A city-wide emissions inventory of plastic pollution

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Abstract: A global agreement on plastic should have quantitative reduction targets for 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 total annual emissions of plastic pollution generated. Using Monte Carlo simulations, we estimate that 2,322 to 2,327 tonnes (T) of plastic pollution were emitted from Toronto in 2020. Littering is the largest source overall (1,733 T), and artificial turf is the largest source of microplastic (238 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 towards reducing plastic pollution.

Keywords: plastic pollution, environment, contamination, emissions, accounting, mitigation, policy, emissions inventory

Synopsis: A framework for emissions inventories of plastic pollution is presented and applied to a city to set emission reduction targets and inform effective mitigation.

Introduction

1.1 The need for formal emissions accounting

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 towards 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. Emissions inventories can be generated for any substance, including plastic pollution. In general, emissions inventories help inform source-reduction, reduction targets, and the progress of signatories towards 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[35–37]. Still, we lack comprehensive and standardized frameworks for measuring multiple emission sources across geographic scales like the climate field. The UNFCCC has mandated the compilation and reporting of emissions inventories of greenhouse gases by countries since the 1990s[38]. This exercise has helped the world to track its progress in terms of reducing emissions to meet the target of keeping global average temperature rise below 1.5°C[39].

To facilitate the success of an international agreement for plastic, we need an equivalent of the UNFCCC mechanism for plastic pollution – we need standardized frameworks for measuring plastic emissions to track global progress towards 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 sleaders and laggers on emission reduction efforts on the global scale, and keeps track of progress towards a globally-defined target[29]. Here, we present a framework for an emissions inventory of plastic pollution (from the micro to the macro scale), and apply this framework to a municipality to demonstrate its utility.

Materials and Methods:

1. Framework for an emissions inventory of plastic pollution

Building the proposed standardized guidelines

Here, plastic emissions include plastic leakage into the environment, not the fraction that reaches the ocean or receiving waters. Our proposed guidelines for compiling and reporting plastic emissions inventories are modelled off of guidelines for greenhouse gases[40,41]. The C40 Global Protocol for Emissions Inventories are the official guidelines used for greenhouse gas emissions inventory compilation for municipalities. The 2006 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. Please refer to **Data S1** for the complete proposed standardized guidelines.

Sources and source groupings

The inventory includes what we understand to be the largest sources of plastic pollution[42,43]. These include 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 aquatic vessels (**Table S1**). These sources are clustered into nine categories: mismanaged waste (MMW; includes littering), recreational (artificial turf), tire dust (airplanes, on-road vehicles), industrial (construction foam, pellet loss), agriculture (cultivation films, mulching, sludge application), textiles (washing machines, vented dryers), cosmetics (microbeads), aquatic (derelict fishing gear, dock foam), and paint (exteriors of houses, road markings, aquatic vessels; see **Table S1**). Note that several of these sources are microplastics.

Gathering data for the inventory

Inventory compilation begins with 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 (please 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**).

Activity data (AD) and emission factors (EF) used to estimate emissions need to be gathered from a variety of sources. AD describes the amount of pollution-generating activity for a source that occurs within a given period of time[40]. AD can be found in 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[40]. EF are quantified by research and can often be found in research reports (e.g., Eunomia reports[42]) and the peer-reviewed scientific literature. Examples include the mass of tire dust shed per km driven and the mass of plastic shed per kg of laundry load.

Calculating emissions

To calculate emissions of plastic pollution from each source, AD and EF are multiplied together to obtain emissions (**Equation 2**).

$$\text{Emission} = \text{AD} \times \text{EF} \quad (\textbf{Equation 2})$$

Estimating uncertainty

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 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 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 were not reported for parameters or when they could not be obtained from experts, uniform PDFs are assigned using data quality rankings (**Table S3**).

In a Monte Carlo analysis, samples from PDFs are 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 RStudio until the corresponding emissions histogram was relatively smooth and the 95% CI for the histogram is within +/-1% of the mean (**Data S5**). Then, the given mean and 95% CI for each source and the overall inventory sum are accepted (**Table S4**).

Removals

Removal terms describe activities that remove plastic pollution that has already entered the environment. Removals are included in an emissions inventory to demonstrate efforts by governments 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, and also because there is no guarantee that removed plastic will not become re-emitted again.

2. Applying framework to the City of Toronto

Toronto's emissions inventory of plastic pollution

An emissions inventory was compiled for the year 2020 and its boundary aligns with the geographic and administrative boundary of the City of Toronto.

Of the 21 initial sources, ultimately 12 of these were estimated 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 x EF approach was used to calculate emissions. Activity data were commonly sourced from City of Toronto and Statistics Canada resources and from personal communication with experts, while emission factors were commonly sourced from the scientific literature. An example of a calculation would involve multiplying the number of vehicles in Toronto by the average mileage of a vehicle per year by the shedding rate of tire dust (**Table S2, Data S3**). All calculations, data, and references consulted are summarized in **Data S3** “Toronto Inventory SI”. However for certain sources, other approaches had to be 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. 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 (**Supplementary 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).

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, respectively. Data quality rankings were assigned to parameters without reported uncertainties by two of the co-authors (**Data S4**). Where there were discrepancies, the third author served as the tiebreaker. All parameters used in emissions calculations and their associated uncertainties can be found in Supplementary Information (**Data S3**).

We used Approach 2 to estimate the uncertainty in emissions for the City of Toronto because the uncertainty probability distribution functions (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 RStudio for each source and for the overall inventory sum (**Data S5**).

QA/QC on the inventory

As mentioned in the Materials and Methods, data quality rankings were assigned to parameters without reported uncertainties for the purposes of calculating uncertainties (**Table S3**). However, 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 co-authors 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 from, the appropriate calculation approach for emissions, minimizing the number of assumptions made, and double-checking calculations for completion and accuracy. A discussion of the uncertainties surrounding the inventory, assumptions we made, and data gaps we faced during the inventory compilation process are described (**Supplementary 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, or 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, 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 mass of plastic removed from community cleanups.

Exploring the reasons for littering and informing future littering predictions

Tweet density, unemployment rate, trash receptacle density, percent of total respondents that finished high school, population density, and average annual income after tax were the six covariates included in a generalized additive model (GAM) to explain variability in the response variable, littering emissions [g/m^2] by neighbourhood (n = 140). Tweet density is a reflection of where people frequent within the city, and was obtained by summing total number of Tweets from 2012 to 2016 in Toronto extracted via the Twitter API by neighbourhood. Trash receptacle density was obtained from the "Street Furniture – Litter Receptacle" shapefile[44] 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 were obtained from a Neighbourhood Profiles dataset for Toronto for 2016[45].

Generalized additive modelling was performed using the *mgcv* package in R 4.0.5[46] (**Data S5**). 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).

Results and Discussion

3.1 A city-level emissions inventory

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. Our official 2020 inventory report can be found in **SM Data S2**. The City of Toronto hosts a population of approximately three million people and is the fourth largest city in North America. Upon running the methods within our framework, we estimate that 2,322 to 2,327 T (mean 2,324 T) of plastic pollution was emitted to the environment by the City of Toronto in 2020 (**Fig. 1, Data S2**). This value is dominated by litter (1,733 T), the top emission source, followed by the shedding of rubber infill from artificial turf (238 T), and paint shedding from the exteriors of houses (169 T). Overall, the top three emissions categories are mismanaged waste, paint, and recreational. MMW alone accounts for 75% of total plastic emissions in the City of Toronto by mass. By count, 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 the 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 total emissions. The amount of litter cleaned by the city is unknown. Removals were not subtracted from overall emissions.

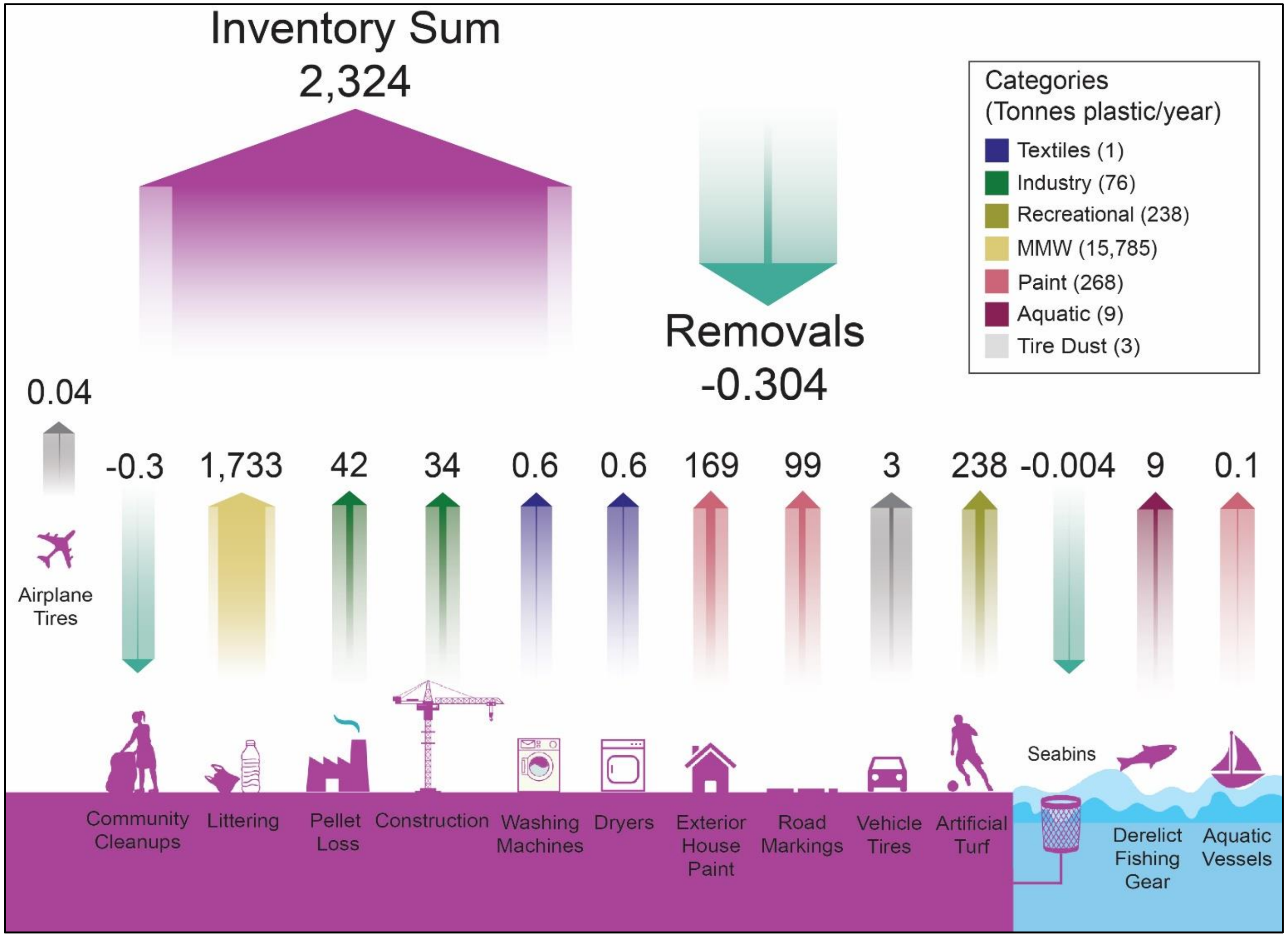

Fig. 1. **Toronto's emissions inventory of plastic pollution.** Sources and removal terms form the foundation of the figure. Emissions are shown as fluxes out of the city, while removals are shown as fluxes into the city. Arrow widths are proportional to emission or removal magnitudes. Categories of sources are color-coded within the arrows and 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)[47]. Although the City of Toronto does street sweeping, data on the amount of mismanaged waste cleaned is not available and thus not included here. Please see **Table S4** for uncertainties associated with emissions.

Toronto's mismanaged waste

In our framework, MMW emissions are calculated using litter audits conducted by the City of Toronto. For the year 2020, we estimate that 1,733 T of plastic MMW was generated within the city (**Fig. 2**). 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 behaviour and inform littering emissions predictions globally (particularly where monitoring data is not available), we fit a GAM to the neighbourhood littering rates. Only population density was significantly correlated with littering rate ($p < 0.05$; **Table S6, 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 neighbourhood 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[48–50], and these covariates could not be explored in our model. Since predictive modelling 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 the number and diversity of sources that were included. In particular, Toronto's littering estimate was informed by empirical monitoring data at the neighbourhood 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 1** shows the calculation methodology for littering emissions used in Jambeck et al.[33]:

Littering emissions = population * waste generated per capita * % plastic in waste stream * 2% littering rate (**Equation 1**)

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, 1,733 T, is of a similar order of magnitude to the Jambeck et al. estimate. This is 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 2,011 T estimate for Toronto is macroplastic MMW emissions, while our overall estimate of 2,324 T is comprised of 75% MMW and 25% microplastic emissions by mass.

It is important to note that our littering estimate is sensitive to what areas we assumed were "litterable" – our calculation (1,733 T) only considered roads and sidewalk areas, but if we were to include parks and beach areas in the city as well, then our littering estimate for Toronto doubles (3689 T).

Hoffman and Hittinger[51] 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 for Toronto agrees with this estimate, because multiplying our MMW value of 1,733 T by a 30% MMW-to-aquatic debris conversion rate gives 520 T or 36% of total estimated Lake Ontario inputs (Hoffman and Hittinger, 2017). The Lake Ontario watershed is home to a population of approximately 8 million people, and the ratio of the populations residing in Toronto to that of the Lake Ontario watershed is also 36% which agrees with the MMW ratio. Again the agreement between our value and model output from the literature is surprising because our value incorporates empirical data while the models do not. Our estimate serves to validate outputs from models that have long needed verification.

Our results, estimating MMW to be by far the largest source of plastic emissions by mass, 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[52].

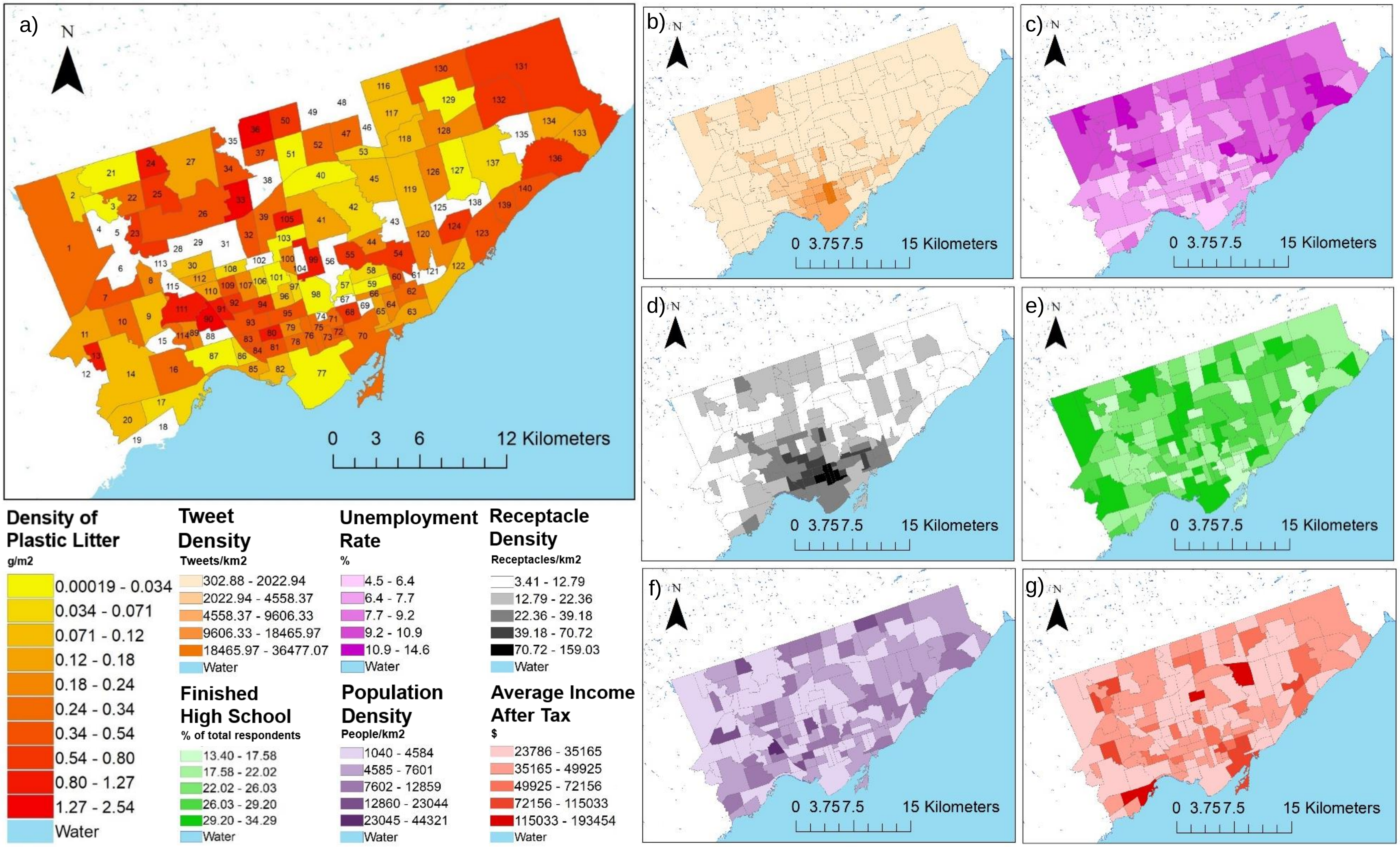

Fig. 2. Maps showing littering emissions and covariates for the littering GAM by Toronto neighbourhood. a) Heat map showing emissions of mismanaged waste in Toronto normalized by area [g/m^2] for each neighbourhood, which includes emissions from littering,

illegal dumping, inadequately managed waste, and spills from garbage cans before entering the waste system. Panels labeled b, c, d, e, f, and g: heat maps showing predictors of littering rate by neighbourhood (i.e., b) Tweet density [Tweets/km^2], c) unemployment rate [%], c) receptacle density [receptacles/km^2], d) proportion of survey respondents that finished high school [% of total respondents], e) population density [people/km^2], and f) average income after tax [\$]). Please see **Table S8** for neighbourhood names which correspond to the labels in the litter heat map.

Toronto's microplastic emissions

Across the literature, emissions of microplastics are reportedly dominated by paint[53], tire dust[54], and microfibers from textiles[43]. 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[53]. Across Europe[42] and the world[54], 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[43] 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 like 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[55], and that the most effective cocktail of actions to tackle plastic pollution varies regionally.

Overall (by mass), microplastic emissions pale in comparison to macroplastic emissions, accounting for only 25% of all plastic pollution emissions from Toronto. This agrees with other studies, such as Lau et al.[56] and Ryberg et al.[54], 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[57]. Recent research suggests that the lowest threshold for risk in aquatic ecosystems is 0.5 particles per L[8]. Concentrations above this threshold are not uncommon, suggesting that mitigation efforts for plastic pollution should not exclude microplastic emissions. Instead, microplastic emissions should be included in all reduction targets.

3.2 Setting emissions reduction targets

The baseline emissions inventory for the City of Toronto presented here 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 to evaluate progress towards any goal or target. There are four methods generally used to set emissions reduction targets for greenhouse gases (**Fig. 3**, Supplementary Materials **Data S1**). Here, we propose an emissions reduction target for the City of Toronto using the base year emissions target method (**Fig. 3a**) 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 (2,324 T) by 2030 for the City of Toronto (**Fig. 3a**). 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 0.79 kg per capita to 0.47 kg per capita by 2030 (**Fig. 3b**). 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 (**Fig. 3c**). 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, 2,957 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 (**Fig. 3d**). 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.

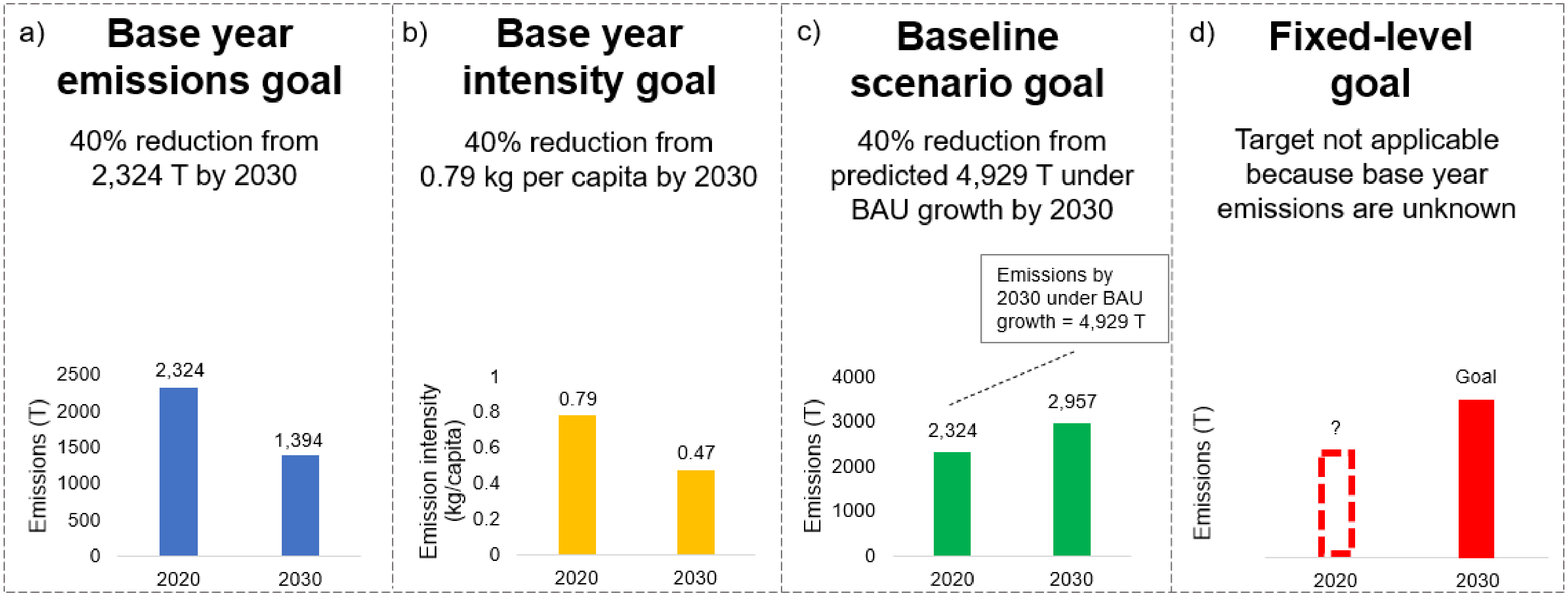

Fig. 4. Different ways of setting emissions reduction targets of plastic pollution for the City of Toronto. The four methods of setting targets are illustrated for Toronto: a) a base year emissions goal of 40% below the 2020 level of 2,324 T by 2030, b) a base year intensity goal of 40% below 2020 level of 0.79 kg per capita by 2030, c) a baseline scenario goal of 40% reduction from predicted 4,929 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.

3.3 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 (**Fig 3a**), Toronto's plastic emissions would need to be reduced by 930 T from 2,324 T in 2020, to 1,394 T in 2030. If Toronto chose to focus solely on MMW, this is equivalent to cutting plastic littering by 54%. Littering can be addressed through behavior change and educational campaigns, which has been found to be successful[48,50,58]. 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[59] and increased funding of the Blue Box recycling program in Ontario[60], which can promote systemic change by increasing the value of plastic waste and necessarily shift the world towards 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 586 T for the year 2020. If we wanted to spread the mitigation effort across macroplastic and microplastic sources, and achieve a 40% reduction in emissions of microplastics (i.e. cutting 234 T), eliminating all emissions of infill from artificial turf (238 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. Still, a 100% reduction of any particular emission is likely not feasible, and it 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 emissions reductions of different sources should be prioritized. For instance, eliminating 50% of emissions of both artificial turf infill and paint (253 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 (235 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 a 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 should switch to ventless dryers, which do not emit fibers directly into the environment[61]. Washing machines should be installed with filters to trap synthetic textile fibers before they enter wastewater treatment plants or WWTPs[62,63].

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[64], raingardens that filter out tire dust and other contaminants in stormwater[65–67], and trash wheels or floating receptacles that skim off floating plastic debris directly from aquatic ecosystems[68]. If we relied on downstream removal by technology and cleanups alone to meet emissions reduction targets, effort would need to increase by four orders of magnitude (roughly 8,000-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 their source must be a priority.

3.4 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 towards 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 between cities, states, and countries will be absolutely critical to fill the many data gaps that exist currently.

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 towards 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 upon 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, risk, 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 wellbeing of people, wildlife, and our planet.

ASSOCIATED CONTENT

Supporting Information

Additional materials and methods pertaining to 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 mean and 95% confidence intervals 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 neighbourhoods (Table S8); top sources of plastic from different studies (Table S9); descriptions of additional data files (Data S1 – S5).

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Notes

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