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The "plastic cycle": a watershed-scale model of plastic pools and fluxes

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Research on plastics in global ecosystems is rapidly evolving. Oceans have been the primary focus of studies to date, whereas rivers are generally considered little more than conduits of plastics to marine ecosystems. Within a watershed, however, plastics of all sizes are retained, transformed, and even extracted via freshwater use or litter cleanup. As such, plastic litter in terrestrial and freshwater ecosystems is an important but underappreciated component of global plastic pollution. To gain a holistic perspective, we developed a conceptual model that synthesizes all sources, fluxes, and fates for plastics in a watershed, including containment (ie disposed in landfill), non-containment (ie persists as environmental pollution), mineralization, export to oceans, atmospheric interactions, and freshwater extraction. We used this model of the "plastic cycle" to illustrate which components have received the most scientific attention and to reveal overlooked pathways. Our main objective is for this framework to inform future research, offer a new perspective to adapt management across diverse waste governance scenarios, and improve global models of plastic litter.

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Plastic waste in the environment is global in scope, pervasive in all parts of the world, increasing in abundance, and a permanent feature of the biosphere on the scale of human lifetimes (Gewert *et al.* 2015). Large-scale plastic industrialization began in the 1950s (Geyer *et al.* 2017), with research on plastic pollution initiated several decades afterward. Attempts to craft global budgets of plastic litter have guided important scientific advancements, but research has mainly focused on oceans; for example, a recent, heavily cited global model estimated the amount of plastic litter generated within 50 km of all coastlines that enters the world's oceans annually (Jambeck *et al.* 2015). Estimated emissions to the oceans were greater than the estimates of plastics floating on the surface (Eriksen *et al.* 2014), which stimulated a productive body of research to balance the plastic budget (Law 2017). Most studies quantified plastics in previously overlooked sinks, including the seafloor, water column, and coastlines. However, few studies have considered plastic sinks upstream of oceans. Because this field of study originated in marine ecosystems, where conspicuous plastic litter accumulates, terrestrial and freshwater ecosystems have generally been considered merely as conduits for plastics to the ocean, and are largely overlooked as another sink (Horton and Dixon 2018; Windsor *et al.* 2019). However, retention, transformation, removal, and permanent storage of plastic litter within inland ecosystems are critical components for understanding plastic budgets.

In a nutshell:

- Although most research on plastic litter has focused on marine systems, plastic is also a major pollutant of terrestrial and freshwater ecosystems
- Plastic litter has a variety of fates at the watershed scale, including retention on land, interactions with food webs, export to the oceans, atmospheric interactions, and unintentional removal during freshwater extraction
- A conceptual model of the "plastic cycle" at the watershed scale is needed to synthesize the sources, sinks, and pathways for plastic litter of all types and sizes
- The conceptual model presented here can be used to inform management, protect freshwater ecosystems, and update models of plastic pollution to unite inland and marine ecosystems

The lack of terrestrial and freshwater estimates in global budgets at this relatively early stage of research on plastic pollution is analogous to the stepwise development of ecosystem budgets for other anthropogenic pollutants, including nutrients. For example, inland waters are sources of nitrogen (N) to oceans, and N loading to rivers contributes to anoxia in estuaries worldwide (Diaz and Rosenberg 2008); however, upstream N retention and loss (ie in soils, streams, and wetlands) is also a major component of global N budgets (Alexander *et al.* 2000). As such, rivers are not simply "pipes" that transport terrestrial materials to oceans, but are physically, chemically, and biologically reactive ecosystems in and of themselves. Similarly, although rivers are a major source of plastics to the oceans (Jambeck *et al.* 2015), retention of plastic litter at the watershed scale has typically been excluded from global budgets.

While knowledge of plastic litter in inland ecosystems lags behind that for marine ecosystems, research focusing on the sources, movement, and export of plastics in freshwater and terrestrial environments is beginning to emerge (Horton and Dixon 2018). One common approach is to measure the abundance and types of plastic litter within an ecosystem to infer its sources and transport mechanisms (Kiessling *et al.* 2019). Fruitful analyses have also focused on point sources, such as wastewater treatment (eg biosolids and treated wastewater;

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Windsor *et al.* 2019). Measurements of particle transport can be used to estimate plastic retention and export along riverine systems and from atmospheric deposition (Dris *et al.* 2016; Hoellein *et al.* 2019). Yet, despite rapid advancements in the recent literature, there are still no detailed models that synthesize sinks, sources, and fluxes of all plastics across freshwater ecosystems.

Our objective was to develop a conceptual model of the "plastic cycle" that unites all pools and fluxes of plastics at the watershed scale using an ecosystem perspective common to the study of element cycles (Horton and Dixon 2018; Bank and Hansson 2019). We use the model to unite commonly disparate components of plastic pollution research (ie demonstrating linkages in plastic cycling across land, air, and water), inform management and prevention efforts for inland ecosystems, and describe knowledge gaps to guide advancements in research on the ecology of plastic litter. (Reader's note: the letters A–G in the headings of the following sections correspond to the same letters within the conceptual models depicted in Figures 1, 2c, and 3c.)

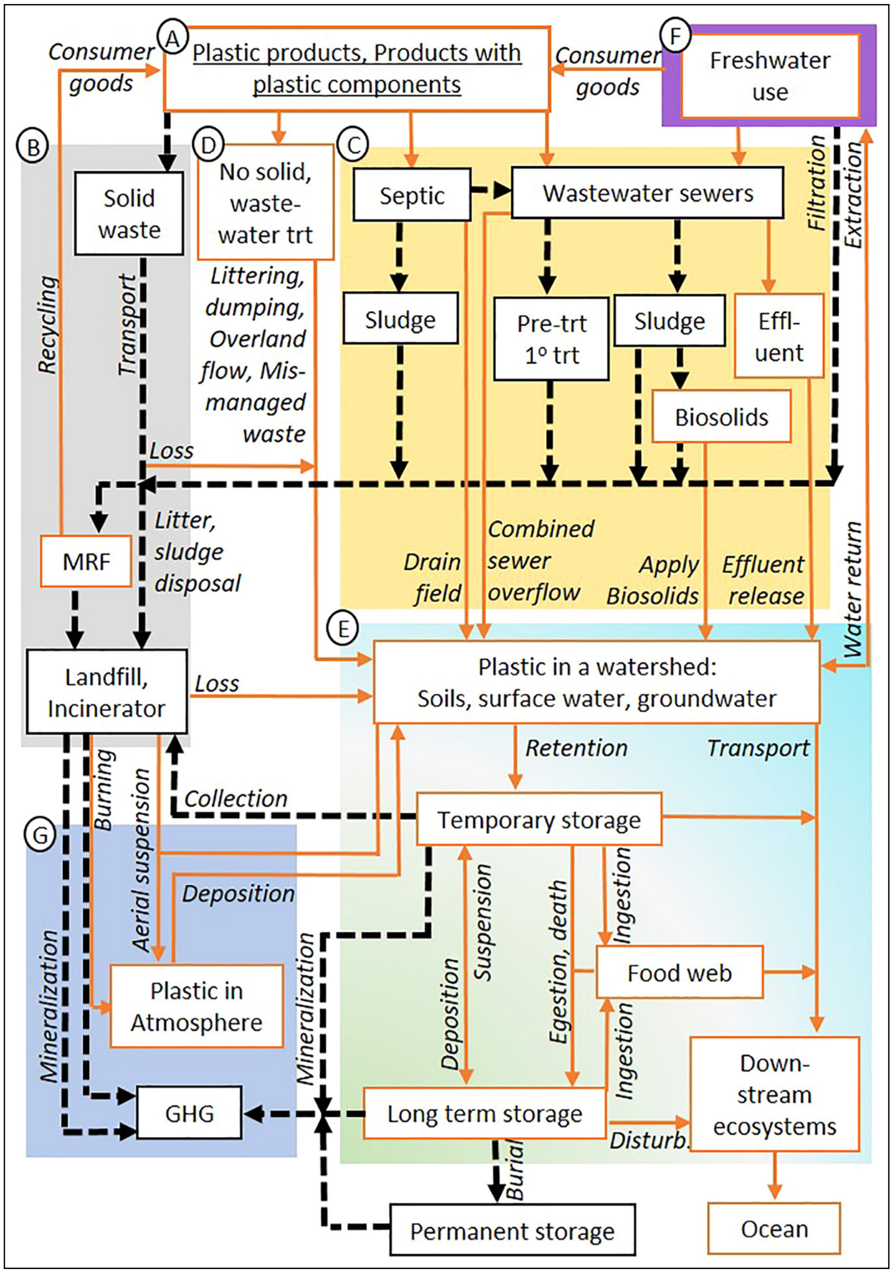

Figure 1. Conceptual model of the plastic cycle at the watershed scale, including pools (rectangles) and fluxes (arrows). Dashed black lines indicate pathways toward waste containment, storage, or greenhouse gases (GHGs). Solid orange lines show fluxes that represent movement of plastic among pools. Letters A–G correspond to each section of the paper that discusses that portion of the figure, and each letter is placed on a rectangle to coalesce major pools of plastic for a watershed budget. A: in-use consumer goods; B: solid waste management; C: wastewater management; D: direct littering and mismanaged waste (litter that does not enter solid waste collection or wastewater treatment); E: watershed litter; F: freshwater use; and G: the atmosphere. MRF: materials recovery or recycling facility; trt: treatment; Disturb: disturbance.

(A) Plastic products encompass a diversity of materials and size classes

The conceptual model starts with plastic products ("A" in Figure 1), which consist of a diversity of sizes, functions, shapes, and chemical compositions. Plastics will enter the environment as a particular product, which varies broadly, and fragment in situ via chemical, biological, or mechanical processes. Where possible, functional descriptors are included to identify litter based on type of use (eg bag, cup, hygiene). Although applied variably, functional descriptors can identify discrete litter sources (McCormick and Hoellein 2016). Broken pieces of plastic may confound functional identification, however, and are common among smaller items. Plastic litter is described by size as macro-, meso-, micro-, and nanoplastics (Hartmann *et al.* 2019), and researchers identify pieces by shapes (eg fibers, spheres, fragments). Some inferences regarding source may be generated from shapes common in wastewater, such as fibers (eg synthetic textiles) and spheres (eg abrasives in soaps) (Rochman *et al.* 2019). Finally, polymer identification is achieved via infrared spectroscopy, gas chromatography, and Raman spectroscopy (Shim *et al.* 2017). In our model, we described plastic litter entering the environment via solid waste management, wastewater management, or direct littering (Figure 1).

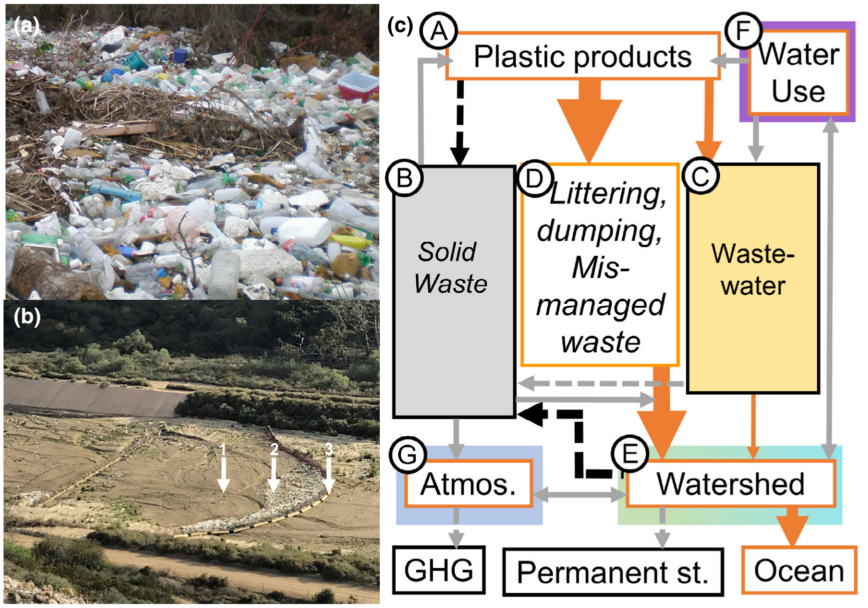

Figure 2. (a) Plastic litter in the riparian zone and floodplain tributaries of the Tijuana River. (b) Litter accumulating on a boom deployed just upstream of the Tijuana River estuary in the US, where "1" indicates the dry streambed, "2" indicates accumulated litter, and "3" indicates the boom. (c) Simplified version of the conceptual model to illustrate predictions for major fluxes of litter in the watershed based on observation (orange and black lines) and those that have not yet been assessed (gray lines). Arrow sizes are estimates of relative flux, to be adjusted as data are generated. Atmos: atmosphere; st: storage; GHG: greenhouse gases.

(B) Solid waste management

Our conceptual model begins when a plastic product is discarded (ie when a consumer is done with the product). The action of discarding varies based on personal habits, geography, and infrastructure, but includes when a consumer disposes of a product to be managed as waste or litters directly into the environment. For managed waste, the cycle includes when waste is collected and transported to a waste management location or facility, and when waste is treated. Waste may be leaked or littered at several steps along this trajectory.

The initial fates for plastic waste are reuse, recycling, incineration, landfill, and the environment. The best-case scenarios are reuse or recycling, which keep plastic in a closed loop (ie material remains in the value chain). Of all plastic produced from 1950–2015, ~9% was recycled (Geyer *et al.* 2017), suggesting substantial opportunity for improvement. Approximately 12% of plastics have been incinerated, and in some cases, heat from incineration is recaptured as energy (Geyer *et al.* 2017). Depending on plant technology, incineration may generate smaller plastic fragments that leak into the atmosphere, soils, or wastewater (Simoneit *et al.* 2005). Overall, ~79% of plastic created from 1950–2015 was sent to landfill or littered into the environment (Geyer *et al.* 2017). Leakage is minimal in an engineered landfill but varies where landfills are less well maintained, and products may be blown into the atmosphere or lost via erosion. Finally, in places lacking solid waste management programs, or where programs exist but are not used by all citizens, discarding plastic implies littering to the environment (eg river, roadside, dumps). In higher income countries with well-developed waste management programs, plastic waste is often shipped to lower income countries as a form of "management" (Brooks *et al.* 2018).

(C) Wastewater management

Plastic litter enters wastewater management systems with stormwater and sewage. Street litter enters sewers and wastewater treatment plants (WWTPs) in combined sewer systems. Plastics are added to wastewater when they are flushed down a drain and enter city sewers or septic tanks. Like direct littering of plastic, untreated wastewater, septic drain fields, and combined sewer overflow events are direct pathways for plastics to enter into aquatic ecosystems (Horton and Dixon 2018; Panno *et al.* 2019).

Plastics may be captured during wastewater treatment. Larger macroplastics can be caught in screens and landfilled, whereas smaller plastics will pass through screens and move into primary treatment areas (ie settling tanks), where roughly 85–99% sink as a component of sludge. Plastic in sludge is removed and landfilled, or incorporated into sludge-derived biosolids used as fertilizer (Windsor *et al.* 2019). When applied to land, microplastics in biosolids may re-enter aquatic environments during irrigation or precipitation (Ng *et al.* 2018). Finally, plastics in wastewater may be removed in tertiary treatment (eg sand filters) or released into aquatic environments.

(D) Direct littering

The availability of solid waste and wastewater management infrastructure varies worldwide, with important implications for plastic litter in watersheds that span gradients of economic development (Capps *et al.* 2016). Because municipal governments typically fund waste management programs, rural populations or less developed cities often lack solid waste collection or wastewater infrastructure (Guerrero *et al.* 2013); in these areas, community sanctioned dumps, private incineration, and informal latrines are common means of solid waste and wastewater disposal (Guerrero *et al.* 2013), and are sources of plastic litter. Illegal dumping is also carried out despite the existence of waste collection to avoid costs for material disposal or transport, and is typically done surreptitiously to evade detection and fines (McCormick and Hoellein 2016). Finally, plastics designed for outdoor use will wear down, and fragmentation of vinyl siding, paint, tires, and agricultural plastics (eg tarps), among other sources, also generates plastic litter (Horton and Dixon 2018).

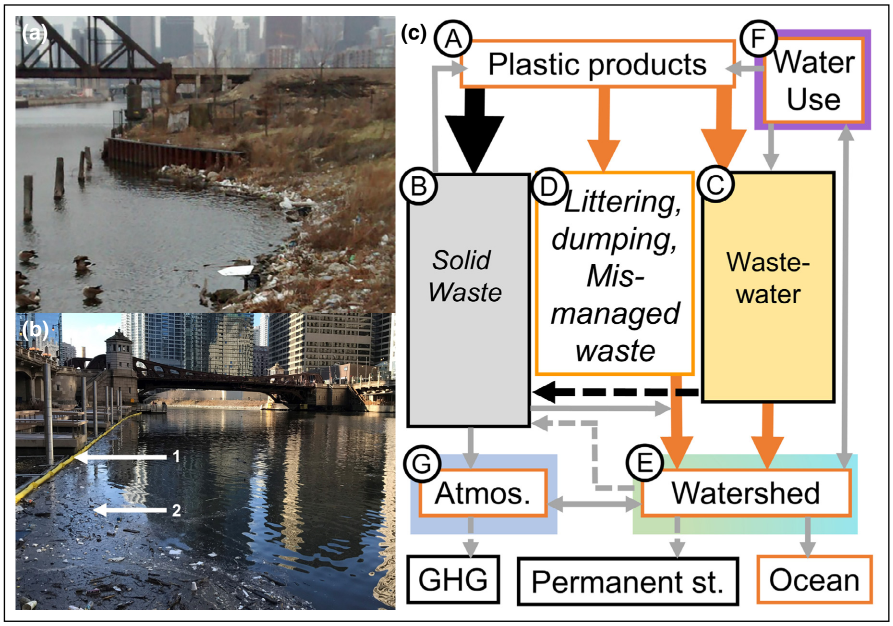

Figure 3. (a) Plastic litter in the riparian zone of the Chicago River. (b) Litter accumulation on a boom deployed in Chicago, where "1" indicates the boom and "2" indicates litter. (c) Simplified version of the conceptual model to illustrate predictions for major fluxes of litter in the watershed based on initial assessments (orange and black lines) and those that have not yet been assessed (gray lines). Arrow sizes are estimates of relative flux, to be adjusted as data are generated. Atmos: atmosphere; st: storage; GHG: greenhouse gases.

(a) Shedd Aquarium

(E) Plastic within a watershed: retention, transformation, and storage

Once in the environment, plastics have entered a watershed, and are transported downwind or downstream, or are temporarily retained. Some global plastic budgets assume that all plastic litter entering rivers and terrestrial ecosystems is transported to the ocean without retention (Jambeck *et al.* 2015). However, accumulations of plastic litter in freshwater ecosystems are common and dense, showing that some portion of plastic waste is retained (McCormick and Hoellein 2016). Retention sites include sediments, vegetation, stream edges, debris dams, and built structures (eg bridges). Environmental conditions at the retention site determine the physical, chemical, and biological interactions that affect retention, movement, and breakdown of plastic (McCormick and Hoellein 2016).

Like allochthonous organic matter (ie leaves, fine particles), plastic litter consists of recalcitrant organic carbon (C) and encompasses a diversity of sizes and chemicals (Rochman *et al.* 2019), and its transport can be measured using methods designed for natural particles (Hoellein *et al.* 2019). The "spiraling concept" is a group of metrics that quantify the downstream transport, retention, remobilization, and decomposition of organic matter in streams. Spiraling metrics show plastic particles in streams follow the same patterns as naturally occurring materials of similar size and density (Hoellein *et al.* 2019). However, the duration of retention following initial retention of plastics has not been quantified. Predictions for plastic retention can be enhanced using existing analytical tools for particle transport, and future studies will benefit from the use of a similar perspective to quantify long-term retention, burial, and flood-mobilized transport of plastic litter.

Plastic retained within a watershed has several possible fates, including fragmentation, mineralization, interactions with food webs, collection, and long-term or permanent storage. The collective fate of plastic litter retained within a watershed will control the relative amount and form of plastic litter that is delivered downstream (Baldwin *et al.* 2016).

Abiotic and biotic processes fragment plastics or mineralize polymers into simple C gases (eg methane, carbon dioxide; Royer *et al.* 2018). Abiotic degradation occurs more quickly than biological breakdown, and the dominant forms are UV light and physical abrasion (Gewert *et al.* 2015). Biological degradation of plastic polymers is slow, but can be accelerated by coupled abiotic–biotic processes. UV light or abrasion can break down C polymers, exposing functional groups amenable to microbial enzymes (Gewert *et al.* 2015). Biological degradation is affected by environmental factors such as redox conditions, nutrient availability, and temperature. Overall, plastic fragmentation and mineralization is most rapid in well-lit locations, and slows following burial (Royer *et al.* 2018).

Plastic litter is colonized by microbes, ingested by organisms across trophic levels, and used as a habitat. Biofilms (eg mixture of bacteria, fungi, and algae) grow on all submerged surfaces in aquatic ecosystems, including plastics. Plastic litter may select for unique biofilm assemblages (eg plastic-degrading microbes), biofilm colonization enhances plastic retention, and biofilms may increase the likelihood of plastic ingestion (Horton and Dixon 2018; Hoellein *et al.* 2019). Plastic ingested by animals could be retained in digestive tissue due to blockage (Rochman *et al.* 2013). However, ingested plastic may pass through an organism with little interaction and be egested to water, sediment, or soil. Finally, plastic litter can provide habitat as a refuge or nest building material (eg fish, birds, bees), and is transported around the landscape by animals (MacIvor and Moore 2013).

Some proportion of plastic litter retained in a watershed can be collected and transferred to recycling or solid waste management systems. Many programs exist for litter collection, including government agencies, volunteer groups, and informal waste collectors (individuals who make a living of collecting recyclable components of litter from dumps and the environment; Guerrero *et al.* 2013). The relative impact of litter collection on total plastic loads at the watershed scale is unknown and may be substantial locally (Vincent and Hoellein 2017).

Plastic litter that is buried can become a long-term or permanent feature of the ecosystem. We consider plastics in long-term storage as those subject to periodic disturbance and biological interactions. This plastic may be encountered by burrowing organisms or remobilized during floods (Hurley *et al*. 2018). Permanent storage, or so-called "geologic" plastic, is buried and preserved under environmental conditions that inhibit fragmentation or mineralization (eg low oxygen, pH). Analyses of lakebed sediment layers suggest long-term preservation of plastic is ongoing since its initial industrialization in the mid-1900s (Turner *et al*. 2019). As such, plastic will become a component of geologic strata and a marker of the Anthropocene era. We note that the duration of plastic retention delineated as "temporary", "long term", and "permanent" in Figure 1 represents a gradient of time scales, and will vary by ecosystem type and research objective. Authors should present a justification for their terms when calculating plastic budgets, as well as for definitions of "disturbance".

(F) Extraction of freshwater as a vector for plastic transport

Plastics in freshwater may be removed when water is extracted for drinking water, irrigation, aquaculture, or other industrial sectors. The associated plastic litter may be redistributed to various pools. When freshwater is extracted for drinking water, microplastics will be subject to drinking water treatment processes that are similar to wastewater management (ie some particles filtered and discarded whereas others remain in treated water; Mintenig *et al*. 2019). When microplastics in treated drinking water enter distribution, they can re-enter the wastewater management system when used (eg drains, washing machines). When water is extracted for irrigation, it is applied to the landscape, where it re-enters pollution pathways in the watershed. Agriculture is a source of microplastic pollution, with some deriving from irrigation (Ng *et al*. 2018). Finally, aquaculture and industry (eg power plants) will extract freshwater and associated microplastics, some of which will be returned to the environment, collected during treatment, or end up in products in the marketplace (eg bottled water, beer; Kosuth *et al*. 2018).

(G) Atmosphere–land–water interactions

Pathways for plastics to cycle in the atmosphere are important, yet understudied. One pathway is waste disposal via incineration conducted by private citizens and at engineered facilities. Waste products of combustion include ash and gases that contain a suite of chemicals, including small plastic particles, an array of organic compounds, and greenhouse gases (Simoneit *et al*. 2005). Wind can carry plastic litter into the atmosphere from containment sites or directly from the landscape (eg dust). Fibers are the dominant shape of plastics in the atmosphere, and consist of a variety of naturally occurring materials (ie cotton), plastic textiles (ie polyester), and mixed materials (Dris *et al*. 2016). Although the movement of plastic from land to air is not well studied, atmospheric deposition of microplastic occurs in remote places, suggesting long-distance transport (Allen *et al*. 2019). Further research of plastic transport via atmospheric pathways is urgently needed at the watershed scale.

Recommendations for future research

Plastic pollution has been studied for decades, but research on plastic litter beyond the marine environment and in terrestrial and freshwater ecosystems is a recent advancement. To fully understand the global plastic budget, we must quantify and characterize plastics at the watershed scale, taking into

Panel 1. Conceptual model application: Tijuana River

The Tijuana River watershed (4500 km^2) lies mostly in northwestern Mexico, and crosses into the US at its Pacific Ocean estuary. Rapid population growth has strained solid waste and wastewater management in the Tijuana region, contributing to rafts of litter that flow across the border and into the ocean (Figure 2a; J Crooks and C Peregrine pers comm). On the US side of the border, litter management is conducted by a large boom (Figure 2b). A consortium of groups in both nations support litter collection and advocate for infrastructure and public education to reduce pollution. Although political dynamics between nations can be complex, legal actions related to pollution have been initiated.

Few plastic fluxes have been quantified for the region, but observations suggest the major inputs are from littering, and plastic is transported downstream during pulsed flood events in the intermittently flowing river (de Jesus Piñon-Colin *et al*. 2019). Substantial amounts of plastic are probably lost to the ocean or collected by the boom deployed at the estuary. Inputs from septic drainage, biosolids, treated wastewater, the atmosphere, or freshwater use are unknown.

We modified the conceptual model (Figure 1) for conditions applicable to the Tijuana River watershed plastic budget (Figure 2c), and sites with similar hydrology and waste governance. Predictions regarding the major fluxes suggest a primary objective toward quantifying the watershed plastic budget is measuring the amount of plastic collected on the boom compared to the amount exported to the ocean. This ratio will illustrate the effectiveness of litter collection and removal. In addition, researchers can prioritize assessments of how improvements in solid waste and wastewater infrastructure may affect plastic dynamics throughout the watershed. Addressing litter flow to the watershed is a major challenge and will require a considerable degree of interdisciplinary and transnational cooperation.

account a holistic "plastic cycle" (Horton and Dixon 2018; Bank and Hansson 2019). At present, the best data available are metrics of plastics in solid waste and wastewater. As such, much work needs to be done to generate data that apply to all the pools and fluxes in our conceptual model. For information on where to begin, there are several detailed reviews on microplastic pollution in freshwater and terrestrial ecosystems that have synthesized the limited available data (Horton and Dixon 2018; Ng *et al*. 2018; Windsor *et al*. 2019).

The field of plastic pollution can look to frameworks used to define elemental cycles, such as N and C, for guidance (Weathers *et al*. 2012). The conceptual model in Figure 1 produces the "scaffolding" around which a watershed-scale plastic budget – in addition to a full watershed life-cycle analysis of plastic – can be built. Although complex, our model can be simplified for different regions, including the Tijuana River (Panel 1; Figure 2) and the Chicago River (Panel 2; Figure 3). Additional considerations for constructing a fully realized plastic budget include (1) measuring all pools and fluxes of all sizes and types of plastics simultaneously, (2) conducting measurements intra- and interannually to understand the temporal variability, and (3) developing a common "currency" for

Panel 2. Conceptual model application: Chicago River

The hydrological characteristics and waste governance of the Chicago River differ from those of the Tijuana River. The Chicago River is an outflow of Lake Michigan, with a system of canals connecting to adjacent waterways. The region has robust solid waste and wastewater management, but low topographic relief, high precipitation, and old infrastructure generate frequent overflows of sewage and stormwater into the river. Major sources of macroplastic litter are illegal dumping of household waste, combined sewer overflows, and direct littering (Figure 3, a and b; McCormick and Hoellein 2016). Microplastic inputs occur via treated wastewater effluent and combined sewer releases. Applications of biosolids and septic drain fields are rare in this urban watershed, while plastic litter interactions with the atmosphere and freshwater use have not been measured, nor has the rate of plastic litter collection. Assessments of plastic accumulation in sediments suggest plastic in long-term storage could be a major sink, but permanent storage has yet to be evaluated.

Additional measurements of plastic fluxes in this watershed are needed to develop a plastic watershed budget, but initial data show two major components of plastic movement are wastewater infrastructure and littering (Figure 3c). Both are policy targets. For example, regional sewage authorities are completing a tunnel and reservoir system to capture and treat sewer overflows, primarily to reduce wastewater-derived microbes and nutrients. The system may also reduce plastic litter. Taxation and bans on the use of common plastic items, such as bags, bottles, and food containers, are in place or under consideration. Researchers will therefore be well positioned to measure how the influence of updated waste governance strategies change the watershed plastic budget of the Chicago River and those with similar ecological and sociological conditions.

Panel 3. Bright spots for plastic litter reduction

The pervasive nature and global scope of plastic pollution is daunting, but it has stimulated communities worldwide to engage in creative solutions (Bennett *et al.* 2016). For example, in the Tijuana River watershed, government agencies and non-governmental organizations from both sides of the US–Mexico border are working to improve public policies, education, and infrastructure funding to prevent litter (https://www.nerra.org/tag/litter). Organizations include the Tijuana River National Estuarine Research Reserve, 4Walls International, Surfrider Foundation, and Proyecto Fronterizo de Educación Ambiental. Likewise, in the city of Chicago, Illinois, similar community engagement is underway to limit plastic litter inputs via a coalition of organizations, including Friends of the Chicago River, Alliance for the Great Lakes, Shedd Aquarium, and the Metropolitan Water Reclamation District (Figure 4; https://bit.ly/39lGeET). In our experience, the shared conviction among organizations is that plastic pollution reduction is possible, and that changes in laws, cultural practices, and individual behaviors occur by maintaining a spirit of optimism and inclusion. Measuring the impact of community sponsored prevention and litter removal will be a key component of future research on the watershed plastic cycle.

Figure 4. "Chicago River Day" participants at Ping Tom Park, in Chicago, Illinois. The goals of this long-term program run by the Friends of the Chicago River coalition are to remove litter, build community networks, and collect data on plastic pollution.

plastic mass. Meeting each requirement is challenging. For example, individual studies do not often collect measurements of plastic litter across multiple habitats (eg water, sediment, food webs; Baldwin *et al*. 2016) and time periods, and rarely measure both micro- and macroplastic abundance. The roles played by disturbances are not commonly considered (Hurley *et al*. 2018), and to our knowledge, intra-annual assessments of plastic pollution are rare (Vincent and Hoellein 2017). Finally, ecosystem budgets for elements are measured in units of mass/area (pools) and mass/area/time (fluxes) (Weathers *et al*. 2012), but quantifying plastic litter in units of mass presents a novel challenge. Plastic litter is often quantified by abundance (eg number of items/volume). Converting abundance to mass requires measurements of the volume and density for each particle. Researchers must also consider whether plastic should be quantified in terms of total plastic mass or converted to units of C. The latter will help place plastic litter budgets within the global C budget, but requires separate conversions for each type of plastic polymer to mass of C. This is complex because some portion of plastic mass consists of added chemicals (ie dyes, plasticizers), which varies among products and duration of environmental exposure (Rochman *et al*. 2019).

Filling in a watershed plastic budget with empirical measurements for any individual watershed is a considerable challenge that will require coordinated research across a wide diversity of specialties. We suggest it may be necessary to follow the model for the global C cycle (eg Intergovernmental Panel on Climate Change). Adopting the paradigm of a "plastic cycle" will not only improve our holistic understanding of patterns and processes, but will also help to prioritize effective strategies for altering the "plastics cycle" by reducing plastic use and mitigating environmental contamination (Panel 3; Figure 4).

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Pests as prey: the consequences of eradication

Cannibalism is not unknown in brown skuas (*Stercorarius antarcticus lonnbergi*), but recorded observations are rare. During the 2017–2018 breeding season on Macquarie Island, in the Southern Ocean, cannibalism of skua chicks by adults was directly observed twice, with five additional carcasses and two skua eggs found in the prey middens of other nests. Multiple instances of skuas harassing conspecifics during incubation and chick rearing were also observed. Cannibalization of chicks has a direct impact on skua breeding success and may be a manifestation of prey scarcity on the island following a recent eradication of invasive prey.

In 2011, European rabbits (*Oryctolagus cuniculus*) and all other non-native mammalian pests were eradicated from Macquarie Island to the benefit of many threatened plant and animal species. However, brown skuas, the island's top-order predator, once preyed upon these rabbits. Each summer, migrating skuas return to Macquarie Island to breed; since the eradication, the birds have arrived to an altered foraging landscape.

The introduction and ultimate eradication of European rabbits caused rapid disruptions to food-web interactions on Macquarie Island. The consequences of both are long-lasting, and while most responses to the eradication have been positive, this highlights how eradications might not always return systems to a historical norm.

Additional figures are available at http://bit.ly/2MzQeGP.

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