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Review article

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The effects of plastic pollution on biodiversity

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Abstract

As plastic is increasingly found in natural environments, concern has grown about its biological effects beyond individual-level impacts, particularly on species health, food-web dynamics and ecosystem functioning. In this Review, we summarize current evidence on plastic exposure pathways, organismal responses and potential effects at higher levels of biological organization. Impacts on individual organisms can be acute or chronic, and include physiological stress, disrupted locomotion, feeding and reproduction, internal injury, and death. Sublethal effects might not be immediately detectable but can have profound implications for individual fitness. Although macroplastics can cause mortality, their role in population declines remains largely uncertain, and demonstrated impacts beyond the individual level are rare. Clear evidence of population-level harm from microplastics to wild organisms is lacking. Nevertheless, emerging research demonstrates a growing likelihood of broader effects, particularly for species with high plastic-encounter rates. Connecting environmental exposure to individual-level fitness and population-level consequences is a critical frontier. Future research must prioritize long-term monitoring, demographic modelling and high-throughput methods to accurately quantify risks to biodiversity. Effective solutions must be context-specific, span local to global scales, account for interactions with other stressors and integrate plastic pollution mitigation policies with broader conservation strategies to safeguard biodiversity in the Anthropocene.

Sections

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Key points

- Thousands of species have been found to interact with plastic debris, largely via ingestion or entanglement.
- Research has historically focused on marine systems, although studies in freshwater and terrestrial ecosystems have expanded rapidly over the past decade.
- Most documented impacts occur at the individual level, and relatively little research has explicitly tested for effects at population, community or ecosystem levels.
- For macroplastics, emerging evidence indicates potential effects on populations and ecosystems in highly exposed or vulnerable contexts, whereas comparable evidence for microplastics in wild populations remains lacking.
- Preventing biodiversity effects will require coordinated actions across local, regional and global scales that reduce plastic exposure while accounting for interactions with other environmental stressors.

Introduction

Since mass production began in the 1950s, the use of plastic and the accumulation of plastic waste in the environment has grown exponentially. By the 1960s, Laysan albatross (*Phoebastria immutabilis*) were discovered bringing plastic items to feed their nestlings in Hawaii[1], and multiple species of fish were found to have ingested 'polystyrene spherules' – now referred to as nurdles – in the Long Island Sound, USA[2]. As of June 2021, plastic debris is ingested by over 1,500 species[3], and it entangles hundreds more. Capitalizing on this enormous global research effort to determine whether, how and at what levels plastic pollution can harm populations and species, their ecosystem services, and biodiversity at large is a mounting challenge. Despite a vast body of literature on plastic pollution, substantial uncertainties remain about the extent and severity of plastic impacts on biodiversity. Most work has relied on opportunistic sampling, laboratory experiments or modelling efforts that do not fully capture real-world scenarios and risk (Box 1).

Plastic pollution comprises a wide range of materials, morphologies and particle sizes, from megaplastics and macroplastics to tiny microplastics and nanoplastics (MNPs). Plastic pollution refers to the accumulation of synthetic polymer materials in the environment, encompassing thousands of polymer types and additives, with polyethylene, polypropylene, polystyrene and polyvinyl chloride among the most common. Plastic is a unique pollutant that has the capacity to induce effects through physical, chemical and biological pathways[4], and organisms across the tree of life interact with plastic pollution through a variety of exposure routes (Fig. 1). Although plastic pollution research has historically centred on marine ecosystems, recent work increasingly reveals its prevalence and impacts across terrestrial and freshwater environments. Entanglement, often resulting in injury or death, has been well documented in invertebrates, fish, marine mammals, sea turtles and seabirds[5–9]. Ingestion, whether direct or indirect via contaminated prey, has been recorded in taxa ranging from zooplankton[10–12] to apex predators[13–15]. Although bioaccumulation and biomagnification are concerns, these processes are infrequently observed in wildlife, and trophic dilution has also been reported in some systems[16,17]. Nonetheless, MNPs have been shown to translocate beyond the gastrointestinal tract[18,19] – including in humans[20] – highlighting the potential for accumulation across diverse taxa.

As negotiations for a global treaty on plastic pollution advance, a pressing need exists for a comprehensive summary of current understanding and knowledge gaps about the impacts of plastic debris on biodiversity. Understanding the scale and scope of these impacts is essential to design effective policy, set priorities for research and conservation, and identify regulatory gaps. This information is also crucial for assessing when and where precautionary action might be warranted, even amid scientific uncertainty.

In this Review, we examine current scientific knowledge on the impacts of plastic pollution on biodiversity across terrestrial, freshwater and marine systems. We explore how different types and sizes of plastic affect organisms, identify patterns of exposure and harm, and highlight emerging tools for assessing risk and evaluating trends. In addition, we explore policies and voluntary initiatives aimed at reducing plastic pollution and evaluate their effectiveness at mitigating harms to biodiversity. We conclude with a discussion of key knowledge gaps, future research priorities and how precautionary, evidence-based actions can help to mitigate risk to wildlife and ecosystems as international agreements begin to take shape.

Ingestion and accumulation impacts

Ingestion of plastic debris by wildlife is one of the most pervasive and well-documented ecological consequences of plastic pollution (Figs. 1 and 2). Since early reports of seabirds ingesting plastic waste in the 1960s[1,21], research on this topic has expanded considerably. However, as knowledge of ingestion and accumulation impacts originates mainly from singular efforts or opportunistic availability of carcasses or by-products (for example, faeces, regurgitations and so on) assessing higher-order impacts is difficult. Most studies focus on organism-level impacts of ingestion on wildlife, ranging from no apparent effect, to sublethal effects (such as changes in blood chemistry, proteomics, the gut microbiome and satiation) to death[22–25]. High variability in ingestion rates within species and across life stages, unknown gut passage and retention times, and limited knowledge of foraging behaviour in many mobile species present further complications.

Plastic ingestion occurs via two primary pathways: passive ingestion through trophic transfer (that is, consuming prey that contains plastic) and active ingestion, in which plastic items are mistaken for prey due to visual, chemical or auditory cues[26–28]. Ingestion is not random; many taxa exhibit specific preferences for particular plastic shapes, sizes or polymers, implying a sensory basis for these interactions[29–33]. The mentioned route based on sensory bias is an 'evolutionary trap' in which evolved foraging strategies are rendered maladaptive because cues emitted by plastic debris hijack sensory strategies that evolved in a world without plastic pollution[3,34].

Effects of plastic size, morphology and polymer type

Plastic size, specifically as related to the organism's gape size, is the most important determinant of ingestion and effect[35]. The main risk comes from particles that are small enough to be swallowed but too large to pass easily through the gut or be excreted, or from particles small enough to cross the gut wall. Macroplastics and mesoplastics (1 m to 5 mm) can cause lesions, gut blockage and malnutrition owing to a false sense of satiety[25,36]. Small MNPs (≤50 µm) can translocate into tissues beyond the gastrointestinal tract, where they can induce

Box 1 | Advances in plastic risk assessment

Ecological risk assessments estimate the likelihood that an anthropogenic stressor, such as plastic pollution, will cause adverse effects at various levels of biological organization — from individuals to ecosystems. Risk is typically assessed as a function of exposure (likelihood of contact) and impact (severity of effect). Microplastic risk assessment methodologies have progressed considerably over the past 5 years[205,234–236]. A key challenge is accounting for the diversity of plastic types, sizes and exposure pathways, while aligning characteristics with toxicity datasets. Emerging methods align data using probability density functions for specific environmental compartments (for example, surface waters), linking particle characteristics (such as volume) to hypothesized effect mechanisms (such as food dilution). These approaches underpin emerging regulatory frameworks, including those for California[234] and the Laurentian Great Lakes[237]. Risk frameworks still lack methods to assess risks from plastic-associated chemicals, including sorbed or additive compounds, but new research is poised to overcome these barriers[205]. Several microplastic risk assessments rely on the Toxicity of Microplastics Explorer (ToMEx), a living database of over 350 toxicity studies on 164 freshwater and marine species[238,239]. ToMEx allows users to visualize, filter and analyse toxicity data, generate species sensitivity distributions, and screen studies based on quality criteria. The tool has been instrumental in developing risk-based thresholds, although high uncertainty remains owing to limited high-quality exposure and toxicity data[240,241].

Risk assessment methodologies for macroplastics are less advanced. Controlled laboratory studies are impractical and unethical owing to the size and vulnerability of the most sensitive species (for example, marine mammals and sea turtles), the size and variety of macroplastic forms, and their diverse impact mechanisms — primarily ingestion and entanglement[88,242]. As a result, macroplastic risk assessments rely heavily on field observations. Key knowledge gaps include exposure data disaggregated by plastic type, ingestion and entanglement rates by plastic morphology, and associated lethal and sublethal effects. Exposure modelling studies conducted over the past decade have focused on a range of taxa, including seabirds[243], sea turtles[89] and marine mammals[244]. These models typically group macroplastic types and assess exposure at the ocean surface, without linking to quantities ingested. The most well-measured impact of macroplastic ingestion is acute mortality[88,245,246], the likelihood of which has been quantified in seabirds, marine mammals and sea turtles based on not only the amount of plastic in the gut but also by plastic type[88]. Research quantifying sublethal effects such as food dilution[95] is rare. Species sensitivity distributions have been applied to entanglement risk using global entanglement rates and macroplastic concentration data[126,247], but these efforts are hampered by data limitations. Semi-quantitative approaches have also been used to estimate exposure and sensitivity scores across species and ecosystems[232,248,249], offering a promising direction for advancing macroplastic risk frameworks.

oxidative stress, inflammation or tissue damage[18,19,37,38]. Nanoplastics (<1 µm) represent a new frontier. Detection requires advanced methods such as pyrolysis-gas chromatography–mass spectrometry (GC/MS) for the quantification of mass, or atomic force microscopy–infrared spectroscopy[39,40] or optical photothermal infrared spectroscopy[40–42] for the quantification of particles, limiting widespread study. Therefore, the effects of nanoplastics on biodiversity remain unknown[43]. Meanwhile, laboratory studies have demonstrated that nanoplastics can cross cell membranes and disrupt gene expression, development and behaviour in exposed organisms[37,44,45]. MNPs can adsorb microorganisms and pollutants that increase the likelihood of plastic additives leaching into tissues[46]. Although knowledge of MNP ingestion impacts is still incomplete, the effects depend on aspects of the exposed organism (such as life stage, body condition and so on) and particles themselves (size, concentration, morphology and polymer type). Particle size and polymer identity have been identified as among the most influential factors determining microplastic ecotoxicity, and smaller particles and certain polymers show higher propensity for cellular uptake, bioaccumulation and oxidative stress[47]. Specifically, polyvinyl chloride has been identified as being more hazardous than polyethylene or polypropylene for some species[48,49].

Plastic morphology influences its bioavailability, accumulation in organisms and biological effects. Fibres are the most common microplastic morphology found in abiotic environmental samples[50,51], and they are frequently the dominant MNPs found in wildlife, potentially owing to their abundance and retention time (although fibres found in organisms are often confirmed to be of natural materials)[52–54]. Plastic fibres are generally found to be the morphology retained most readily and are therefore potentially the most harmful, although some findings suggest the opposite[55]. Harmful effects have also been observed for other morphologies, including fragments and spheres[55].

Effects by taxon

Plastic ingestion and accumulation have been reported across nearly all major taxonomic groups, from plants and invertebrates to fish, birds, reptiles and mammals. The extent and consequences of these interactions vary widely, reflecting differences in exposure, life history and susceptibility.

Plants. Mounting evidence indicates that MNPs can have detrimental effects on plant health, productivity and ecosystem function — dependent on plant species, polymer type and MNP concentration[56]. Experimental studies have demonstrated that MNPs can impede seed germination, root elongation and nutrient uptake, which has cascading consequences for plant development[56,57]. Across multiple plant species, exposure to MNPs at concentrations ≥20 g kg^{-1} of MNP in soil or ≥100 mg l^{-1} of MNPs in water has been associated with mean reductions of 13% in total biomass and 18% in photosynthetic efficiency[56], suggesting that plastics can compromise both carbon assimilation and energy production in plants. Globally, MNP exposure could be responsible for a ~10% global decline in photosynthetic rates in plants and algae[58]. These findings raise concerns for global primary productivity and food security, particularly considering increasing plastic contamination in agricultural systems. Indeed, field trials have found that microplastic exposure in croplands can reduce plant biomass and chlorophyll content[59]. Smaller plastic particles and higher exposure concentrations elicit more severe responses and affect root biomass and below-ground activity, which are vital for water and nutrient

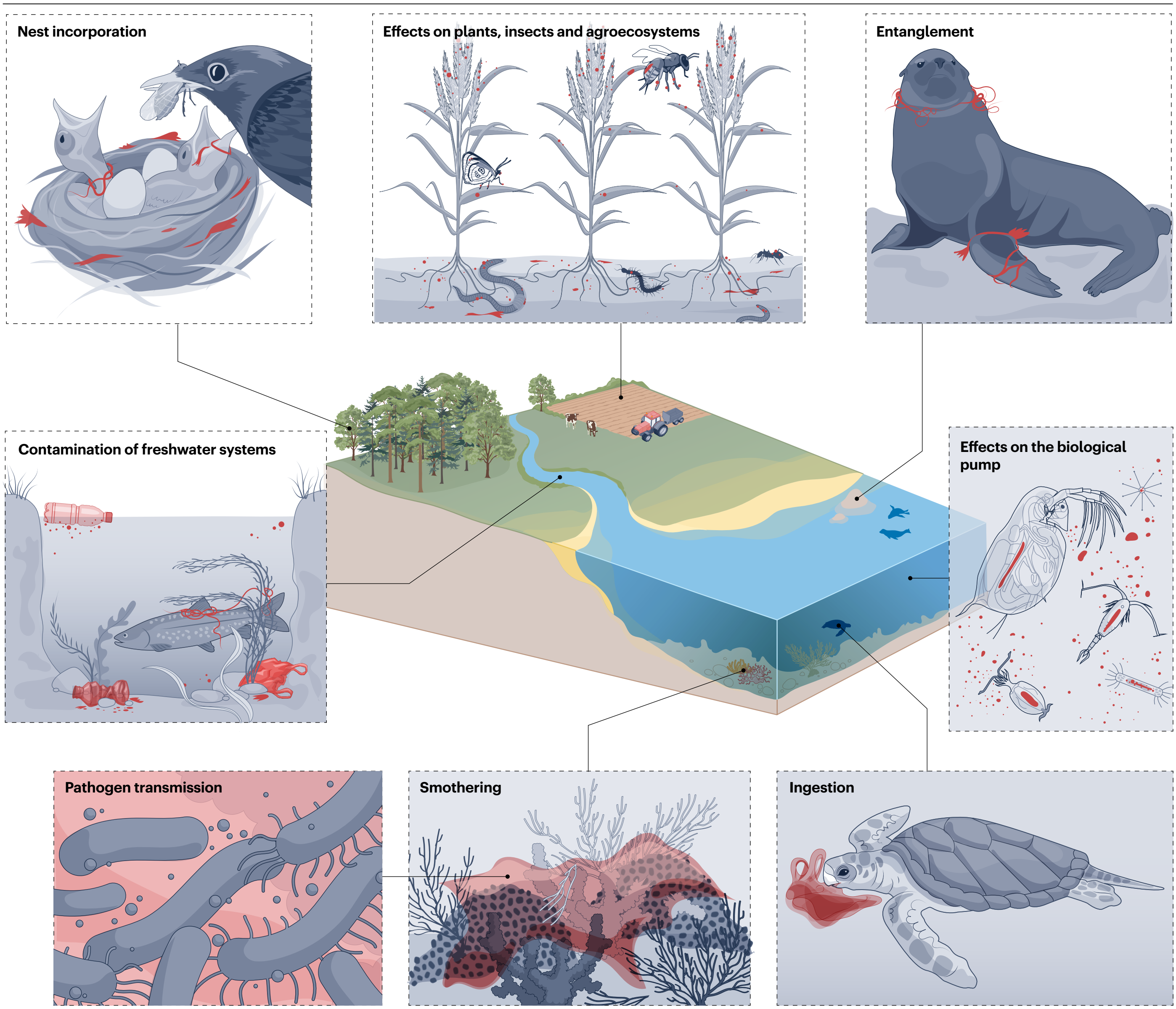

Fig. 1 | The interactions of plastic with biodiversity. Plastic waste affects ecological processes throughout the biosphere. In some cases, the negative effects are well demonstrated under both natural and laboratory conditions (such as ingestion), whereas for others foundational evidence is in place, but more detailed information is needed (for example, effects on plant life and ecosystem services).

acquisition[59]. Beyond direct effects on plant tissues, MNPs have been shown to reduce a diversity and depress key soil enzyme activities, undermining nutrient cycling and soil fertility[60,61].

Invertebrates. As primary and secondary consumers, invertebrates are central to plastic cycling. Ingestion of microplastics by invertebrates is well documented, often detected through full-body digestion or gastrointestinal tract dissection. Although impacts are often minimal[62–65], chronic effects could potentially have deleterious consequences – not just for the species but for overall biosphere functioning, given the foundational importance of these species. For example, consumption of MNPs by zooplankton can reduce their grazing on primary producers, which can exacerbate the global loss of ocean oxygen[66]. This phenomenon could affect biodiversity at large and take centuries to reverse[67]. Another ecosystem-wide impact mediated by zooplankton ingestion of MNPs is a reduction in the strength of the biological carbon pump. This reduction occurs because MNPs lower the carbon content and sinking rates of zooplankton faecal pellets[68,69], which are important vectors of particulate organic carbon to the deep sea. Through this mechanism, MNPs are predicted to decrease carbon sequestration via the biological pump by 4–5 Gt C globally between 1950 and 2100 (ref. 70). Furthermore, invertebrates can fragment microplastics into nanoplastics during digestion, increasing the probability that they will be incorporated in food webs[71,72].

The ecological impacts of MNPs on invertebrates could have cascading effects on ecosystems if they disrupt pollinator health or behaviour. MNPs can interfere with honeybee cognition[73] and increase the risk of viral infection for this species[74], reducing pollination efficiency and reproductive success in flowering plants. As terrestrial insects form the base of many food webs, impacts from MNPs on these species could affect ecosystem services broadly and food security for people[75]. Interestingly, emerging research suggests that some invertebrate species can contribute to plastic biodegradation by breaking down polymers into less persistent — and potentially less harmful — constituent compounds[76,77]. The extent to which this ability will be applied as a potential remediation technique remains unclear.

Fish. Fish were among the first taxa shown to ingest plastics, from micro to macro, and remain one of the best-studied groups, as over 1,000 fish species have been sampled to date[3,78]; however, research remains biased to the Northern Hemisphere and marine species[78]. Translocation of small particles beyond the gastrointestinal tract has become commonly reported[18,79], and laboratory studies on fish have demonstrated that microplastics can disrupt gut microbiota, impair locomotion, reduce feeding activity and offspring viability, induce oxidative stress, and cause endocrine disruption and epigenetic changes[80–84]. However, many of these controlled experiments are short in duration (days to weeks) and do not capture long-term chronic effects. Earlier laboratory studies often used polymer blends, morphologies and concentrations that were unrealistic with respect to natural systems, and field studies often do not measure, or fail to detect, health consequences[65]. However, recent attention to this issue has prompted rapid procedural standardization and improved method reporting, enhancing the ability to interpret and extrapolate laboratory-based findings to real-world contexts and higher levels of biological organization[85,86].

Reptiles and amphibians. Sea turtles might be some of the most vulnerable species to plastic ingestion, and data suggest that ingestion rates could be increasing over time[87]. Models developed for sea turtles estimate that a 1-m-long individual that ingests 552 cm^3 of plastic has a 90% probability of mortality[88]. The ingestion risk is modulated by diet, life stage and region, and a range of health outcomes have been

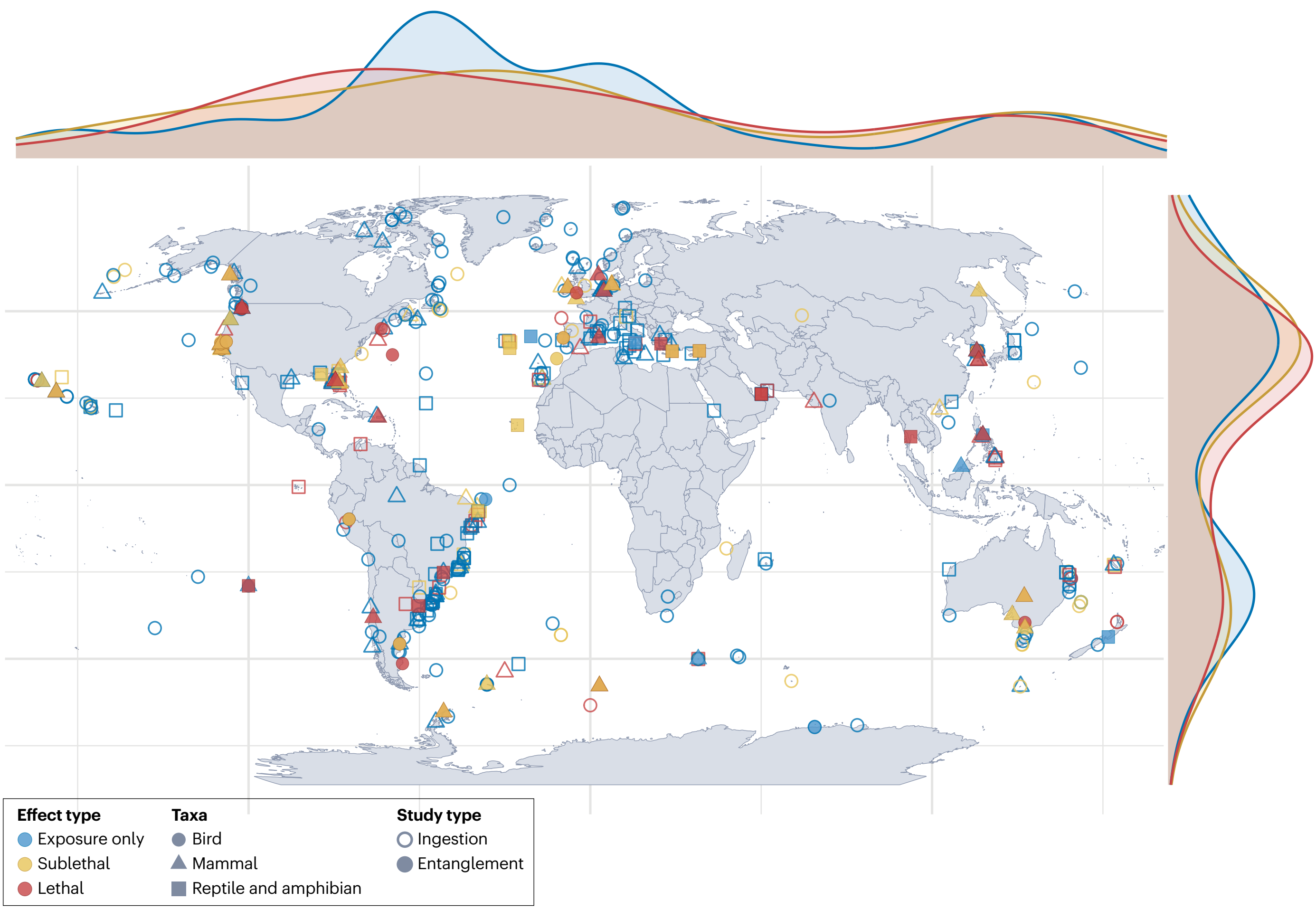

Fig. 2 | Geographic coverage of entanglement and ingestion research. Macroplastic studies (n = 441) on vertebrates excluding fish conducted from 1980 to 2024 (following methods reported previously[232], extending literature search from 2021 to 2024). Hollow points represent ingestion and filled points represent entanglement. Most work to date has been conducted near coasts, in the Northern Hemisphere, and in the Atlantic Ocean and Mediterranean Sea. The majority of research does not test for effects beyond exposure of individual organisms to plastic (that is, it does not test for broader effects of plastic on populations, communities or ecosystems). Data and code can be found at https://github.com/mssavoca/NRB_PlasticImpacts.

documented, including false satiation, gut perforation and reduced body condition, sometimes leading to death[3,89,90]. Post-hatchling and juvenile sea turtles are considered more prone to ingesting plastics and to being negatively affected than adults[87,91]. Although microplastic ingestion by sea turtles has now been widely reported[92], further research is needed to comprehensively understand its health effects. A concerning new finding is the potential for microplastics to transfer maternally to eggs[93,94], where the severity of impacts is probaly increased owing to bioconcentration. Additionally, turtle population declines as a result of reduced energy intake caused by plastic ingestion have been modelled, indicating that plastic ingestion impacts might extend beyond individual-level effects[95]. For other reptiles and amphibians, data remain sparse, but ingestion has been reported in alligators, lizards, snakes, tortoises, freshwater turtles and toads[3,96,97]. Early life stages, such as tadpoles, might be particularly vulnerable, although experiential evidence for the effects of MNPs on tadpole behaviour, growth, immune response and survivorship is mixed[98] and dose-dependent. For example, elevated tadpole mortality at extremely high MNP concentrations (1,800 MNPs per millilitre) has been documented, but lower concentrations showed no effects[99].

Birds. Birds, particularly seabirds, are some of the earliest and most comprehensively studied taxa in relation to plastic ingestion. Frequency of occurrence and impacts of ingested plastic, as in other taxa, vary by species, and frequencies range from near 0% for some species to near ubiquitous plastic ingestion for others[100,101]. The frequency of plastic ingestion in birds is often linked with their diet and exposure to plastic in the environment[101,102]. Observed effects include neurodegeneration, reduced body condition, and lesions or perforations of the gastrointestinal tract, all of which can lead to death[24,36,103,104]. Rubber is particularly harmful, as only three ingested pieces equates to a 50% chance of mortality and six ingested rubber items raise that risk to 90% (ref. 88). Birds also transport plastic from marine to terrestrial environments[105–107], yet the effects of this plastic transfer to recipient ecosystems remain largely unknown. Although the majority of studies have focused on marine birds, research conducted over the past 5 years has documented plastic ingestion in a range of terrestrial and freshwater species[101]; still, insufficient long-term data exist to robustly test for effects on terrestrial and freshwater species.

Mammals. Plastic ingestion by marine mammals is frequently observed during necropsies of stranded individuals[108–111]. Deep-diving toothed whales regularly ingest plastic, which is often listed as their cause of death[109,112]. More concerningly, emerging research suggests that plastic might acoustically resemble prey, highlighting an evolutionary trap for these species[28]. Other research has looked for, but found no evidence of, plastic ingestion in marine mammals, or found ingestion at levels unlikely to cause negative effects[113–115]. In filter-feeding baleen whales, MNP ingestion occurs most often through trophic transfer[13,116,117], because zooplankton bioconcentrate MNPs relative to seawater[13,116,118]. These predators have been found to ingest millions of microplastic particles daily, primarily through trophic transfer of contaminated prey[13,116,119]. Translocation has been confirmed in tissue samples[19], but downstream health effects remain largely unexplored. Freshwater mammals remain mostly unstudied[120], but the distribution of river dolphins – often confined to regions of intense human activity – combined with their endangered status raises serious conservation concerns[121]. Although laboratory mice are commonly used to test the effects of ingested plastic[122], wild terrestrial mammals are greatly understudied[123]. However, some studies have shown that megafaunal species, such as Asian elephants (*Elephas maximus*) and one-horned rhinoceros (*Rhinoceros unicornis*) ingest plastic[124,125], which can threaten these species and transport plastics through defecation deep into terrestrial ecosystems, potentially making plastic available to other species.

Entanglement and smothering impacts

Entanglement in marine litter poses the most unambiguous threat to marine biodiversity from plastic pollution[126] (Figs. 1 and 2). Derelict fishing gear – often referred to as abandoned, lost or discarded fishing gear (ALDFG) – are among the most dangerous materials, causing entanglements that often lead to injuries and deaths. All gear types contribute, including nets, traps, ropes and fishing lines[9,127,128]. For marine mammals, sea turtles and seabirds, derelict nets are particularly dangerous, because they can drown these air-breathing species[9,128–130]. Other gear types – line, rope and packing bands – are often associated with severe injuries, such as lacerations, infections and limb amputations[131–133]. For fish and invertebrates, derelict traps and pots might be the deadliest debris types[134]. Entanglement is also observed in freshwater and terrestrial species, causing similar injuries and mortality, although these impacts are far less studied and documented than in marine systems[135].

Invertebrates

Plastic pollution has negative effects on reef biodiversity through entanglement and smothering of corals[136,137]. These effects have been associated with fragmentation[138], tissue loss[138] and increased rates of disease[139]. More generally, marine animal forests, dominated by sessile suspension feeders like corals and gorgonians, are highly vulnerable to marine litter entanglement owing to their large morphologies, slow growth, longevity and widespread presence in both shallow and deep waters[137,140]. Derelict fishing nets and other large plastic items such as plastic bags and sheeting are particularly damaging because they can blanket and abrade structurally complex colonies, remain in place for years, and repeatedly snag and break living tissue, leading to persistent reductions in coral cover and increases in bare substrate at affected sites, which can persist even after debris is removed[141,142]. These changes in benthic cover illustrate one pathway by which macroplastic debris can drive community shifts on reefs, especially where branching *Porites*, *Pocillopora*, and *Acropora* spp. act as 'catchers' for drifting gear[138,140,142]. For mobile invertebrates, catch rates of abandoned gillnets have been estimated at more than five individuals per net per week, or more than 500 individuals over a net's lifetime[9,143]. Derelict traps entrap invertebrates at high enough rates to reduce fishery efficiency and population stability, particularly of target species[144,145].

Effects of plastic entanglement are not restricted to aquatic invertebrates alone. Terrestrial invertebrates, such as ants (Hymenoptera), have been recorded entangled in synthetic plastic fibres[146]. Entanglement of earthworms can cause lethal and sublethal effects, which can induce alterations to behaviour, growth, oxidative stress and physiology; owing to their role as ecosystem engineers, these effects could affect biodiversity at large[147]. Conversely, in some environments, plastic macro-litter has been found to facilitate higher invertebrate species diversity and richness via the creation of micro-habitats[148].

Fish

Entanglement is less researched for fish than other vertebrates, but evidence suggests a threat to many fish species. Derelict crab traps in the Gulf of Mexico have been estimated to catch 600,000 kg of finfish annually[134], and mortality rates for fish in the Caribbean from derelict fish traps have been estimated at 0.3 fish $trap^{-1}$ $month^{-1}$ (ref. 149). Derelict gillnets in Puget Sound had estimated catch rates of 0.74 fish $week^{-1}$ or 14 fish net^{-1} over their lifespan[9,143]. Injuries have also been observed from entanglement in ropes, lines and consumer plastics[150,151]. High rates of injuries from entanglement are a particular concern for the population stability of threatened and endangered species. Elasmobranchs (sharks and rays) are among the most threatened fish taxa globally, and at least 34 species have been recorded entangled in plastic waste, most often ALDFG[8]. High rates of entanglement have been observed in the critically endangered smalltooth sawfish (*Pristis pectinata*)[152] and the near-threatened blue shark (*Prionace glauca*)[153,154]. However, further population-level studies are required to understand the risk that entanglement poses to these or other fish species, focusing in particular on small and endangered populations that overlap with fisheries.

Reptiles and amphibians

Plastic entanglement and smothering of sea turtles in the aquatic environment has been widely studied. Entanglement has been attributed to death in all seven species of sea turtles in every life stage[5]. Although research at the population level is scarce, plastic entanglement of sea turtles is prevalent enough that population-level effects could probably occur in regions worldwide with high plastic concentrations[126]. For instance, in the Maldives, two-thirds of stranded turtles exhibited signs of entanglement, which was sufficient to drive a decline in the Sri Lankan population; however, the East Indian population remained stable[127,128]. Sustained laceration, traumatic amputation and abrasion to sea turtles' flippers, shells and heads are the most common signs of injuries inflicted by entanglement in ghost nets or lines[128]. Plastic pollution along the shore also threatens nesting turtles and hatchlings. Research has reported mixed outcomes of beach debris concentrations on nest distribution: debris has been found to alter nest distribution in green sea turtles (*Chelonia mydas*)[155], whereas no change in nest distribution or nest success was observed in loggerheads (*Caretta caretta*)[156]. The biggest threat of coastal debris to sea turtles is the threat to hatchlings. Both ALDFG and consumer plastics reduced the likelihood of hatchlings reaching the ocean (crawl success) and increased the average crawl time of successful hatchlings[156,157].

The impacts of entanglement on reptiles beyond sea turtles is still poorly understood, despite numerous reports of snakes, lizards and tortoises becoming entangled in a variety of plastic litter[158–161]. The plastic materials in most cases caused deep lacerations, impaired movement, exposure to predators and death[158–161]. Many instances of entangled reptiles in remote regions and developing nations are probably unreported, and no research has been conducted on the effect of entanglement on populations or species of terrestrial or freshwater reptiles. The authors are unaware of reports or studies on entanglement of amphibians by plastic waste.

Birds

Death from entanglement has been observed in bird species around the world[6,162,163], although some difficulty exists in distinguishing between entanglement resulting from interactions with active gear (that is, fishing gear in use) and from interactions with derelict gear (ALDFG). Diving and fishing species – such as penguins, gulls, pelicans and auks – appear to be at greater risk of life-threatening injury and death than other species; however, injuries and reduced mobility have also been observed in other families[162,164]. Although few population-level studies have been conducted, research suggests that entanglement can lead to population decline[126,165]. For instance, the northern gannet (*Morus bassanus*), northern fulmar (*Fulmarus glacialis*) and common murre (*Uria aalge*) are all at risk of population decline caused by entanglement in parts of their range[126]. Along the US West Coast, entanglement has been reported as the cause of death for 0.2–1.2% of seabirds annually[164]. Furthermore, derelict gillnets in Puget Sound killed an average of 0.37 birds per week and have been recovered with 16 species[9,143].

Mammals

Entanglement, specifically by ALDFG, poses a substantial threat to marine mammals. Mortality, primarily through drowning, has been observed in species worldwide, including manatees, seals, sea lions, whales, dolphins and porpoises[129,166,167]. In pinnipeds, entanglements primarily occur around the neck and constrict animals as they grow, causing deep lacerations and infections[168,169]. The severity of these infections and low resight rates suggest that entanglements can lead to mortality[170]. Injuries and mortality have also been reported in cetaceans[171,172], although long-term studies are less feasible, as these individuals cannot be repeatedly observed at haul-out sites. Entanglement has been linked to population declines in several species of pinnipeds: the Hawaiian monk seal (*Monachus schauinslandi*)[173], the Australian sea lion (*Neophoca cinerea*)[174] and the South American fur seal (*Arctocephalus australis*)[175]. Several species of cetaceans and the common minke whale (*Balaenoptera acutorostrata*) have also been identified as vulnerable to population declines from entanglement in parts of their range[126]. However, other research has reported entanglement rates low enough to have no effect on populations[176], although juvenile males were found to be more susceptible, which could have demographic effects[177]. Higher rates of mortality in these life stages could pose risks to population stability in populations for which sex ratios are imbalanced. Entanglement of terrestrial mammals is relatively unstudied, but smaller species (such as the European hedgehog (*Erinaceus europaeus*))[178] might be severely affected.

Other impacts

Although ingestion and entanglement remain the most widely documented impacts of plastic pollution, other, often overlooked, consequences have the potential to reshape ecological communities, ecosystem processes and species distributions. Rafting and long-distance dispersal of species is one such example[179] (Fig. 1). Unlike natural materials such as wood or macroalgae, synthetic polymers can remain afloat for decades, offering stable substrates for colonization and transoceanic transport. Marine organisms including barnacles, molluscs, bryozoans and decapod crustaceans have been observed 'hitchhiking' on plastic debris, some travelling thousands of kilometres and surviving in conditions previously thought uninhabitable[180,181]. The 2011 Japanese tsunami provided a striking example: hundreds of coastal species were transported across the Pacific on tsunami-generated debris, and plastic items supported viable populations for over 5 years at sea[182]. This transportation could facilitate biological invasions, potentially disrupting native assemblages, altering food webs and accelerating eco-evolutionary change[180,183].

Plastics can also act as vectors for pathogen transmission, via colonization by microbial communities on their surfaces (Fig. 1). These complex biofilms – collectively termed the 'plastisphere' – are dominated by bacteria, algae, fungi and protozoans[184]. The composition of these communities differs markedly from surrounding seawater

Table 1 | Key international and regional agreements relevant to plastic pollution

Policy/intervention	Scope	Year entered into force	Details
Existing multilateral environmental agreements to regulate plastics			
MARPOL Annex V (International Convention for the Prevention of Pollution from Ships)	International — global	1988	Prohibits the disposal of any plastic waste at sea
Basel Convention	International — global	1992	The Convention was amended to include plastic waste as a regulated material, requiring environmentally sound management and managing the exports of plastic waste
London Convention	International — global	1975	Regulates the disposal of waste at sea
International legally binding instrument to end plastic pollution	International — global	NA	A legally binding instrument to end plastic pollution, commonly known as the global plastics treaty, is actively being negotiated following the passage of UNEA resolution 5/14 in 2022 (ref. 231)
The Ocean Plastics Charter	International — global	2018	The Charter brings together governments, businesses and civil society organizations to establish a foundation for sustainable plastics management, encouraging a full-life-cycle approach to reducing plastic waste
The EU Single-Use Plastics Directive	International — EU	2019	Ban of single-use plastics in the EU
G20 Action Plan on Marine Litter	International — global	2019	Global monitoring (microplastics) and coordinated reduction measures
The Marine Strategy Framework Directive	International — EU	2008	Monitoring of four marine litter indicators, including ingested litter in birds and sea turtles, and programme of reduction measures
UN Regional Sea Conventions	Regional	1974	Monitoring of plastic pollution, regionally harmonized reduction measures
Example policy interventions across plastics life cycle			
Packaging and Packaging Waste Regulation (Regulation 2025/40)	Regional — EU	2024	This regulation replaces the EU's previous Packaging and Packaging Waste Directive, outlines reduction targets in packaging waste per person, requires packaging to be economically recyclable by 2030, outlines increased requirements for post-consumer recycled content, and promotes reuse and refill systems
Barcelona Convention (Convention for the Protection of the Mediterranean Sea Against Pollution)	Regional — Mediterranean	1978	The Convention is implemented through a set of binding protocols designed to prevent at-sea disposal, manage litter and coordinate responses to pollution incidents with the broad goal to prevent, reduce, combat and eliminate pollution in the Mediterranean Sea
OSPAR Convention	Regional — Northeast Atlantic	1998	The Convention is implemented through a Regional Action Plan to monitor marine litter indicators (including ingested litter by birds and sea turtles), prevent at-sea disposal and coordinate mitigation measures

These instruments illustrate both the progress made and the gaps that remain in governing plastics at global and regional scales. EU, European Union; NA, not applicable; UNEA, United Nations Environment Assembly.

and sediments, often harbouring potential pathogens, including antibiotic-resistant strains of bacteria[185]. This microbial contamination could have implications not only for disease transmission[186] but also for species with vulnerable early-life stages. For example, changes to gut microbiota in seabirds associated with plastic ingestion demonstrate how the plastisphere can influence microbial communities[187].

The additives from plastic debris can also have effects on biodiversity. For example, emerging evidence suggests that microplastics can infiltrate sea turtle nesting habitats where chemical additives – such as polybrominated diphenyl ethers, used as flame retardants – can leach from heated debris and penetrate beach substrates to depths of at least 20 cm, potentially affecting sea turtle eggs. These compounds have been linked to increased rates of leucism (loss of pigmentation) in embryos, a condition that might impair survival later in life[188].

Birds are well known to incorporate plastic debris into nests. Of nearly 11,000 nests of two dozen species, plastic was found to be incorporated into 31% of all nests, with no difference between marine or terrestrial species[189]. The use of plastic materials in nests increases the risk of entanglement for nestlings[146,190,191]; for example, research on white storks (*Ciconia ciconia*) reported that 91% of nests contained anthropogenic debris and 12% of all nestlings were entangled in this debris – most commonly synthetic rope – which was often lethal[192]. Conversely, plastic waste can have positive effects in bird nests. For example, house sparrows (*Passer domesticus*) and house finches (*Carpodacus mexicanus*) incorporate synthetic fibres from smoked cigarette butts into their nests, which repel ectoparasites[193,194].

Implications for biodiversity

Despite thousands of documented interactions between wildlife and plastic pollution, important questions remain about how exposure translates into impacts beyond individual organisms at the population, community and ecosystem level. Establishing causality in complex ecological systems is difficult, particularly because plastic rarely acts in isolation from other anthropogenic stressors. Nevertheless, accumulating evidence of individual-level harm, especially among highly exposed or vulnerable species, raises concerns that plastic pollution might be eroding population viability, altering community structure or diminishing ecosystem function.

Marine mammals, seabirds and sea turtles are among the best-studied groups and therefore provide the clearest indications of potential biodiversity-scale effects. Although relatively few population-level analyses exist, available research suggests that entanglement can drive population declines in some pinnipeds and cetacean populations in certain portions of their range[126,173–175]. Similar patterns are emerging in other taxa: for example, entanglement in plastic rope within nests represents a substantial source of mortality for white storks in Europe[192], and entanglement in ALDFG is a major cause of injury and death for sea turtles in the Indian Ocean[128]. Ingestion-related effects remain more challenging to quantify than entanglement effects, yet post mortem studies consistently implicate plastic as a contributory cause of death in a small but meaningful fraction of individuals. In Brazil, plastic ingestion contributed to mortality in roughly 5% of 13 examined seabird species[195] and, globally, at least 4.4% of necropsied sea turtles have died from plastic ingestion across diverse regions and life stages[88]. In some contexts, impacts are far more pronounced: among post-hatchling loggerhead turtles in South Africa, plastic was implicated in 40% of mortalities[196]. Demographic modelling indicates that even modest increases in mortality or reductions in energy intake from plastic ingestion could shift population trajectories for some sea turtle populations[95], highlighting the value of incorporating plastic exposure into demographic assessments, even as these models await further validation. Whether by ingestion or entanglement, biodiversity-level impacts most probably occur where exposure is high, demographic buffering capacity is low or the affected species have a keystone ecological role.

The potential for plastic pollution to reshape communities and ecosystem processes is also plausible[183] but remains under-documented. Declines in seabird populations, for example, might diminish nutrient subsidies to island ecosystems, reducing productivity in guano-dependent plant and invertebrate communities[197,198]. Plastic can also disrupt species interactions that involve foundational habitat-forming taxa. On coral reefs, the entanglement and smothering of corals and gorgonians has been associated with shifts towards algal dominance and reduced habitat complexity[137]. In an ocean increasingly characterized by marine heatwaves and mass bleaching, plastic debris further exacerbates coral decline by elevating disease and bleaching risk[137,139].

At smaller size classes, MNPs can alter zooplankton grazing, which has downstream effects on primary production, biogeochemical cycling and, potentially, oxygen dynamics[66,68,69]. For terrestrial invertebrates, macroplastic can be an ecological trap drawing numerous individuals to their death[199], and can impair the neurocognition of pollinators, such as honeybees[73]. For microorganisms, plastisphere communities' taxonomic composition and metabolic functions differ considerably among polymers and from surrounding seawater[185,200]. Recent in situ and meta-omic studies demonstrate that these plastisphere biofilms selectively enrich hydrocarbon-degrading and potentially pathogenic taxa, while simultaneously reshaping marine microbial diversity and biogeochemical functions at ecosystem scales[201,202]. Together, these examples illustrate that ecosystem-level consequences can arise even in the absence of clearly documented population declines.

Chronic exposure to multiple stressors is the norm for species worldwide. Plastic can reduce individual fitness while simultaneously degrading food quality, habitat structure and nutrient flows. Lessons from other pollutant-driven population collapses, such as those documented for vultures[203] or anticipated for killer whales[204], reinforce the risks posed by chronic, sublethal exposures. Potential impacts from >16,000 plastic-associated chemicals, a quarter of which are persistent, bioaccumulative, mobile or toxic[205], suggest additional pathways for ecosystem-level effects that remain poorly understood. Combining these threats into quantitative assessments of ecological risk is challenging, but some of the first global examples are emerging[206] (Box 1). In addition, evidence that plastic ingestion is an evolutionary trap for some taxa[3,28,34] implies that maladaptive foraging responses might persist even as environments change, potentially constraining recovery.

Interventions and effectiveness

Growing awareness of the ecological consequences of plastic pollution has led to increased interest in mitigative actions across the life cycle

a

Intervention	Examples	Potential biodiversity impact
Local	• Trash traps • Clean-ups • Microplastic capture device	• At-risk species • Biodiversity hotspots
National	• Bans of single-use plastic • Virgin resin tax • Extended producer responsibility	• Ecosystem benefits • Specific population benefits
Global	• Global treaty efforts • Managing at-sea disposal	• Migratory species • Biodiversity benefits

b

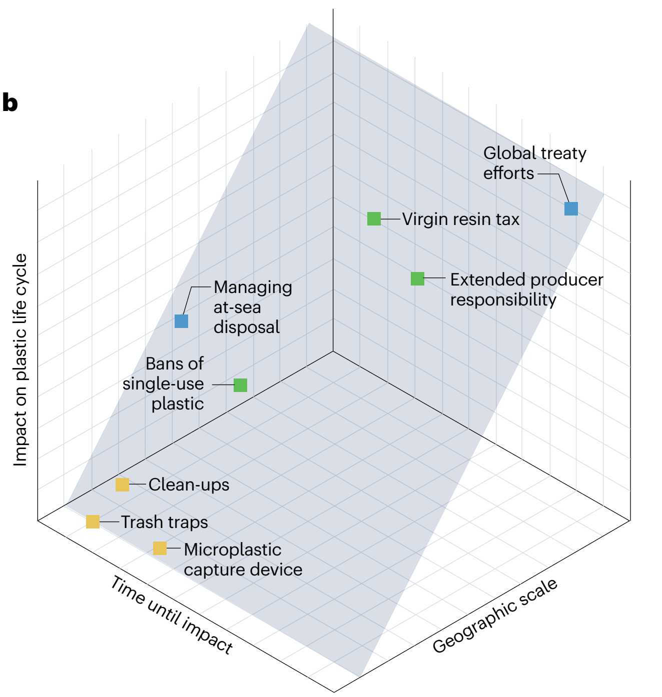

Fig. 3 | Intervention effectiveness and spatiotemporal scales. a, Schematic of plastic pollution life cycle and interventions at local (yellow), national (green) and global (blue) levels. **b**, Relationship and trade-offs of plastic pollution interventions across geographic scale of impact, time until impact and impact on the plastics life cycle. Local interventions are often fastest to implement, and their impacts can therefore occur on a shorter timescale that is more relevant for protection of vulnerable plastics-exposed species, whereas systemic or global interventions are slower to implement and slower to have an impact, but can potentially have broader ecosystem-level impacts. Part **b** adapted from ref. 233, CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Box 2 | Using bioindicators to monitor changes and assess risk

Bioindicators are a species or group of species that can be monitored or assessed to provide data on a specific ecosystem stressor, and they are increasingly recognized as critical tools for assessing the spread and impact of plastic pollution[222,250] as they offer an efficient approach that maximizes information gained with limited resources. Effective bioindicator species are relatively common, have a wide geographic distribution, and are of commercial or ecological importance[222,251]. Crucially, these species should also regularly interact with plastic, enabling researchers to assess risks to individuals and populations. Baseline assessments are required before monitoring can take place, if data on the species of interest are limited or non-existent.

Specifically, bioindicators can serve as useful proxies for threatened species, which are at increased risk of any stressor, including plastic pollution. These indirect data can be valuable to minimize the stress to rare and sensitive species caused by handling and sampling. Regardless of the conservation status of the sampled species, ethical considerations during sampling are paramount. Ideally, non-lethal sampling (for example, collection of scat, blood or regurgitated pellets, or seabird nest surveys) should be used. When non-lethal sampling is not viable, analysing existing data or using deceased animals (for example, individuals stranded, bycaught or harvested for human consumption) is preferred over killing individuals for the singular purpose of studying plastic ingestion. In all cases, replacement, reduction and refinement — the 'three Rs' of institutional animal care[252] — should be carefully considered. 'Replacement', in this case, might include substituting the study of rare species for more common proxies (that is, bioindicators) with similar ecological roles and life history traits[222].

Although plastic pollution bioindicators can be used to assess megaplastic and macroplastic via entanglement rates and nest incorporation[101,131], they have typically been used to track plastic incorporation in food webs via ingestion[222,250]. Examples include the monitoring programmes involving the northern fulmar (*Fulmarus glacialis*) that provide long-term records of mesoplastics in the North Sea and Arctic Oceans (for example, the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR)[253] and Canadian Environmental Sustainability Indicators (CESI) programmes). Ongoing research is slowly uncovering the mechanisms through which so many individuals and species consume plastic debris[3,28,32]. For example, plastic bags and sheeting can acoustically resemble cephalopod prey to echolocating toothed whales[28]. In situations such as these, species' preferences for specific debris types can serve as a powerful biological assay, revealing whether those items persist in the environment even when human surveys fail to detect them. Integrating this mechanistic work into risk assessments and bioindicator selection will refine our ability to evaluate species-specific vulnerabilities, aligning plastic exposure risks with the types of plastic most frequently ingested or encountered.

of plastics. Biodiversity impacts are often cited as a key motivation for addressing plastic pollution, but they are frequently absent from the evaluation metrics used to assess intervention success. This disconnect risks undermining efforts to protect ecosystems and species most vulnerable to plastic exposure. At the global level, multilateral environmental agreements such as the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex V, the Basel Convention and the London Convention address several aspects of plastic pollution at different stages of the plastic life cycle (Table 1). Although these agreements have contributed to the gradual reduction in marine litter in some jurisdictions[207], compliance challenges exist in other jurisdictions[208]. One key weakness of these agreements is the absence of targets and indicators to track progress towards reducing the environmental and ecological impacts of plastic pollution at the global level[207–209].

The global plastic policy landscape is generally fragmented and uncoordinated at regional, national and even subnational levels. Many countries across the globe have introduced national and subnational plastic policies in the form of complete and partial bans, levies, taxes, extended producer responsibility schemes, end-of-life-cycle management, and education and/or outreach strategies[210]. These policies have been implemented with varying levels of success in different regions. Voluntary agreements have also gained popularity over the past decade, as businesses representing nearly 20% of global plastic packaging have signed on to agreements to reduce plastics in the design of their products, and they have provided incentives that encourage reusable products. The most extensive voluntary agreement, the 2018 New Plastics Economy Global Commitment, showed that these voluntary agreements can be effective and complementary to other policy interventions in achieving plastic pollution reduction (Table 1). Education and behaviour change campaigns, both legislative and voluntary, have also had some degree of positive effect on plastic consumption[211–213].

The efficacy of various policy interventions in reducing biodiversity impacts is not well documented. Research evaluating the effectiveness of plastic policies largely focus on reductions in consumption and in quantities released into the environment[212,214], rather than on biodiversity impacts. Scenarios or models developed to predict the impacts of plastic waste management strategies also focus mainly on quantities released into the environment. The interventions modelled are global and systemic, and project overall pollution reduction[215–218]. Introducing interventions that could be effectively implemented at the global scale to reduce impacts at the species or ecological level might be slow[207]. This challenge is particularly acute for species that are long-distance migrants and have annual ranges that cover entire ocean basins (such as some seabird and shark species), as only a global reduction in plastic pollution will decrease their exposure. Again, existing geographical disparities in the urgency of interventions required for already at-risk species within national jurisdictions will probably require local solutions, which could be most effective at reducing the impact on affected organisms and ecosystems (Fig. 3). For example, locally deployed bioswales could substantially reduce the near-term impact of tyre wear particles and associated chemicals on fish found in coastal waters[219,220]. The highly transient nature of plastics once in the environment requires local and global interventions to protect biodiversity in the long term.

In addition to the focus of research and models on pollution reduction metrics such as decreases in plastic production, consumption or leakage[215–218], long-term monitoring frameworks that assess the effectiveness of specific interventions in terms of biodiversity and ecosystem health are severely lacking (Box 2). Although limited, two investigations in 2024 and 2025 quantified how targeted interventions directly affect local biodiversity[173,221], highlighting the potential of well-designed interventions to have tangible ecosystem benefits and the need for increased monitoring of these impacts. The study published in 2025 used a novel approach to link policy interventions on plastic bags, either bans or fees, to measurable reductions in shoreline litter and entanglement risk using extensive citizen-science data and conditional logit modelling[221]. The study published in 2024, using four decades of data, found that marine debris removal in the Northwestern Hawaiian Islands helped to stabilize the declining Hawaiian monk seal population, and population benefits were directly attributed to clean-up efforts[173]. Beyond these limited examples, a critical gap remains that limits our understanding of how interventions translate into ecological benefits, hindering adaptive management. Looking ahead, a combination of global and local actions is essential. Systemic, international interventions are necessary to reduce overall plastic pollution entering the environment over the long term. However, to protect specific species and ecosystems facing acute plastic-related threats, global efforts must be complemented by local-scale tailored measures. Importantly, future strategies, including those emerging from the UN Global Plastics Treaty, should integrate robust monitoring systems including bioindicators (Box 2) that track both pollution and ecologically relevant metrics for biodiversity. These systems will provide crucial data for refining interventions and directing funding to the most effective, context-specific solutions.

Summary and future directions

Plastic pollution threatens biodiversity through multifaceted routes (Fig. 1), and thousands of reported cases — largely involving ingestion and entanglement (Figs. 2 and 3) — now exist of plastic interactions spanning diverse taxa and ecosystems. Although individual-level effects, particularly from macroplastics, are increasingly well-documented, population-level consequences remain uncertain in most cases owing to limited long-term monitoring[222] and insufficient integration of plastic-related mortality into demographic analyses and assessments (Fig. 4). However, some of the first examples of population-level and species-level effects are beginning to emerge[137,173,195]. Microplastics, despite their widespread presence, show no clear population-level impacts in wild species to date (Fig. 4). Connecting microplastic exposure to biodiversity outcomes will require mechanistic insight into how sublethal effects might scale beyond individuals. Controlled experiments are beginning to identify where such signals can emerge in nature; for example, altered fish schooling behaviour following ingestion of microplastics that leach specific additives[223]. At the submicrometre scale, widespread exposure and potential impacts of nanoplastics in biological systems remain little understood. Newly developed technologies (such as atomic force microscopy–infrared spectroscopy and optical photothermal infrared spectroscopy) and reductions in cost and sample processing effort of well-established technologies (such as micro-Fourier-transform infrared spectroscopy, Raman spectroscopy, pyrolysis-GC/MS) will lead to breakthroughs in our understanding of the effects of small MNPs (≤50 µm) in the coming years.

Future research must address the outstanding knowledge gaps of plastic pollution on biodiversity through several main pathways. To begin with, long-term studies that couple robust demographic data (for example, survival, reproduction and recruitment) with quantifiable plastic exposure metrics are sorely needed. For microplastics specifically, an urgent need exists to develop scalable and high-throughput analytical tools. The ongoing revolution in artificial intelligence could dramatically improve sample site selection,

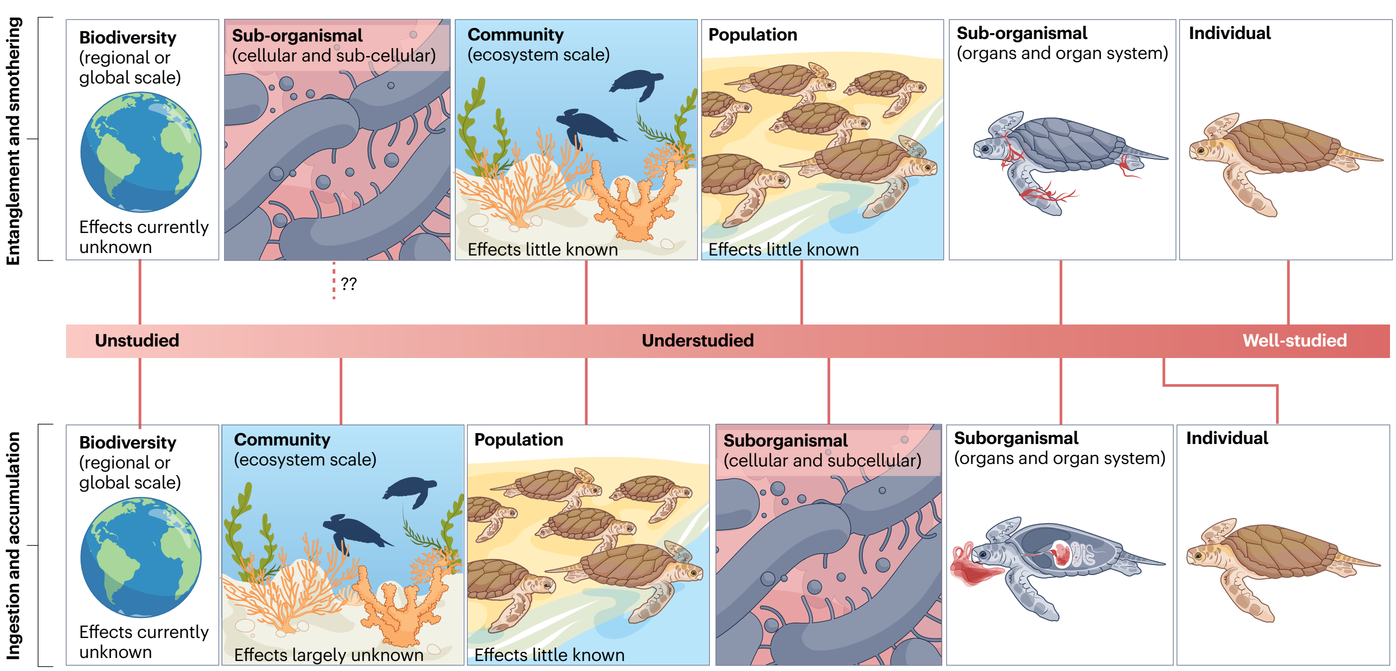

Fig. 4 | Scientific knowledge of plastic pollution effects across levels of biological organization. The majority of available evidence shows strong effects at the individual level from both ingestion and entanglement, and evidence becomes increasingly sparse moving up levels of biological organization. Whether or how effects of entanglement at the microscopic level occur remains unclear.

processing and meta-analyses in microplastic research[224–226]. Environmental metabolomics, transcriptomics and microbiome profiling offer promising avenues for assessing subtle physiological disruptions[24], particularly in sentinel species. However, these approaches must be grounded in ecologically relevant exposures and complemented by studies in natural systems with multiple stressors. The emerging field of plastic-source attribution using forensic chemical profiling should be expanded to inform targeted interventions on the most concerning products and sectors (single-use, non-critical, additive-replete items).

These approaches align with a One Health perspective, emphasizing that plastic pollution represents a shared risk to ecosystem integrity, wildlife health and human well-being through interconnected exposure pathways. Impacts on biodiversity therefore have direct relevance for food webs, ecosystem services and downstream human health, reinforcing the need for integrated solutions that span environmental, ecological and public-health domains. To guide effective mitigation, future work should account for context-specific vulnerabilities across ecosystems and taxa. A one-size-fits-all approach is unlikely to succeed. For example, in the deep sea, preventing gear loss and other plastic inputs might be most impactful. In coastal systems, by comparison, spatially explicit mitigation (such as clean-ups) might be warranted, especially for species at risk and critically important ecosystems. The impacts of plastic pollution should not be seen as a distraction from other global threats such as climate change[227,228]. Rather, climate change and plastic pollution are deeply interconnected, through shared sources (fossil fuel dependence), synergistic impacts[229,230] and overlapping solutions[228]. The ability of plastic pollution to galvanize public attention should be used as an opportunity to build integrated, biodiversity-positive policies to address these pressing global issues.

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Author contributions
M.S.S. led the writing of the first draft with contributions from all authors. E.L.M., C.D. and R.G.S. compiled the data used to create Figs. 2 and 3. M.S.S., E.L.M., A.M.B. and L.M.T.H. conceived and drafted the figures. All authors reviewed and edited the manuscript before submission.

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The authors declare no competing interests.

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International legally binding instrument to end plastic pollution: https://www.unep.org/inc-plastic-pollution
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Packaging and Packaging Waste Regulation: https://eur-lex.europa.eu/eli/reg/2025/40/oj/eng
The EU Single-Use Plastics Directive: https://environment.ec.europa.eu/topics/plastics/single-use-plastics_en
The Global Commitment: https://www.unep.org/new-plastics-economy-global-commitment
The Marine Strategy Framework Directive: https://environment.ec.europa.eu/topics/marine-environment/implementation-marine-strategy-framework-directive_en
The Ocean Plastics Charter: https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/international-commitments/ocean-plastics-charter.html
Toxicity of Microplastics Explorer: https://sccwrp.shinyapps.io/aq_mp_tox_shiny/
UN Regional Sea Conventions: https://www.unep.org/topics/ocean-seas-and-coasts/regional-seas-programme

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