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A City-Wide Emissions Inventory of Plastic Pollution

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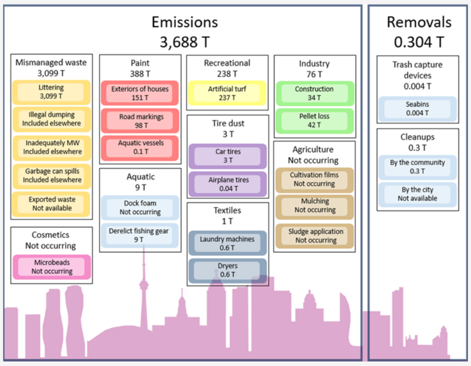
ABSTRACT: A global agreement on plastic should have quantitative reduction targets for the emissions of plastic pollution and regular measurements to track success. Here, we present a framework for measuring plastic emissions, akin to greenhouse gas emissions, and demonstrate its utility by calculating a baseline measurement for the City of Toronto in Ontario, Canada. We identify relevant sources of plastic pollution in the city, calculate emissions for each source by multiplying activity data by emission factors for each source, and sum the emissions to obtain the total annual emissions of plastic pollution generated. Using Monte Carlo simulations, we estimate that 3,531 to 3,852 tonnes (T) of plastic pollution were emitted from Toronto in 2020. Littering is the largest source overall (3,099 T), and artificial turf is the largest source of microplastic (237 T). Quantifying source emissions can inform the most effective mitigation strategies to achieve reduction targets. We recommend this framework be scaled up and replicated in cities, states, provinces, and countries around the world to inform global reduction targets and measure progress toward reducing plastic pollution.



KEYWORDS: *plastic pollution, environment, contamination, emissions, accounting, mitigation, policy*

■ INTRODUCTION

Over the past several decades, there has been growing awareness of the ubiquity of plastic pollution in the natural environment[1−4] and the multitude of impacts it has on living organisms and ecosystems.[5−8] Plastic pollution is a chemical stressor: it leaches toxic substances over time,[9−11] which may induce hepatic stress,[12] affect reproductive success,[13] and lead to increased rates of mortality in living organisms.[13,14] Plastic can also cause physical damage through entanglement[15−17] or through a false sense of satiation[18,19] when it is ingested. Plastic can alter the cycling of carbon and nitrogen as it breaks down.[20−22] The multidimensional nature of plastic pollution makes it a wicked problem[23] that transcends geographic boundaries, warranting global cooperation.

Although the number of local and global policies aimed at tackling plastic pollution is increasing, including the prohibition of dumping of plastic waste into oceanic waters,[24,25] fines for littering,[25] and fees and bans on single-use plastic items,[25] the majority are voluntary and their effectiveness is not measured.[25] Today, calls for global cooperation to tackle this issue are loud and clear,[26−30] but we continue to lack mechanisms for generating specific, measurable targets and for tracking progress toward reaching those targets that will help inform a successful, binding global agreement on plastic pollution at the UN level.[31] To fill this gap, and to inform the development of such an agreement,[32] we introduce a framework for an emissions inventory for plastic pollution.

Borrowed from climate policy, an emissions inventory quantifies emissions or inputs of a given substance from all major sources into the environment within an administrative unit (i.e., city, province/state, country). Emissions inventories quantify local sources into the environment rather than quantifying environmental contamination (which may also include external emissions due to long-range transport). Emissions inventories can be generated for any substance, including plastic pollution. In general, emissions inventories help inform targeted source reduction, reduction targets, and the progress of signatories toward meeting those targets. Over the years, estimations of emissions or inputs of plastic pollution into the environment have evolved from crude, global estimates of one or two sources of plastic[33,34] to those accounting for emissions from multiple sources at the regional or national level.[35−39] Still, we lack comprehensive and standardized frameworks for measuring multiple emission sources across geographic scales like the climate field. The United Nations Framework Convention on Climate Change (UNFCCC) has mandated the compilation and reporting of emissions inventories of greenhouse gases by countries since the 1990s.[40] This exercise has helped the world track its progress in terms of reducing emissions to meet the target of keeping global average temperature rise below 1.5 °C.[41]

To facilitate the success of an international agreement for plastic, we need an equivalent of the UNFCCC mechanism for

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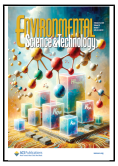

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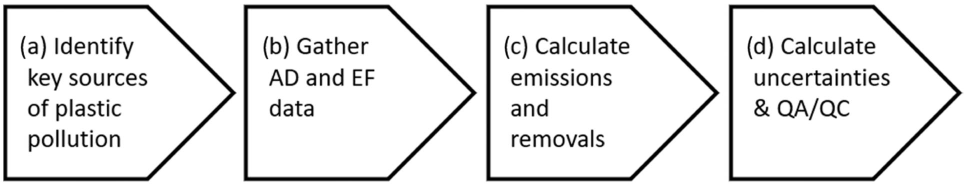

Figure 1. Compiling an emissions inventory of plastic pollution involves (a) identifying key sources of plastic pollution, (b) gathering activity data (AD) and emission factor (EF) data, (c) calculating emissions and removal terms, and (d) estimating emission uncertainties and exercising quality assurance/quality control best practices.

plastic pollution; we need standardized frameworks for measuring plastic emissions to track global progress toward reducing plastic pollution. Inventories need to be compiled for cities, provinces, states, and countries as they all serve important roles.[29] Local inventories shed light on which sources are the most offending and offer insight into their mitigation.[29] National inventories are reported to an international governing body that reveal leaders and laggers on emission reduction efforts on the global scale and keep track of progress toward a globally defined target.[29] Inventories compiled for nonpolitical units, e.g., watersheds and river basins, make it difficult to assign sole responsibility for the pollution production to a single political entity and therefore lack the ability to inform a global treaty. Here, we present a framework for an emissions inventory of plastic pollution (from the micro- to the macroscale) and apply this framework to a municipality to demonstrate its utility. We chose to focus on the municipal level because the granularity of the data allows us to demonstrate the utility of an emissions inventory of plastic pollution for informing policy, and we chose the City of Toronto because it is a major city with many sources of plastic pollution: it hosts a population of approximately three million people and is the fourth largest city in North America.

■ MATERIALS AND METHODS

First, we present the generic framework for compiling and reporting emissions inventories of plastic pollution (methodology summarized in Figure 1). Then, we show the outcome from applying this framework to the City of Toronto, demonstrating its utility.

Framework for an Emissions Inventory of Plastic Pollution. *Building the Proposed Standardized Guidelines.* We drafted proposed guidelines for the compilation and reporting of emission inventories of plastic pollution (Data S1). Here, plastic emissions include plastic leakage into the environment as a whole, not just the fraction that reaches the ocean or receiving waters. Our proposed guidelines for compiling and reporting plastic emissions inventories are modeled off of guidelines for greenhouse gases.[42,43] The C40 Global Protocol for Emissions Inventories are the official guidelines used for greenhouse gas emissions inventory compilation for municipalities. The 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines are used by Annex I countries under the Kyoto Protocol to compile and report national emissions inventories on an annual basis. These two documents were consulted and adapted into proposed standardized guidelines for the compilation and reporting of emissions inventories of plastic pollution.

Sources and Source Groupings of Emissions. The first step to compiling an emissions inventory is to determine the largest sources of plastic pollution in a given area[44,45] (Figure 1a). This involves identifying which sources occur in the region of interest from the full list of plastic-emitting sources in our proposed standardized guidelines, which contain a total of 21 sources (see Data S1 for the proposed guidelines). These sources should be added to an emissions inventory spreadsheet (Data S3). One column is designated to indicate the availability of data for each source; briefly, "E" indicates if the source was successfully estimated, "IE" indicates the source was included elsewhere as part of another source, "NA" indicates information on the source is not available, "NO" indicates the source does not occur within the geographic region of interest, and "C" indicates the data are considered confidential and thus also not available (Data S1).[44,45]

The generic list of sources includes littering (which includes contributions from illegal dumping, inadequately managed waste, and spills from trash receptables), the shedding of rubber infill from artificial turf, tire dust from airplanes and on-road vehicles, foam loss from construction activities, pellet loss from industry, plastic loss from agricultural activities, textile pollution from washing machines and vented dryers, microbead emissions from cosmetic products, dock foam, derelict fishing gear, paint shedding from the exteriors of houses, road markings, and paint shedding from aquatic vessels (Table S1). These sources are clustered into nine categories: mismanaged waste (MMW; includes littering), recreational (artificial turf), tire dust (airplanes and on-road vehicles), industrial (construction foam, pellet loss), agriculture (cultivation films, mulching, and sludge application), textiles (washing machines and vented dryers), cosmetics (microbeads), aquatic (derelict fishing gear and dock foam), and paint (exteriors of houses, road markings, and aquatic vessels; see Table S1). Note that several of these sources predominantly emit microplastics (i.e., all sources except littering and derelict fishing gear).

Gathering Data for the Inventory. After relevant major sources are identified, activity data (AD) and emission factors (EF) are collected for estimating emissions (Figure 1b). AD describes the amount of pollution-generating activity for a source that occurs within a given period of time.[42] AD can be found in various resources, including government websites, scientific literature, organization websites, and through personal communication with experts. Examples include distance driven by vehicles per year and amount of household laundry washed per year. EF describe the intensity of emissions or the amount of pollution generated per unit of activity.[42] EF are generally quantified by research and can often be found in research reports (e.g., Eunomia reports[44]) and the peer-reviewed scientific literature. Examples include the mass of the tire dust shed per kilometer driven and the mass of the plastic shed per kilogram of laundry.

Calculating Emissions and Removals. The third step in inventory compilation involves calculating emissions (Figure 1c). To calculate the emissions of plastic pollution from each source, AD and EF are multiplied together to obtain emissions eq 1.

$$\text{emission} = \text{AD} \times \text{EF} \tag{1}$$

Removal terms describe activities that remove plastic pollution that has already entered the environment. Removals are included in an emissions inventory to demonstrate efforts to tackle plastic pollution within a given year. However, they will not be subtracted for the purposes of measuring emissions because the pollution does enter the environment for an unknown amount of time and has the potential to cause harm.

Estimating Uncertainty. The final step in inventory compilation is an estimation of uncertainty associated with each of the sources as well as for the overall inventory estimate (Figure 1d). There are two approaches for estimating the overall uncertainty of an emissions inventory (Data S1). Approach 1 uses an error propagation method, while Approach 2 uses Monte Carlo simulations. When dealing with large, asymmetrical distributions, Monte Carlo simulations provide more accurate estimates of the overall mean and 95% confidence intervals (CI) compared to Approach 1, which assumes probability density functions (PDFs) are symmetrical and uncertainties are small—the standard deviation divided by the mean is <0.3 (Data S1). Approach 1 also requires estimates of both the mean and the standard deviation for each parameter. When such information is unavailable, Monte Carlo simulations may be the more appropriate choice because it is more flexible in terms of the uncertainty PDFs that can be input.

Ideally, uncertainty PDFs are reported along with the parameter of interest. When uncertainty PDFs are not reported for parameters or when they could not be obtained from experts, uniform PDFs should be assigned using data quality rankings (Table S3).

In a Monte Carlo analysis, samples from PDFs should be extracted and carried through calculations to obtain an emissions estimate for each source, as well as for the overall inventory sum. This process is repeated many times (i.e., on the magnitude of 10,000 times or greater) in R 4.2.2[46] until the corresponding emissions histogram is relatively smooth and the 95% CI for the histogram is within ±1% of the mean. Then, the given PDF for each of the sources and the overall inventory sum are accepted (Table S4).

Applying the Framework to the City of Toronto. *Toronto's Emissions Inventory of Plastic Pollution.* To demonstrate the utility and feasibility of our framework, we built an emissions inventory for the City of Toronto (Ontario, Canada) for the year 2020. The inventory boundary aligns with the geographic and administrative boundaries of the City of Toronto.

Of the 21 initial sources, ultimately 12 of these were quantified for the City of Toronto. Five were not occurring within the City (cultivation films, mulching, sludge application, microbeads, and dock foam); three were included elsewhere in other sources (illegal dumping, inadequately managed waste, and spills from garbage cans); and one was not available for the City of Toronto (exported waste; Table S1).

Emissions Calculations. For the majority of sources, the AD × EF approach was used to calculate emissions. For example, in calculating the emission of tire dust, the number of vehicles in Toronto was multiplied by the average mileage per vehicle per year to obtain the activity data (total miles driven). The total miles was then multiplied by the emissions factor (the shedding rate of tire dust per mile) to estimate the total emissions (Table S2 and Data S3). Activity data were commonly sourced from City of Toronto and Statistics Canada resources and from personal communication with experts, and emission factors were commonly sourced from the scientific literature. All calculations, data, and references consulted are summarized in Data S3 "Toronto Inventory SI". For certain sources, other approaches were used due to the nature of the available data (Table S2). For example, a more direct approach was used to estimate emissions of mismanaged waste from the city due to the availability of empirical data; fortunately, the City of Toronto conducts a litter audit every four years, so these direct measurements of littering rates were used to estimate the total amount of mismanaged waste produced within the city for the year 2020 (Supporting Text Section 1). Litter audit data in 2020 came from 300 sites across the city adjacent to roads that were visually surveyed by field teams for large litter items (>4 sq in.) and small litter items (<4 sq in.).

Quantifying Uncertainties. Expert elicitation was used to estimate the values of two activity data-related pieces of information: proportion of house exterior painted (%) and number of aquatic vessels in Toronto in 2020 (see Data S2 for expert elicitation documents and Data S3 for all AD, EF, and calculations). Experts were interviewed following the protocol in Appendix D 'Guide to conducting expert elicitations' of our Proposed Standardized Guidelines document (Data S1).

For parameters missing uncertainty PDFs, a quality ranking of "Low", "Medium", or "High" are assigned to parameters, which pertain to uniform distribution widths of 2, 6, and 12% of the mean,[47] respectively (see methodology in Data S1). Data quality rankings were assigned to parameters without reported uncertainties by two of the coauthors (Data S4). Where there were discrepancies, the third author served as the tiebreaker. All parameters used in the emissions calculations and their associated uncertainties can be found in the Supporting Information (Data S3).

We used Approach 2 to estimate the uncertainty in emissions for the City of Toronto because the uncertainty PDFs for several parameters used in the calculations are not symmetrical and the uncertainties are large compared to the mean. Monte Carlo simulations were performed 10,000 to 50,000 times in R 4.2.2[46] for each source and for the overall inventory sum (code found here: https://github.com/xiazhu111/EmissionsInventory).

QA/QC on the Inventory. As mentioned in the Materials and Methods section, data quality rankings were assigned to parameters without reported uncertainties for the purposes of calculating uncertainties (Table S3). In addition, these rankings serve another purpose: together with uncertainty PDFs that were reported for parameters, this information can motivate an improvement in data quality in future iterations of the inventory. Calculations and Monte Carlo simulations were reviewed by all coauthors independently before being reported.

Aside from quantifying uncertainty in the inventory results, throughout the entire process of calculating emissions, care was taken to reduce uncertainty as much as possible. Reducing uncertainty involves making careful decisions about where to collect data, choosing the appropriate calculation approach for emissions, and minimizing the number of assumptions made. We also double-checked the calculations for completion and accuracy. A discussion of the uncertainties surrounding the

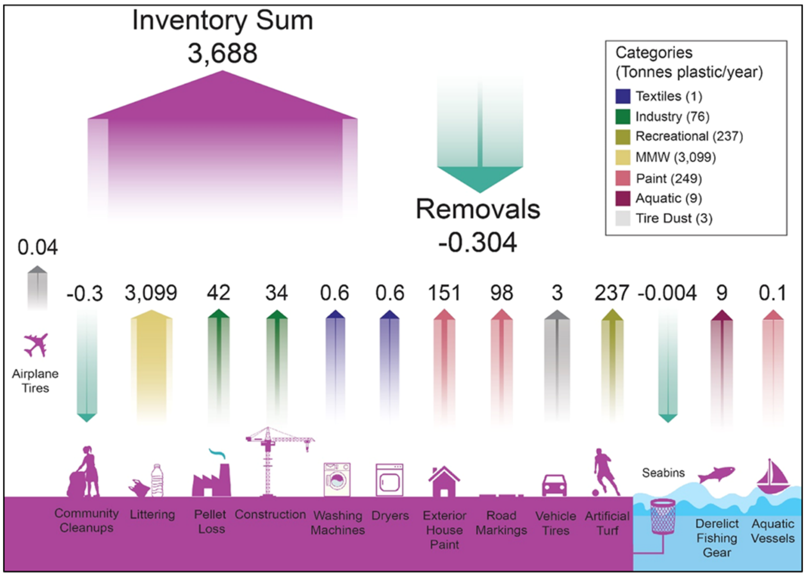

Figure 2. Toronto's emissions inventory of plastic pollution. Sources and removal terms form the foundation of the figure. Emissions are shown as fluxes out of the city, while removals are shown as fluxes into the city. Thicker widths of the arrows indicate higher emissions; however, these are not to scale. Categories of sources are color-coded within the arrows and are shown in the legend. The overall emissions sum and overall removals are shown as large arrows above the individual source/removal fluxes. Emissions from cosmetics, dock foam, and agriculture are not shown because agricultural activities and unencapsulated dock foam do not occur within the City of Toronto, and microbeads were banned from cosmetics in Canada (as of 2019).[51] Although the City of Toronto does street sweeping, data on the amount of mismanaged waste cleaned are not available and thus not included here. See Table S4 for uncertainties associated with emissions.

inventory, assumptions made, and data gaps is described in Supporting Text Section 2.

Removal Activities in Toronto. Out of the three removal terms in the proposed guidelines, trash trapping technology and cleanups by the community occurred in the City of Toronto in 2020. Data on cleanups conducted by the city were not available (Table S5).

Every summer since 2019, Seabins, which are floating trash cans that skim plastic pollution from surface water, have been deployed in Lake Ontario. Removal of plastic pollution via Seabins was calculated by multiplying the average mass of plastic removed per day in 2020 by the total number of days of deployment in summer of 2020.

Community cleanup data for Toronto was obtained from the Great Canadian Shoreline Cleanup. Removal of plastic pollution from community cleanups was calculated by multiplying the average mass of each plastic litter item reported (from Ocean Conservancy's TrashLab database) by the corresponding item count for each cleanup, adding up the masses of all plastic litter items for each cleanup, and then summing the masses across all cleanups conducted in 2020 in Toronto. The same procedure was repeated for all cleanups in 2019 to obtain a mean and standard deviation for the mass of plastic removed from community cleanups.

Exploring the Reasons for Littering and Informing Future Littering Predictions. Since we have direct field measurements of littering rates, we were interested in exploring what factors were driving littering. To do so, we included the covariates of Tweet density, unemployment rate, trash receptacle density, percent of total respondents that finished high school, population density, and average annual income after tax in a generalized additive model (GAM) to explain variability in the response variable, littering emissions [g/m^2] by neighborhood (n = 140). Tweet density is a reflection of where people frequent within the city and was obtained by summing the total number of Tweets from 2012 to 2016 in Toronto extracted via the Twitter API by neighborhood. Trash receptacle density was obtained from the "Street Furniture − Litter Receptacle" shapefile[48] which shows the locations of 12,000 litter receptacles owned and maintained by the city in collaboration with Astral Out-of-Home. Information on unemployment rate, education level, population density, and income after tax was obtained from a Neighborhood Profiles data set for Toronto for 2016.[49]

Generalized additive modeling was performed using the *mgcv* package in R 4.0.5.[50] The distribution of littering rates was unimodal with a mode around zero and a long right-tail, and thus, a Tweedie distribution was fit to the data using the *mgcv* package in R. The best-fitting model was chosen using Akaike's Information Criteria (AIC).

Limitations of the Study. Our study has various limitations (fully discussed in SI Text 2.2). In brief, assumptions were made to reduce complexity while still allowing our work to be useful. For instance, we chose to focus on what we believe were the greatest sources of plastic pollution in the City of Toronto. Moreover, the 2020 litter audit in Toronto took place during the global pandemic, which could affect the representativeness of this data and therefore its robustness in being used to set targets for future years. However, we note that the 2020 litter audit data are similar to those of the previous litter audit that occurred in 2016, despite COVID (3433 total pieces of large litter retrieved in 2016 vs 3024 pieces in 2020). In addition, we chose Tweet density as a representation of where people frequent in the city; however, we understand that this proxy is not perfect because the use of Twitter varies with demographics and socioeconomics, and there may be a nonlinear relationship between the number of Tweets in an area and the actual amount of visiting that occurs.

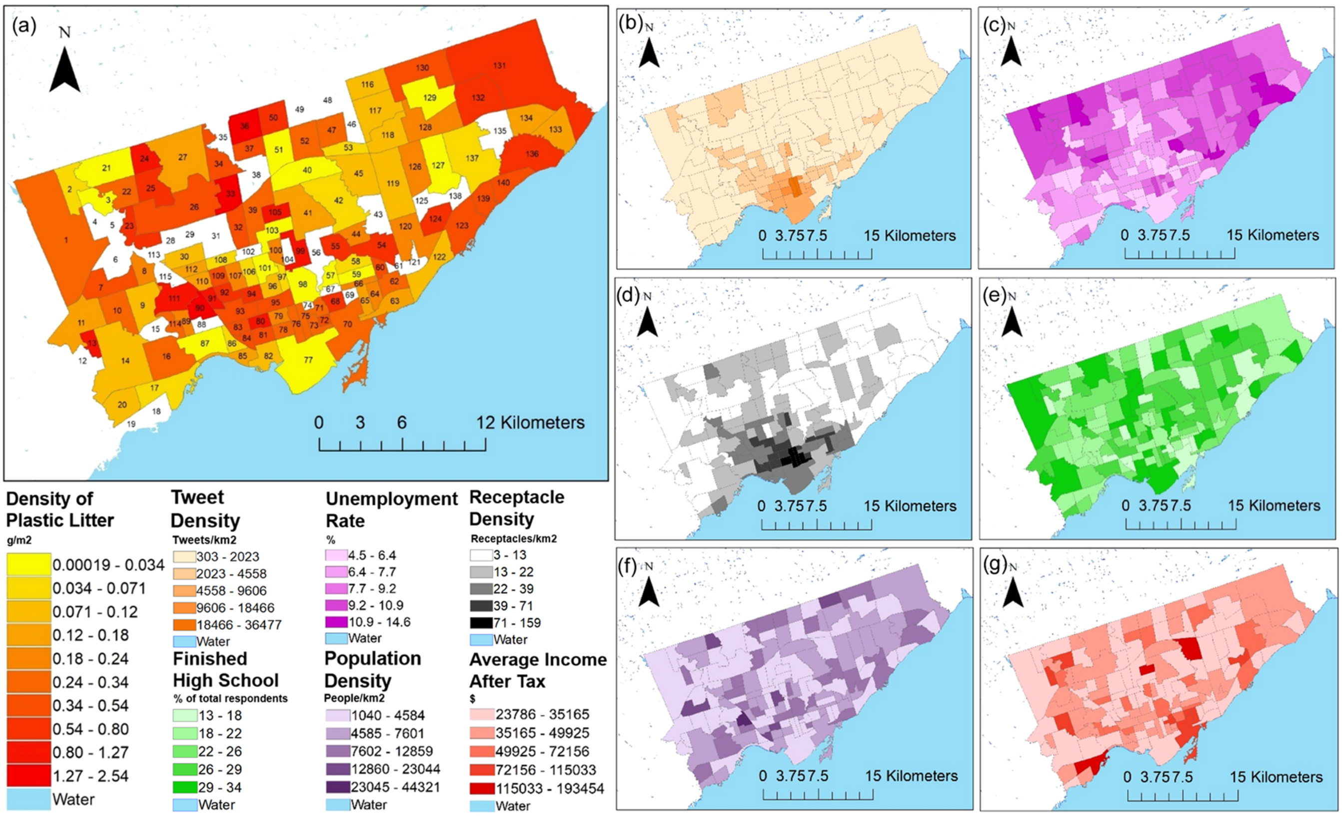

Figure 3. Maps showing littering emissions and covariates for the littering GAM by Toronto neighborhood. (a) Heat map showing emissions of mismanaged waste in Toronto normalized by area [g/m^2] for each neighborhood, which includes emissions from littering, illegal dumping, inadequately managed waste, and spills from garbage cans before entering the waste system. (b−g) Heat maps showing predictors of littering rate by neighborhood (i.e., b) Tweet density [Tweets/km^2], (c) unemployment rate [%], (d) receptacle density [receptacles/km^2], (e) proportion of survey respondents that finished high school [% of total respondents], (f) population density [people/km^2], and (g) average income after tax [$]. See Table S8 for neighborhood names which correspond to the labels in the litter heat map.

■ RESULTS AND DISCUSSION

City-Level Emissions Inventory. Upon running the methods within our framework, we estimate the total amount of plastic pollution that was emitted to the environment by the City of Toronto in 2020: using the 25th percentile from our Monte Carlo analysis, the lower bound is 3531 T, and using the 75th percentile, the upper bound is 3,852 T (median 3,688 T) (Figure 2 and Data S2; preprint: 10.31223/X55D50). Here, we provide the 25th and 75th percentiles as bounds on the emissions estimate instead of the 95% CI to better represent the uncertainty associated with our estimate. Our official 2020 inventory report can be found in Supporting Materials, Data S2. This value is dominated by litter (3,099 T), the top emission source, followed by the shedding of rubber infill from artificial turf (237 T), and paint shedding from the exteriors of houses (151 T). Overall, the top three emissions categories are mismanaged waste, paint, and recreational. MMW alone accounts for 75% of the total plastic emissions in the City of Toronto by mass. By counting, emissions are likely dominated by microplastics. The top three microplastic categories are paint, recreational, and industry. The smallest sources of emissions of plastic pollution from Toronto are washing and drying clothes (both at 0.6 T) and shedding of paint from aquatic vessels (0.1 T). Removal efforts, from trash capture technology and community cleanup activities, totaled 0.304 T, or only 0.01% of the total emissions. The amount of litter cleaned by the city is unknown. Removals were not subtracted from the overall emissions.

A Netherlands-wide study estimated annual plastic emissions to be 4,300−21,200 T.[39] Their per capita plastic emissions amount to 0.72 kg/person/year. Another study estimated annual plastic emissions from Switzerland to be 5300 ± 1100 T.[38] Toronto's per capita plastic emission estimate of 1.25 kg/person/year is approximately twice the amount of plastic emissions produced on average by a person in the Netherlands or Switzerland.

Toronto's Mismanaged Waste. For the year 2020, we estimate that 3,099 T of plastic MMW was generated within the city (Figure 3). Regular monitoring and availability of data are critical to compiling accurate emissions of plastic pollution. In this respect, we were fortunate that Toronto conducts litter audits every four years. To calculate total littering emissions, we extrapolated to the area of the entire city (see SM Materials and Methods, Section 3). To explore the drivers of littering behavior and inform littering emissions predictions globally (particularly where monitoring data is not available), we fit a GAM to the neighborhood littering rates. Only population density was significantly correlated with littering rate ($p < 0.05$; Tables S6 and S7), and the predictive ability of the model was poor (percent deviance explained = 7%), showing the inherent difficulty in attempting to explain a complex anthropogenic phenomenon. The covariates we explored may have had predictive value, but not at the geographic scale we used (at the neighborhood scale). In addition, people's propensity for littering has also been found to be related to age, social norms, physical setting, psychological factors, and environment during upbringing,[52−54] and these covariates could not be explored in our model. Since predictive modeling of littering is challenging without relevant data, it is important that we increase littering monitoring efforts to more accurately quantify emissions and to better inform future models.

Our emissions estimates for Toronto are a step up from estimates of previous studies in terms of resolution, both spatially and in terms of the number and diversity of sources that were included. In particular, Toronto's littering estimate was informed by empirical monitoring data at the neighborhood scale. We compared our on-the-ground littering data used to estimate MMW to the 2% littering rate used in Jambeck et al.[33] Equation 2 shows the calculation methodology for littering emissions used in Jambeck et al.[33]

$$\begin{aligned}\text{littering emissions} = \text{population} \\ \times \text{waste generated per capita} \times \% \\ \text{plastic in waste stream} \times 2\% \\ \text{littering rate}\end{aligned} \qquad (2)$$

Using Toronto's population of 2,956,024 people, Canada's per capita waste generation rate of 2.33 kg/person/day,[33] 4% of plastic in the waste stream, and a 2% littering rate (from Jambeck et al.[33]), we obtain an estimate of 2,011 T of plastic littered in Toronto. Our litter emissions (or MMW estimate) calculated here, 3,099 T, is higher than the Jambeck et al.[55] estimate but of a similar order of magnitude. The Jambeck et al. model makes a simplified assumption that 2% of all plastic waste is littered in addition to any inadequately managed waste. Our findings suggest that the Jambeck et al. model underestimates MMW emissions by underestimating litter. This is not surprising because the Jambeck et al.[33] model, for high-income countries, only accounts for littering, while our estimate is derived from empirical data that also includes contributions from other forms of MMW including illegal dumping, inadequately managed waste, and spills from overflowing garbage cans. The Jambeck et al. model is also missing contributions from microplastic emissions: 100% of their 2011 T estimate for Toronto is macroplastic MMW emissions, while our overall estimate of 3,688 T is composed of 84% MMW and 16% microplastic emissions by mass. This ratio is very similar to the ratio of 89% macroplastic to 11% microplastic by mass exported globally by rivers.[56]

The poor ability of our predictive model to explain littering patterns and the discrepancy between our results and Jambeck et al.'s results show that, ideally, every region measures its own MMW generation rates on a regular basis because these rates are bound to vary across geography and time.

It is important to note that our littering estimate is sensitive to what areas we assumed were "litterable" − if we only consider roads and sidewalk areas, the littering estimate becomes 1,733 T. However, when we include parks and beach areas in the city, our littering estimate for Toronto doubles (3,689 T). The variability in what is considered "litterable area" is accounted for in our littering estimate: we both exclude and include the areas of parks and beaches, and the associated emission masses per neighborhood, in the 140 neighborhood uniform distributions used in our Monte Carlo analysis. The reason why we only considered roads and sidewalks for the lower bound of our litterable area estimate is because those were the only places where littering rates were directly measured during Toronto's litter audits.

Hoffman and Hittinger[57] also used the 2% litter rate to determine how much plastic inputs are emitted into Lake Ontario from the entire surrounding population. They estimate that 1,438 T of MMW plastic enter Lake Ontario annually, using the 2% littering rate and the assumption that 30% of MMW enters the water. Our MMW value is double what Hoffman and Hittinger would expect to come from Toronto: the population in Toronto relative to that of the Lake Ontario watershed (8 million) is 36%, yet our model results account for 65% of Hoffman and Hittinger's total estimated Lake Ontario inputs (multiplying our MMW value of 3,099 T by a 30% MMW-to-aquatic debris conversion rate gives 930 T or 65% of total estimated Lake Ontario inputs).[57] This comparison provides additional evidence that the 2% littering rate used in previous models may be an underestimate.

Our results, estimating MMW as an estimate, we suggest that improving waste management infrastructure and reducing littering behavior are important mitigation strategies worldwide. This sentiment is echoed by Jambeck et al.,[33] Borrelle et al.,[26] and Borrelle et al.,[34] who call for improvements in waste management infrastructure with the ultimate goal of reducing waste by transitioning to a circular economy.[58]

Toronto's Microplastic Emissions. Across the literature, emissions of microplastics are reportedly dominated by paint,[47] tire dust,[59] and microfibers from textiles.[45] Here, paint was the largest category of microplastic emissions from Toronto, agreeing with a global study conducted recently which reported that paint was the largest category of microplastics.[47] Across Europe[44] and the world,[59] other studies have found that tire dust is the dominant category of microplastic emissions, accounting for 47 and 63% of all microplastic emissions, respectively. In contrast, a study conducted by Boucher and Friot[45] concluded that releases of microplastics from laundry was the largest source, accounting for 35% of global microplastic emissions. In Toronto, tire dust and textile pollution were not among the top three categories of microplastic emissions; instead, they were paint, artificial turf, and industrial activity (Table S9). The high emissions from industrial activity relative to other microplastic sources such as tire dust may be symptomatic of high commercial activity upstream. Our local study does not suggest these global studies are incorrect but rather highlights the importance of local estimates. Regional differences in the relative proportions of microplastic emission sources agree that there is no one-size-fits-all approach to mitigating microplastic pollution,[60] and that the most effective cocktail of actions to tackle plastic pollution varies by location.

Overall (by mass), microplastic emissions pale in comparison to macroplastic emissions, accounting for only 16% of all plastic pollution emissions from Toronto. This agrees with other studies, such as Strokal et al.,[56] Lau et al.,[61] and Ryberg et al.,[59] which also found that macroplastic emissions matter more in terms of mass. Still, by count, microplastics are likely the largest source. Microplastics are globally ubiquitous, and their small size facilitates their contamination across nearly all levels of biological organization.[62] Recent research suggests that the lowest threshold for risk in aquatic ecosystems is 0.5 particles/L.[8] Concentrations above this threshold are not uncommon, suggesting that efforts to mitigate plastic pollution should not exclude microplastic emissions. Instead, microplastic emissions should be included in all reduction targets.

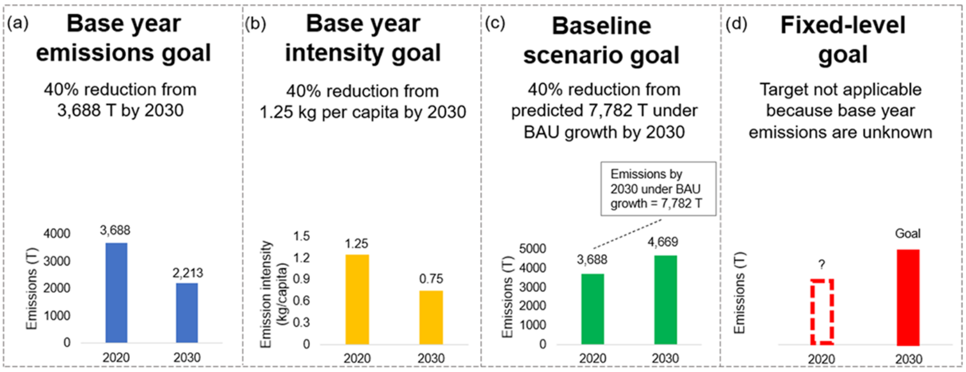

Figure 4. Different ways of setting emissions reduction targets of plastic pollution for the City of Toronto. The four methods of setting targets are illustrated for Toronto: (a) a base year emissions goal of 40% below the 2020 level of 3,688 T by 2030, (b) a base year intensity goal of 40% below 2020 level of 1.25 kg per capita by 2030, (c) a baseline scenario goal of 40% reduction from predicted 7,782 T under BAU growth by 2030, and (d) a fixed-level goal where the target is not informed by emissions monitoring for the base year.

Setting Emissions Reduction Targets. Here, we show how the baseline emissions inventory for the City of Toronto we presented can be used to inform reduction targets and prioritize source reduction. How emissions vary over time allows policymakers to assess the effectiveness of policy interventions and evaluate progress toward any goal or target. There are four methods generally used to set emissions reduction targets for greenhouse gases (Figure 4 and Supporting Information, Data S1). Here, we propose an emissions reduction target for the City of Toronto using the base year emissions target method (Figure 4a) to demonstrate how to set targets using baseline knowledge from our emissions inventory. Here a base year and target year are chosen along with a goal to reduce plastic emissions by a given percentage below base year levels by a target year. Borrelle et al.[34] set a reduction target of 8 million tonnes (MT) by 2030 (based on Jambeck et al.[33]), which is a 73% reduction based on their projection of global plastic emissions under a business-as-usual (BAU) scenario for 2020. This reduction is likely too ambitious to be realistic, so instead, we propose a 40% emissions reduction from 2020 levels (3,688 T) by 2030 for the City of Toronto (Figure 4a). Another method is a base year intensity goal, which is expressed as a ratio of emissions to population; this goal places emissions in the context of a region's affluence and places greater responsibility on those geographies with higher emissions per capita. The proposed base year intensity goal for Toronto is a 40% reduction from 1.25 kg per capita to 0.75 kg per capita by 2030 (Figure 4b). A third method extrapolates emissions from base year levels to the target year under a BAU scenario and sets the emissions reduction target based on that extrapolated number (Figure 4c). This target is not as ambitious as the first two targets and, in fact, in this case, accepts more pollution than what we began with in the base year. Here, 4,669 T would be the target for 2030. The 2030 BAU emission for Toronto was extrapolated from 2020 levels based on how much Borrelle et al.'s emissions increased during this decade globally under their BAU scenario. The final method is a fixed-level target, which sets an emissions reduction target with no prior knowledge about emissions during the base year (Figure 4d). This type of target requires monitoring of emissions for the target year but does not require the compilation of an emissions inventory for the base year. As a result, it is not clear whether a true reduction in emissions is being achieved.

Informing Mitigation Scenarios. Once a target is set, a base year emissions inventory can inform priorities for source reduction. For the City of Toronto, the emissions inventory demonstrates which emissions rank the highest. Policymakers can combine this information with knowledge about resources and feasibility to inform management actions aimed at achieving reduction targets. For example, to achieve the proposed base year emissions target (Figure 4a), Toronto's plastic emissions would need to be reduced by 1,475 T from 3,688 T in 2020, to 2,213 T in 2030. If Toronto chose to focus solely on MMW, this is equivalent to cutting plastic littering by 48%. Littering can be addressed through behavior change and educational campaigns, which has been found to be successful.[52,54,63] Littering, illegal dumping, and spills from trash receptacles can be reduced through infrastructure and service improvements. Specifically, this may involve installing larger trash receptacles around the city as well as implementing more frequent garbage collections in locations where trash receptacles have a tendency to overflow. Companies have a role to play in reducing MMW as well—we need more extended producer responsibility initiatives such as container-deposit schemes[64] and increased funding of the Blue Box recycling program in Ontario,[65] which can promote systemic change by increasing the value of plastic waste and necessarily shift the world toward a circular economy.

As noted above, cities should also prioritize microplastics by incorporating them specifically into their goals. In Toronto, microplastic emissions were estimated to be 566 T for the year 2020. If we wanted to spread the mitigation effort equally across macroplastic and microplastic sources, and achieve a 40% reduction in emissions of microplastics (i.e., cutting 226 T), eliminating all emissions of infill from artificial turf (237 T) would fulfill this target. This can be accomplished by replacing all artificial turf in Toronto with natural fields or capturing all rubber infill emissions using microplastic capture technology installed close to the source.[66−68] Still, a 100% reduction of any particular emission is likely not feasible and does not address the potential risk of different types of microplastics in aquatic ecosystems. As such, policymakers may want to consider management scenarios that include multiple sources of microplastics. As such, various combinations of emission reductions of different sources should be prioritized. For instance, eliminating 50% of emissions of both artificial turf infill and paint (243 T) would achieve this target; or, a combination of 80% reduction from artificial turf, 50%

reduction of pellet loss, and 70% reduction of construction foam emissions (234 T) would achieve this target. The first mitigation scenario can be realized by replacing half of artificial fields in Toronto with natural fields or capturing rubber infill emissions using microplastic filter technology such as raingardens as well as using 100% biodegradable paint or increasing the lifetime of paint. In the case of the latter scenario, one may successfully reduce emissions via a combination of reducing artificial turf presence in the city, mandating zero pellet loss from industry, and penalizing construction activities that leave foam behind. We did not include derelict fishing gear in a mitigation scenario because it accounted for so little mass; however, it is worth noting that in other more maritime cities, derelict fishing gear might be an important source to tackle.

In general, policymakers should consider the combination of feasibility, affordability, and risk management when choosing mitigation scenarios. Other ways to reduce microplastic emissions may involve encouraging the use of vessel paint that is longer-lasting or biodegradable and encouraging the practice of light sanding and recoating every other year as opposed to reapplying paint every year to avoid the paint getting thicker until it starts flaking off in large chunks. To reduce emissions of synthetic fibers from dryers, households can avoid vented dryers and consider alternative forms of clothes drying.[69] Washing machines should be installed with filters to trap synthetic textile fibers before they enter wastewater treatment plants or WWTPs.[70,71]

Once plastics are emitted, removals are the next line of defense. Although they should not be the first solution, they are useful for protecting the environment, while source reduction strategies are put in place. Removal technologies collect plastic pollution downstream of their emission sources, and some examples include storm drain litter traps that collect pellets and large plastic objects,[72] raingardens that filter out tire dust and other contaminants in stormwater,[66−68] and trash wheels or floating receptacles that skim off floating plastic debris directly from aquatic ecosystems.[73] If we relied on downstream removal by technology and cleanups alone to meet emissions reduction targets, effort would need to increase by 4 orders of magnitude (roughly 12,000-fold) from what they are now. This large increase in removal activity is an extraordinary effort and is, thus, highly unrealistic. Therefore, upstream mitigation of plastic emissions at the source must be a priority.

Informing the Future Global Agreement. A global agreement on plastic pollution is currently being negotiated through 2024. We envision that a global treaty may have similarities to the Paris Agreement for greenhouse gases, where countries are mandated to report emissions of plastic pollution on a regular basis to the United Nations, and their cumulative emissions reductions summed toward reaching a globally defined target. Here and elsewhere scientists have demonstrated that there is a paucity of data on plastic emissions (e.g., Borrelle et al.[34]), even for an affluent, high-income city like Toronto. To ensure the quality and robustness of emissions inventories of plastic pollution, transparency of data and collaboration among cities, states, and countries will be absolutely critical to fill the many data gaps that exist currently. From our exercise of compiling an inventory for Toronto, we found numerous missing pieces of data including data on the amount of plastic waste that is inadequately managed, amount of plastic waste exported, and emission factors of plastic pollution-generating activities that are specific to Toronto, e.g., shedding rate of clothing that Torontonians usually wear, shedding rate of car tire brands that are predominant in Toronto, and a pellet loss rate specific to Toronto. Using data that are specific to Toronto will greatly help to reduce uncertainty in our estimates.

We believe that quantitative emissions inventories of plastic pollution must be a foundational piece of a successful global treaty on plastic. Emissions inventories will provide a baseline of pollution to inform reduction targets, and measure progress toward reaching those targets. Emissions inventories will also identify leaders and laggers and help signatories prioritize source reduction strategies locally, nationally, and regionally. Here, we provide a framework for an emissions inventory of plastic pollution based on a globally accepted framework for greenhouse gases. This framework advances the foundational work by Jambeck et al.,[33] who estimate plastic emissions to the environment focusing on one source − MMW. We quantify emissions across many sources, which allows for holistic and effective mitigation based on factors such as the polymer type, potential harm to ecosystems and wildlife, or feasibility of reduction of the sources. We hope this framework can be adopted and used to inform reduction policies in cities, states, and countries around the world to protect the well-being of people, wildlife, and our planet.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.3c04348.

> Additional materials and methods pertaining to the estimation of emissions of mismanaged waste, and details regarding uncertainties, assumptions, and data gaps; general list of sources of plastic pollution and their specific data availabilities for the City of Toronto (Table S1); calculation methodologies for different sources of plastic emissions in the City of Toronto (Table S2); conditions for assignment of data quality rankings when the uncertainty of a parameter is not provided (Table S3); histograms of Monte Carlo simulations to estimate median, 25th, and 75th percentiles for emissions from each source (Table S4); removal terms and their data availabilities (Table S5); AIC scores of models for describing litter emissions (Table S6); summary of variables in the best-fit model for litter emissions (Table S7); labels for Toronto neighborhoods (Table S8); and top sources of plastic from different studies (Table S9) (PDF)
>
> Proposed standardized guidelines accepted changes (PDF)
>
> City of Toronto official report accepted changes (PDF)
>
> Toronto inventory SI accepted changes (XLSX)
>
> Assigning uncertainties SI accepted changes (XLSX)

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Notes

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