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REVIEW

Microplastics and terrestrial birds: a review on plastic ingestion in ecological linchpins

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Abstract
Microplastic (MP; plastics 5 mm or less) pollution appears to be ubiquitous, leading to concerns on how MPs affect organisms. While some plastics are manufactured at a small size, most MPs are broken down from larger plastics with often unknown origin. With documented risks of intestinal blockage, false satiation, and developmental dysfunction in organisms, understanding how MPs move through food webs is imperative to determine what organisms may be predisposed to MP pollution and where to focus regulations. Terrestrial birds have the potential to strategically inform researchers about MP pollution, since they are incredibly diverse, span many different habitats and behaviors, and are readily accessible to study. However, research is lacking for how important this group is as ecological indicators, with most studies focused on aquatic birds and those that exist on terrestrials focus on larger raptors. This review details the origins of MPs, their potential toxicity, movement through the environment, and our understanding of the role terrestrial birds play in ingestion and movement of MPs. Research on this topic is increasing, with plastics found in almost all terrestrial species that were sampled in the reviewed studies. Recent findings and future interests are focused on the varying levels of MPs in terrestrial bird species, likely due to individual behavior, morphology, and daily habitat use.

Keywords Microplastics · Plastics · Terrestrial birds · Pollution · Indicator species · Toxicity

Zusammenfassung
Mikroplastik und Landvögel: ein Überblick über die Aufnahme von Plastik an ökologischen Schlüsselstellen.
Die Verschmutzung durch Mikroplastik (MP; Plastikteilchen mit einer Größe von 5 mm oder kleiner) scheint allgegenwärtig zu sein und gibt Anlass zur Sorge über die Auswirkungen von Mikroplastik auf Organismen. Während einige Plastikarten in kleiner Größe hergestellt werden, einstehen die meisten MP aus dem Zerfall von größeren Plastikteilen mit oft unbekanntem Ursprung. Angesichts der dokumentierten Risiken einer Darmverstopfung, einer falschen Sättigung und von Entwicklungsstörungen bei Organismen ist es wichtig zu verstehen, wie sich MP durch die Nahrungsnetze bewegen, um festzustellen, welche Organismen für eine MP-Verschmutzung anfällig sind und worauf sich Vorschriften konzentrieren sollten. Landvögel haben das Potenzial, Forscher strategisch über die MP-Verschmutzung zu informieren, da sie unglaublich vielfältig sind, viele verschiedene Lebensräume und Verhaltensweisen abdecken und für Studien leicht zugänglich sind. Es gibt jedoch keine Untersuchungen darüber, wie wichtig diese Gruppe als ökologische Indikatoren ist. Die meisten Studien konzentrieren sich auf Wasservögel, und die Studien, die es zu Landvögeln gibt, konzentrieren sich auf größere Greifvögel. In dieser Übersicht werden die Herkunft der MP, ihre potenzielle Toxizität, ihre Verbreitung in der Umwelt und unser Verständnis der Rolle, die Landvögel bei der Aufnahme und Verbreitung von MP spielen, näher erläutert. Die Forschung zu diesem Thema nimmt zu, wobei Plastik in fast allen terrestrischen Arten gefunden wurden, die in den untersuchten Studien beprobt wurden. Jüngste Erkenntnisse und künftige Interessen konzentrieren sich auf die unterschiedlichen Mengen an

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MPs bei terrestrischen Vogelarten, welche wahrscheinlich auf das individuelle Verhalten, die Morphologie und die tägliche Nutzung des Lebensraums zurückzuführen sind.

Background

Plastics are a double-edged sword; while their multipurpose utility and durability aids in their consumer popularity, these properties also make them difficult to safely discard without environmental contamination (Horton 2017; Katsanou et al. 2019). Plastics are a synthetic organic polymer formed by monomers extracted from oil and gas, commonly used in manufacturing (Rios et al. 2007; Cole et al. 2011). Plastics arose in the early twentieth century in the form of Bakelite (condensed formaldehyde and phenol), but modern plastics were not widespread until the 1950s (Geyer et al. 2017). Since then, plastic production has expanded seemingly exponentially while sustainable disposal of those plastics has not.

Since the creation of plastic polymers, 8300 million metric tons (Mt) of virgin plastics have been produced and an estimated 12,000 Mt of plastic waste will be in landfills or the natural environment by 2050 (Geyer et al 2017). From 1950 to 2015, 9% of recorded plastic production was recycled, 12% incinerated, and 79% disposed of in landfills (Geyer et al. 2017; Rhodes 2018). In addition, plastic waste has become so prevalent in modern life that several studies describe plastics as a geological indicator of the recently proposed Anthropocene Era (Zalasiewicz et al. 2016). Humans have altered the earth so significantly (plastic production included in those alterations) that they have replaced nature as a dominating force (Ruddiman et al. 2015). Hence, the effects will be documented in geological strata.

The term “microplastic”, commonly referred to as MP, is a catch-all term first reported by Thompson et al. (2004) describing a wide array of degraded primary plastics and deliberately manufactured plastic particles five millimeters or less in size. Despite being defined in 2004, the presence of small plastic particles in the ocean dates back as early as the 1970’s (Rochman 2018). Primary MPs are manufactured to this small size while secondary MPs are plastics not originally intended to be smaller than five millimeters, but created from fragmentation of larger items via biological, physical, and chemical processes (Sivan 2011; Rochman et al. 2018). Here, we discuss both primary and secondary sources.

MP sources

The consuming sector is the largest source of plastic use. Forty-two percent of all non-fiber plastics were used for packaging while construction accounts for 19% (Geyer et al. 2017). However, while sectors like construction use a lot of plastic, the lifetime of construction-based plastics is often much longer than weaker plastics used for single use applications. The result is non-fiber plastic waste being dominated by the consumer sector at 54%, over construction 5%. Simply, single-use plastic development is transitory, being both frequently produced and immediately thrown away.

The average intended lifespan (generation to disposal) of common plastics varies depending on their intended purpose but includes packaging (1 year), construction (35 years), transportation (13 years), electronics (8 years), textiles (5 years), and consumer products (3 years) (Geyer et al. 207; Rhodes 2018). MPs are often applied by modern agriculture practices in mulch, bale twine, and wrapping which can be improperly disposed of and then transported via nearby streams (Rhodes 2018). Also, sewage sludge from municipal treatment applications being applied to farmlands is likely a major source of MPs into agricultural soil (Nizetto et al. 2016).

MP concentrations are highly variable; while exposure tends to be higher near largely populated areas (Jahandari 2023), they have also been found in remote areas like within the cryosphere (Zhang et al. 2022) and atop the Pyrenees mountains in France, 100 km from their suspected source (Allen et al. 2019). Their sporadic occurrence in remote areas suggests that MPs infiltrate multi-level habitats through a variety of vectors, including atmospheric transport. In turn, these reports sparked concerns of MP inhalation in the surrounding environment of different organisms (Free et al. 2014; Zhang et al. 2020).

Primary and secondary MPs

Primary MPs are commonly sourced from personal care products, air-blasting processes, and leachates from any plastics accumulated in landfills that can find their way to open water sources (Cole et al. 2011). Further, preproduction pellets and beads from personal care products are often missed by standard waste management (Rhodes 2018). These plastics commonly referred to as “scrubbers”, are frequently used in exfoliating scrubs and cleansers. The use of plastic as scrubbers is a relatively recent occurrence, while traditional materials used in cleansers included ground almonds, oatmeal, and pumice (Rochman et al. 2015). In addition, melamine and polyester MP scrubbers are used for air-blast cleaning of machinery, engines, and boat hulls. MP cleaning additives break down and may carry toxic heavy metals such as cadmium, chromium, and lead (Browne et al. 2011; Rhodes 2018). Microbeads, pellets, and scrubbers in cosmetics (5 um to 1 mm) have gained the most attention, becoming the poster child for MP source reduction which led to some countries banning their production (Rochman et al. 2015). However, MP pollution can come from unassuming sources such as road dust, road markings, and plastic turf athletic fields (Kitahara and Nakata 2020; Xu et al. 2020).

As primary plastics degrade, their structural integrity tends to break down into smaller particles (Weinstein et al. 2016). However, degradation can be hard to quantify; due to the durability of most plastics, it may take decades to fully break down and, therefore, be difficult to approximate the source quickly for regulation (Browne et al. 2011; Weinstein et al. 2016). Tsiota et al. (2017) studied the degradation of polyethylene films exposed to UV radiation and found a significant weight decrease, implying that secondary MPs were released throughout the exposure. Even primary particles, such as industrialized beads, may be broken apart over time to a diameter as small as 70 um (Thompson et al. 2004). Further, products advertised as "biodegradable", often are formed from combinations of products such as starch and plastic products, resulting in biodegradable composites leaving behind the broken MPs which they were once formed with (Klemchuk 1990).

Typically, wastewater treatment plants (WWTP) work to speed the natural processes of purifying water. Solids settle in the wastewater and WWTPs form a final effluent that is theoretically free of all solids. This is a common pathway for MPs to enter drinking water and other secondary sources (waterways, soils, etc.) (Conley et al. 2019). Past studies found at least 2% of plastics were missed by WWTP in one processing of wastewater (~ 10–24 h) and in some cases, this could result in approximately 65 million MPs passing through treatment in ten to 24 h into water outlets (Murphy et al. 2016). Consequently, there is risk of further environmental contamination by MPs missed by WWTP along with absorbed harmful cleaning agents (Ziajahromi 2017). Further, MPs are in human sources of food and drink with one study (Kosuth et al. 2018) finding 92% of drinking water samples taken from the United States and 72% taken from Europe had MPs present (Rhodes 2018). Importantly, whatever anthropogenic pollution that is affecting human populations is affecting other animals, both wild and domestic (Rhind 2012).

Potential acute and chronic toxicity of MPs in organisms and ecosystems

Defining toxicity of MPs is incredibly complex, since often it is not the plastic itself that is toxic, but additives that MPs are manufactured with or later absorb from the environment (Campanale et al. 2020). MPs impact organisms via two pathways: (1) physical, such as causing intestinal blockage, false satiation, or altering microbiota in the gut leading to starvation or a decreased immune system (Susanti et al. 2020; Jing et al. 2023), and (2) chemical alteration in the body, which has severe risks for short-term and long-term health of the immune system, reproductive development, and improper functioning of the thyroid largely due to endocrine dysfunction (Ullah et al. 2023) (Fig. 1). Other toxins which

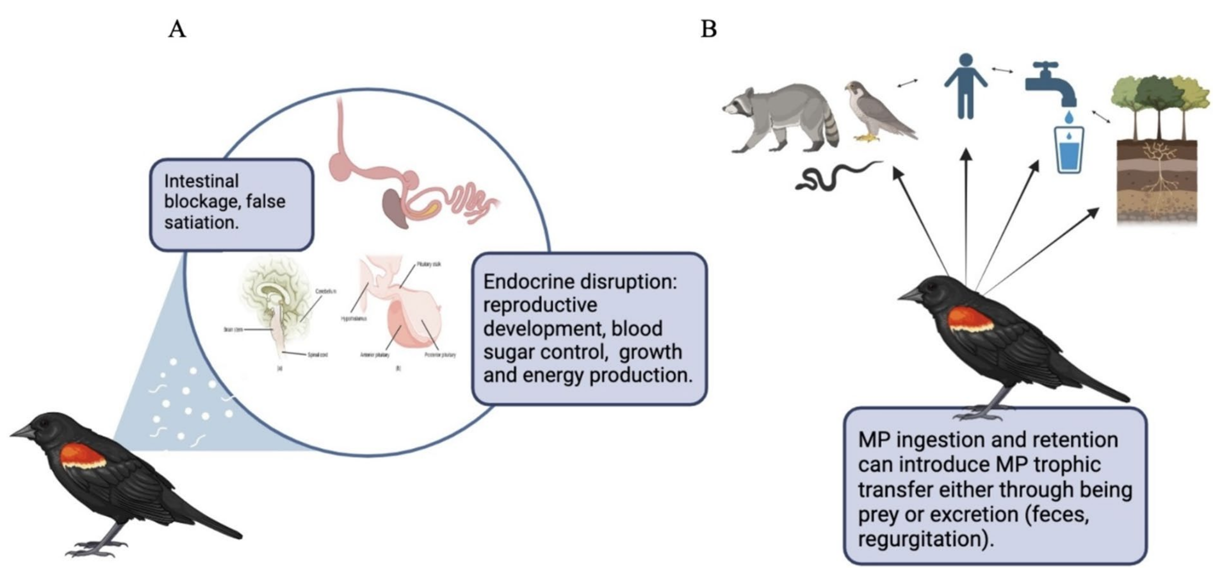

Fig. 1 An example of the ingestion, transfer, and dangers of MPs when introduced to common terrestrial birds such as the Red-winged Blackbird (*Agelaius phoeniceus*) pictured above. **A** Direct ingestion could alter the organism's GI tract either through false satiation or intestinal blockage, leading to starvation. Accumulating smaller MPs could disrupt the endocrine system which is responsible for development, reproductive success, blood sugar control, and energy production. **B** The potential risks do not end with the organism that ingests MPs, but they may pass them on to other organisms, water supplies, or soil via excretion or predation. Image created using BioRender ®

MPs absorb could cause neurological damage or cancer, however, toxicity is largely dependent on the size, shape, and concentration of the MPs (Yao et al. 2022).

MP effects on organismal internal systems are unique and attributed to their microscopic characteristics. While plastics generally do not interact with the endocrine system of animals due to their large molecular size, plastic debris are minute and act as sponges, which carry chemicals of smaller molecular size capable of penetrating into cells (Teuten et al. 2009; Santana-Viera et al. 2021). Respectively, broken down MP chemicals bear potential to target and disrupt the endocrine system responsible for regulating biological development of the brain, nervous system, reproductive system, and other important processes within the body (Ullah et al. 2023). Plastic additives for fire resistance such as phthalates and polybrominated diphenyl ethers are known to contain endocrine disrupting compounds and studies found these chemicals bioaccumulate in human bodies (Liu et al. 2017). Flame retardants commonly absorbed by plastics often contain chlorine or bromine, which release when ignited and may be inhaled by surrounding humans, which have acute volatile effects and long-term exposure issues (Dufton 1998). These chemicals (and others) are often released very easily from the plastic to the surrounding environment since they are often not chemically bound to the plastic (Hahladakis et al. 2018).

Exposure to MP compounds raises concerns for developing young children, specifically with respect to healthy thyroid hormones essential for normal neurological development or developing a healthy immune system (Talsness et al. 2009). In addition, many of these additives can alter the chemical structure of plastics, which makes chemical leaching and plastic degradation more likely over time (Campanale et al. 2020). For example, organotin is a stabilizing compound capable of causing immune system deterioration and a common additive in polyvinyl chloride (PVC) (Teuten et al. 2009). Polystyrene (PS), which is used in protective packaging, containers, and bottles is known to alter the vascular system and decrease growth when accumulated in the body which in past studies led to reproductive disruption, energy uptake, and offspring performance such as survival and growth (Messinetti et al. 2018; Yan et al. 2023).

Some of the most dangerous additives to plastic include Bisphenol A (BPA) and phthalates. While past regulation and consumer concern has decreased the amount of BPA used in plastic in the United States, BPA is still used internationally in some polycarbonate plastics, epoxy resins, and other polymers which can enter the food web and transfer between ecosystems (Vogel 2009; Ma et al. 2019). BPA can enter the body through the digestive or respiratory systems as well as passing through the integument and works as an endocrine disrupter (Ma et al. 2019). Specifically, BPA has severe effects on the reproductive system and neuroendocrine system. BPA disrupts the activity of the hypothalamus–pituitary–gonadal glands and pituitary-adrenal function which will decrease reproductive success (responsible for body temperature, satiation, sex drive, reproductive development, etc.) as well as downregulate T cells and antioxidant genes which degrade the immune system (Tarafdar et al. 2022).

Trophic interactions of MPs

MPs can enter terrestrial food webs through trophic transfer. For example, Huerta Lwanga et al. (2017) measured the transfer of MPs from soil to earthworm casts which were then transferred to foraging chickens, with the lowest average being 45.82 MPs per gizzard and 11 per crop. Further, past observations suggested that dimethyl sulfide signatures (DMS) absorbed by MPs falsely advertised natural trophic interaction odorants. DMS is a common odorant emitted during enzymatic breakdown of phytoplankton, which increases during grazing by zooplankton. Therefore, high DMS activity attracts larger organisms that rely on olfactory stimulus for hunting, however, chemical cues form MPs may hijack trophic chemical cues for other foraging behavior which would disrupt the entire food web (Savoca et al. 2016). Trophic level transfer of MPs in higher trophic organisms, such as birds, is in its infancy but critically important due to the high level of food energy usually demanded from higher trophic beings (Huang et al. 2021) (Fig. 1).

MP ingestion and toxicity in terrestrial birds

Modern terrestrial birds, often referred to under the clade Telluraves, emerged near 66 million years ago after the K-Pg extinction (Barrowclough et al. 2016). Terrestrial birds are exceptionally diverse, and most have flight-related traits that allow them to occupy ground and arboreal habitats (Crouch et al. 2018). Terrestrial birds are one of the most studied group of organisms because (1) their vocalizations make it very easy to identify species without seeing them, (2) mist-netting is a capture method to study many different bird species in a relatively short sampling period, which allows for expansive datasets, and (3) birds are unique, in that they have always captivated the attention of professionals and amateurs alike leading to citizen scientists being the driving force behind some of these expansive datasets (Barrowclough et al. 2016).

MP studies focusing on terrestrial passerines are scarce; most research focuses on aquatic birds. Yet, the ability of terrestrial birds to span multiple habitat types and their role as both predator and prey makes them imperative to understanding MP introduction, exposure, and toxicity in the environment (Morrison 1986; Egwumah et al. 2017). Moreover, their diversity and easiness to study compared to other groups of species makes them useful to any research on broad ecology. Terrestrial birds are model ecological predictors, since they span many different sizes, foraging and nesting behaviors, habitats, and diet which could influence how and how much MPs are ingested (Barrowclough et al. 2016; Elias 2023). These differences between like species are crucial to understanding the ecology of an organism and its interaction with surrounding environmental factors (Arnold 1983; Miles and Ricklefs 1984). For example, Darwin (1859) found bill morphology to predict Galapagos finches' diet. Foundational studies like this highlight the potential for studying diet, behavior, and morphology to help tease apart the relationship between plastic ingestion, organismal health, and community dynamics.

In a study quantifying the abundance of MPs in the gastrointestinal (GI) tracts in raptors, Carlin et al. (2020), sampled 63 deceased birds brought to a Florida Audubon Center finding that every bird had MP fibers in its GI tract. In addition, Carlin et al. (2020) found more MPs in species that hunt multiple prey items in different habitats, like the Red-shouldered Hawk (*Buteo lineatus*) when compared to species more obligate to one food source, like the Osprey (*Pandion haliaetus*). Zhoa et al. (2016), one of the earliest studies on MPs in terrestrial birds, inspected the GI tract of 17 terrestrial passerines found in China documenting 364 total items of anthropogenic origin. Particles smaller than 5 mm (standard MP size) represented 90% of the total number of pollutant items and they concluded that a larger sample size in future studies would benefit stronger conclusions on MP exposure in small migratory birds. Emerging research (Elias 2023) found that MPs are present in almost all terrestrial bird species sampled in the United States ($n = 63$ species) in varying habitats and spanning different behaviors and morphology. This is of importance, since terrestrial birds are indicators of most species and ecosystems (Morrison 1986; Egwumah et al. 2017), highlighting the severity of MP pollution in the environment. Studies like this utilizing a diverse dataset of bird species using the same habitat is vital to understand the animal characteristics that might influence MP loading, and the potential sources of pollution. This will allow further progress in limiting MP exposure in all animals.

The accumulation of MPs in terrestrial environments has implications for all species, including those endangered such as the California Condor (*Gymnogyps californianus*). Houston et al. (2007), reported heavy plastic consumption in 6 out of 8 total wild-hatched condor chicks between 2001 and 2005. In addition, the number of plastic debris found in scavengers in Northwest Patagonia varied depending on foraging habits in waste disposal dumps (Ballejo et al. 2021), further indicating that MPs are dependent on the ecology of specific species. In this study, primarily Black Vultures (*Coragyps atratus*) and Turkey Vultures (*Cathartes aura*) had a high occurrence of plastic debris in their regurgitated pellets leading researchers to conclude plastic debris might be transported across terrestrial habitats by the scavengers and introduced in other habitats via excretion.

Research over the past decade on MP interactions in specific species suggested that foraging tendencies and habitat plays a large role in MP contamination. Sherlock et al. (2022), studied the GI tracts of Tree Swallows (*Tachycineta bicolor*) and found MP loading more prevalent in chicks being fed aquatic-based insects compared to chicks fed a more terrestrial-based diet. In this study, MPs were identified in 83% of the nestlings' GI tract and 90% of fecal sacs, which are membrane enclosed feces produced by chicks for the adult to dispose of outside the nest. Recently, Hoang and Mitten (2022) sampled the GI tract of six species of migratory birds collected from window collisions in Illinois and found MPs in every species. Similar to Sherlock et al. (2022) this study found MPs were (1) possibly introduced by an insectivorous diet and (2) highly concentrated in adult Tree Swallows, which might indicate MPs being retained in the GI tract over a lifetime, rather than excreted after feeding. Future research should build on these previous findings and focus on the differences between bird species utilizing the same resources and how this might impact species-specific MP loading.

Most studies on terrestrial birds use necropsies to study long-term retention in the GI tract which is useful but time intensive. Also, deceased birds are not always readily available to researchers. Sherlock et al. (2022) use an interesting approach by using fecal sacs from the nest, underlining the need for readily available, less invasive methods to study MP ingestion. Recently, the use of bird banding was tested to study MP exposure in small terrestrial birds by analyzing excreted samples in the same way one would GI tracts (Elias in prep). In this study, the use of feces collected during bird banding proved useful in studying MP loading in terrestrial birds, especially when coupled with GI tract dissections collected from window collisions. These methods allow for rapid analysis of MP pollution in different habitats, since bird banding is a popular tool used by researchers to study many different species in a relatively short amount of time.

Current regulation and future aims to limit MP contamination

Past policy has focused on especially harmful plastic chemicals such as BPA, which have chronic contributions to breast and prostate cancer, as well as obesity, neurobehavioral problems, and reproductive abnormalities (Vogel 2009). In 2012, the Food and Drug Administration (FDA) banned BPA from baby bottles and other plastics used by children due to its development-disrupting properties. Since then, BPA has been removed from most plastic material, especially bottles, single use eatery, and other plastic materials commonly used to eat or drink by humans (Marie Metzet al. 2016).

Current policy focuses on primary MPs, namely microbeads, which since 2014 are banned in cosmetic products by Australia, Canada, Italy, Korea, New Zealand, Sweden, the United Kingdom, and the United States (Rochman et al. 2015; Rhodes 2018). In the US, the Microbead-Free Waters Act prohibits the manufacturing, introduction, or delivery of "rinse-off" cosmetics containing plastic microbeads (H.R.1321 Microbead-Free Waters Act 2015). Initiatives taken to reduce plastic emissions include the United Nations' Marine Litter and MP resolution (United Nations Environmental Assembly 2019) and several local community action and non-governmental organizations (NGOs) (1% for the Planet, Plastic Free Seas, Plastic Pollution Coalition) which lobby for harder regulations on plastic use, disposal, and containment (United Nations Environment Programme 2021). However, regulation is limited for secondary MPs, which is likely the most prominent type of MP in most ecosystems (Rhodes 2018). Secondary MPs break down from larger plastics, so without knowing potential sources of exposure it is difficult to target legislation. A continual accumulation of research surveying MPs in many species and differing environments which shows the same potential sources, might help this deficit.

Future direction of MP pollution and regulation

Currently, models predict a total of 90 Mt/year could infiltrate aquatic ecosystems alone by the year 2030 (Borrelle et al. 2020). This study aptly reasons that even though a country may have strict in situ plastic regulations, they may still export or import banned plastic to or from countries with poor regulations depending on individual legislation, which misrepresents the level of truly effective plastic management (Brooks et al. 2018). Also, evidence of poor reporting exists in some countries, where data on plastic production are often omitted (Lebreton and Andrady 2019). Recently, there has been a greater call by consumers for cooperative policies that increase recycling technologies, retain a lower amount of plastic use, and overturn the concept of single use plastics in modern economies (North and Halden 2014; Rhodes 2019).

Conclusion

The international dilemma of MP pollution is widespread across geographic location and species. Based on the reviewed literature, pathways to consider include wastewater and single-use plastics, however, plastics seem to present a novel problem since point-source pollution control of MPs is exceptionally hard to obtain. While physical blockage from MPs is possible, especially in smaller animals, current evidence suggests the main toxicity MPs present is endocrine disruption, which impacts healthy development and reproductive success as well as several other immune responses. Since MPs are essentially sponges that absorb a cocktail of chemicals during use and after disposal, their true potential for toxicity in communities, populations, and single organisms is largely unknown, but based on the studies reviewed in this paper MPs can be cancerous or disrupt development. There appears to be movement away from single-use plastics, like PS, polyethylene, and others used in bagging, clothing, and other materials.

Terrestrial birds are a novel group to accurately understand the variables influencing MP ingestion. Terrestrial birds are a large group with diverse behavior and morphology that can influence how plastic is introduced into their body and move through an ecosystem. Despite their diversity, ease of capture, and plethora of amateur and professional ornithologists observing and capturing terrestrial birds, MP research on this group is limited when compared to aquatic birds. Moving forward, studies should focus on large datasets of terrestrial birds to compare morphology and behavior to MP ingestion, which could apply to other organisms with similar characteristics. MP pollution is such a fast-moving issue, quick and accurate research that can be generalized to other species could help to curb the negative effects on ecosystems.

In short, while plastics are beneficial economically, the toxic potential they present for organisms will likely worsen if measures are not taken to reduce plastic use. A combination of continual scientific research on MP loading in indicators like terrestrial birds, and consumers holding industry and legislators responsible is possibly our only hope to curb the MP crisis.

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