land-use patterns, smoking prevalence, social norms, tobacco-prevention policies, sociodemographic conditions, and municipal maintenance practices are expected to yield distinct accumulation dynamics. Second, the model assumes a constant input rate, which may not reflect real-world fluctuations due to daily, seasonal, or event-based smoking behaviors (e.g., tourism surges, street fairs). Third, while the model accounts for removal processes broadly, the study was unable to disaggregate the relative contributions of any specific efforts, such as street sweeping, runoff, degradation, displacement, and informal cleanup.

Another limitation is that the rain events during the study period produced relatively little precipitation, limiting our ability to assess the full impact of significant rainfall on runoff into the Reserve. Lastly, our study focused on CBs, which remain the dominant form of TPW, but the increasing use of nicotine pouches, electronic nicotine delivery systems, and smokeless tobacco products suggests that future accumulation models must include these emerging waste streams, which pose unique additional hazards (e.g., lithium batteries, heavy metals, nicotine, and plastics).

Future Research Directions

Future studies are needed to extend these lines of inquiry. Longitudinal monitoring across multiple urban contexts and climate conditions would help determine the generalizability of the input−output parameters estimated here. Coupling CB accumulation models with hydrological models could more precisely quantify pollutant flow into aquatic ecosystems. Moreover, integrating behavioral data on smoking and discard patterns could refine input estimates. For example, high population density urban environments may produce significant generalized trash without the possibility of specific estimates for TPW. It is likely that the marginal TPW burden will be significantly smaller in such settings, but nonetheless, large quantities of TPW will have significant ecotoxicological impacts.

While our study was able to determine the overall aggregate removal rate, additional research is urgently needed to disaggregate the different removal processes. Importantly, future studies should determine what fractions of the total amount of deposited CB waste are (a) physically removed by street sweeping and other cleanups, (b) degrade, are redistributed, but remain (i.e., are stored), in the local environment, and (c) are carried from street surfaces to aquatic ecosystems in various stages of degradation.

Controlled field experiments should be conducted to carefully evaluate the effects of collection receptacles, local smoking bans, targeted public education campaigns, and filter bans on TPW in general and CB pollution in particular. Finally, given the rapid rise of e-cigarettes and other nicotine products, adapting the first-order model to account for mixed waste streams will be critical to understanding TPW accumulation as tobacco product use evolves.

■ CONCLUSION

This study demonstrates that CB accumulation near storm drains in a defined urban setting follows predictable dynamics that can be accurately described using a first-order accumulation model. The findings reveal both the scale of the problem and the futility of relying primarily on cleanups to mitigate CB pollution. Cleanups, even when frequent, cannot meaningfully reduce accumulation without prohibitive efforts and costs. Instead, interventions must target input reduction through product redesign, restrictions on outdoor smoking, and effective economic, educational, and behavioral interventions to reduce tobacco use. Addressing this issue requires a fundamental shift from reactive cleanup to proactive prevention approaches.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestwater.5c01109.

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Additional experimental details, maps, and schematics, including additional Tables S1 and S2, Figures S1−S3, and applications and sensitivity analyses for the first-order accumulation model, as mentioned in the text (PDF)

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Author Contributions

The manuscript was written through the contributions of all authors. All authors have given approval to the final version of the manuscript. CRediT: **Georg Matt** conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, writing - original draft, writing - review & editing; **Lydia Greiner** conceptualization, data curation, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, writing - review & editing; **Michael Vingiello** conceptualization, data curation, formal analysis, investigation, methodology, validation, writing - review & editing; **Gunnar Wooldridge** data curation, investigation, writing - review & editing; **Kris Tran** data curation, investigation, writing - review & editing; **Thomas E. Novotny** conceptualization, funding acquisition, methodology, writing - review & editing.

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Notes

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