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OPINION

Addressing chemical pollution in biodiversity research

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Abstract

Climate change, biodiversity loss, and chemical pollution are planetary-scale emergencies requiring urgent mitigation actions. As these "triple crises" are deeply interlinked, they need to be tackled in an integrative manner. However, while climate change and biodiversity are often studied together, chemical pollution as a global change factor contributing to worldwide biodiversity loss has received much less attention in biodiversity research so far. Here, we review evidence showing that the multifaceted effects of anthropogenic chemicals in the environment are posing a growing threat to biodiversity and ecosystems. Therefore, failure to account for pollution effects may significantly undermine the success of biodiversity protection efforts. We argue that progress in understanding and counteracting the negative impact of chemical pollution on biodiversity requires collective efforts of scientists from different disciplines, including but not limited to ecology, ecotoxicology, and environmental chemistry. Importantly, recent developments in these fields have now enabled comprehensive studies that could efficiently address the manifold interactions between chemicals and ecosystems. Based on their experience with intricate studies of biodiversity, ecologists are well equipped to embrace the additional challenge of chemical complexity through interdisciplinary collaborations. This offers a unique opportunity to jointly advance a seminal frontier in pollution ecology and facilitate the development of innovative solutions for environmental protection.

KEYWORDS
biodiversity loss, chemical pollution, combined stressor, ecology, ecotoxicology

1 | INTRODUCTION

Environmental change threatens biodiversity worldwide. Five major drivers of biodiversity loss have been recognized which are (i) habitat destruction, also referred to as land/sea-use change (e.g., deforestation for agricultural purposes), (ii) overexploitation of natural resources (e.g., overfishing), (iii) climate change (e.g., changes in temperature, rainfall, and extreme weather events), (iv) invasive alien species including new pathogens, and (v) pollution (EC, 2020; IPBES, 2019; MEA, 2005). Traditionally, ecologists have focused on the first four drivers, while chemical pollution has been addressed mainly with regard to eutrophication (i.e., overfertilization with nitrogen and phosphorus) and occasionally the toxicity caused by a few selected classes of chemicals, most notably pesticides and some metal(loid)s (Groh et al., 2022). Similarly, to date, the ecology community has given minimal attention to chemical pollution as a global change factor (Bernhardt et al., 2017). However, since the "triple crises" of climate change, biodiversity loss, and an increasingly toxified natural environment are deeply interlinked (Baste & Watson, 2022; Secretariats of the BRS and MC, 2021a), they should not be addressed in isolation but rather need to be researched and acted upon from an integrated perspective. Here, we focus specifically on exploring the connections between biodiversity and anthropogenic chemical pollution.

Attaining progress in counteracting the negative impact of chemical pollution on biodiversity requires that the totality of anthropogenic chemicals in the environment be addressed through the collective efforts of scientists from different disciplines, including but not limited to ecology, ecotoxicology, and environmental chemistry (Groh et al., 2022; Sigmund, Ågerstrand, et al., 2022). Crucially, recent methodological and conceptual developments in these fields have now opened up the possibility of comprehensively tackling this complex problem, thus presenting an opportunity to advance a seminal frontier in pollution ecology. Here, we briefly explain how the multitude of anthropogenic chemicals and their multifaceted effects in the environment pose a growing threat to biodiversity and ecosystems and discuss possibilities for addressing chemical pollution in ecological research on biodiversity loss. Finally, we sketch ways forward for improving interdisciplinary collaborations that could enable formative solutions for environmental protection.

2 | A MULTITUDE OF ANTHROPOGENIC CHEMICALS

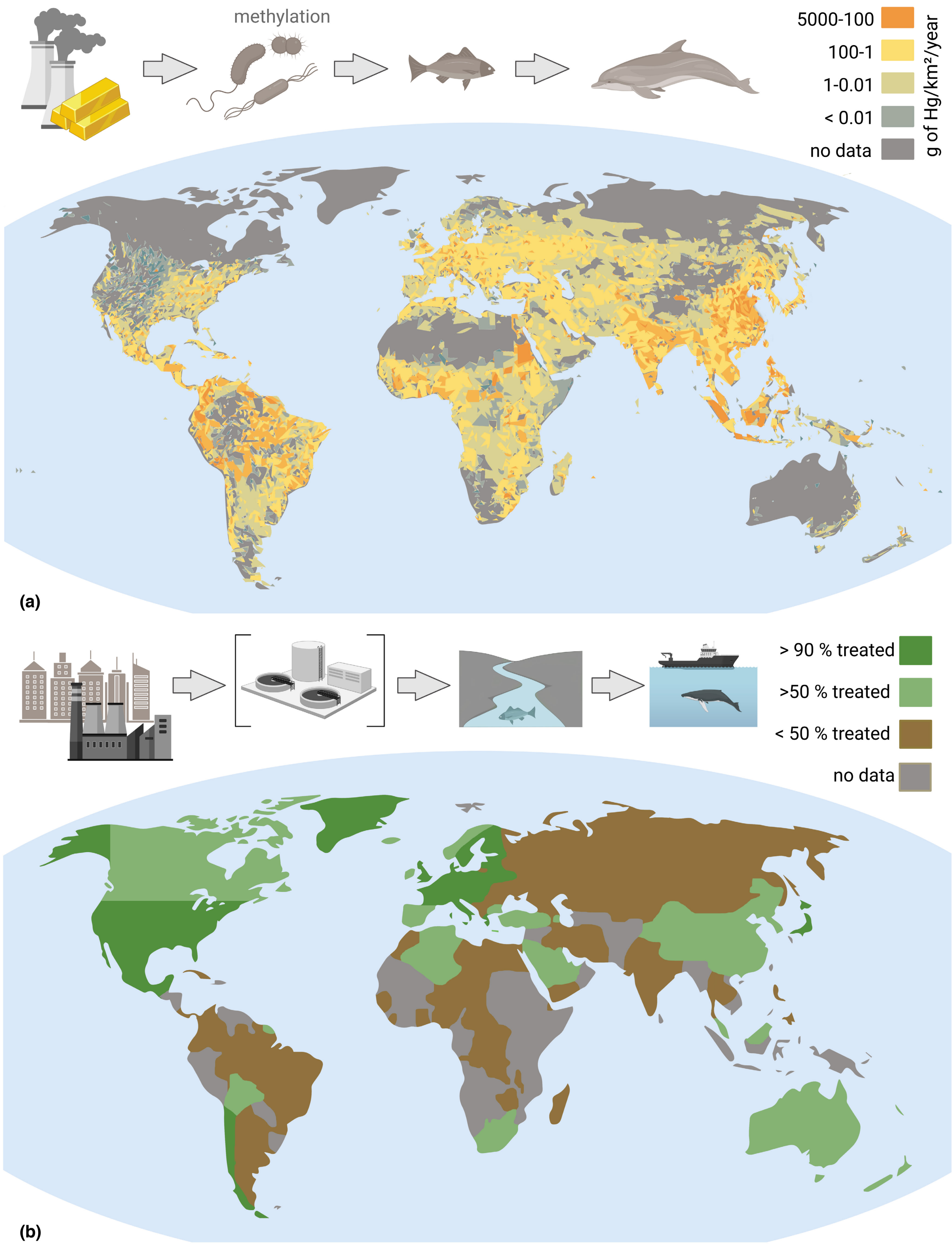
Chemical pollution can have profound and far-reaching effects on biodiversity and ecosystem health (Bernhardt et al., 2017; Groh et al., 2022; Rillig et al., 2019; Secretariats of the BRS and MC, 2021a, 2021b). Among the five major drivers of biodiversity loss, the greatest pressure is currently exerted by habitat destruction, whereas contributions from other drivers have been estimated to be 3–4 times lower but nonetheless substantial (Sánchez-Bayo & Wyckhuys, 2019). For example, more than 11,500 out of 83,669 assessed animal species are considered to be impacted by pollution in the latest compilation of the Red List led by the International Union for Conservation of Nature (IUCN, 2022). Another study estimated that from the 20,784 species for which detailed Red List data were available, pollution threatened 18.2%, while habitat destruction, overexploitation, invasive species, and climate change impacted 88.3%, 26.6%, 25%, and 16.8% of these species, respectively; for 4.7% of species, pollution was the main threat (Hogue & Breon, 2022). Most recently, pollution ranked third among the five drivers, based on empirical comparisons of driver impacts documented through a comprehensive review (Jaureguiberry et al., 2022). Additional quantitative evidence has been delivered by investigations looking at specific ecosystems. For example, in lowland streams in Germany, pesticides were found to be the dominant stressors for vulnerable insects (Liess et al., 2021). However, disentangling pollution impacts in a fully comprehensive and quantitative manner from the contributions by other factors remains a challenging and resource-intensive task, especially in complex ecosystems (Stubbington et al., 2022; Weitere et al., 2021). Due to these difficulties, detailed quantitative studies are still rare and, thus, remain a future research need. Another limitation stems from the narrow scope of pollutants considered in most of the assessments available to date, with gross nutrients and pesticides receiving the most attention despite a well-documented environmental presence of a much wider variety of harmful anthropogenic chemicals. Consequently, the impacts of pollution on biodiversity and ecosystem health could have been underestimated.

Indeed, by 2022 over 350,000 chemicals and mixtures of chemicals had been registered for commercial use worldwide, with even more new chemicals expected to appear in the future (Wang et al., 2020). Some modern chemicals may exhibit increased toxicity for particular groups of plants or invertebrates (Schulz et al., 2021). Persson et al. (2022) summarized that global chemical production has increased 50-fold since the 1950s, with an anticipated tripling by 2050 compared with 2010. Consequently, chemical monitoring studies worldwide routinely find dozens or even hundreds of anthropogenic chemicals in every environmental compartment studied, noting the dearth of data from Global South countries (Posthuma, van Gils, et al., 2019; Wilkinson et al., 2022). Chemicals that contaminate the environment typically occur in mixtures and can include, for example, metal(loid)s and organometal(loid) compounds such as chromated arsenicals, tributyltin, and methylmercury; organic substances currently or previously used in pesticides, pharmaceuticals, consumer products or industrial applications, including solvents, per- and polyfluoroalkyl substances (PFASs), polychlorinated biphenyls (PCBs), plastic additives, as well as substances of unknown or variable composition, complex reaction products or biological materials (UVCBs), such as petroleum oil or essential oils (Lai et al., 2022; Persson et al., 2022; Wang et al., 2021). In line with recommendations elicited by the academic community (Mueller et al., 2023), the need to tackle not only pesticides but also other hazardous chemicals when developing biodiversity protection measures has been recently agreed upon in the post-2020 global biodiversity framework (COP15, 2022).

Anthropogenic chemicals present in the environment can stem from a myriad of sources, ranging from the intentional application of pesticides in agriculture to emissions of chemicals from mining and manufacturing sites, to fugitive releases of chemicals from consumer products during manufacturing, use, and disposal, and to incidentally occurring, highly concentrated chemical plumes from industrial accidents or spills. As shown in Figure 1, the sites of original releases and with them the initial rates of environmental contamination can vary greatly depending on the geographical location. This variation may stem from the differences in the primary location of industrial operations, such as mining sites in the case of mercury (Figure 1a), but may also reflect the differences in resources available for proper chemical management, as illustrated in the example of the global prevalence of wastewater treatment facilities (Figure 1b). Biodiversity in mid- and low-income countries may suffer from higher pollution pressure compared with high-income countries, because of inequalities in capacity and resources. This, however, is not always the case. For example, a recent modelling study based on the Red List data showed that in the tropical regions, biodiversity pressures such as agriculture, hunting, and logging were more pronounced than pollution, whereas Europe was identified as a hotspot for pollution-induced loss of amphibian and mammalian biodiversity (Harfoot et al., 2021).

Since many chemicals are widely and diffusely distributed once released, they can become ubiquitous in the environment over time, as is illustrated by the global occurrence of, for example, pesticides (Silva et al., 2019), pharmaceuticals (Wilkinson et al., 2022), PFASs (Kurwadkar et al., 2022), PCBs (Jamieson et al., 2017), or chemicals associated with (micro)plastics, fibers, and tire wear particles (Tuuri & Leterme, 2023; van Sebille et al., 2015). As a result, the Earth is now devoid of "pristine" ecosystems unaffected by anthropogenic chemicals. Therefore, any work on pollution ecology needs to recognize that ambient levels of chemical pollution are never zero but rather a baseline stressor that needs to be accounted for in any and all ecosystems. Ecologists need to reckon with this ubiquity of pollution when designing studies to understand and explain stressor- or global

FIGURE 1 Geographical differences in chemical releases across the globe, shown for the example of mercury and wastewater effluents. Panel (a) Artisanal gold mining and coal burning are the most important anthropogenic sources of mercury (Hg) emissions, which are then atmospherically distributed. Subsequently, microorganisms can transform elemental mercury into methylated Hg, which is highly toxic. The figure shows anthropogenic Hg emissions in 2015, as quantified on a global scale by members of the Minamata Convention and compiled in the 2018 mercury assessment report by the UN Environment Programme (UNEP, 2018). Panel (b) Wastewater treatment facilities are a crucial component of modern chemical management as they allow for reducing nutrient loads and micropollutant contamination of surface water, and, consequentially oceans. The proportion of wastewater that is being treated before being released into the environment widely differs between different countries, as demonstrated by the values taken from the 2021 report by the United Nations Human Settlements Programme (UN-Habitat) and World Health Organization (UN-Habitat and WHO, 2021).


methylation
5000-100
100-1
1-0.01
< 0.01
no data
g of Hg/km²/year
(a)
> 90 % treated
>50 % treated
< 50 % treated
no data
(b)

change-affected processes in the environment (Rillig et al., 2022). In doing so, they could be helped by knowledge and methods developed by ecotoxicologists and environmental chemists, as we will explore later.

3 | MULTIFACETED ECOLOGICAL IMPACTS OF CHEMICALS

Ecosystems are affected by chemical pollution via a multitude of direct impacts on exposed organisms, manifesting either as overt toxicity or as more subtle, non-lethal effects, as well as a variety of indirect influences, such as changes in species interactions, trophic chains, or abiotic factors (see below and examples in Figure 2a–d). Both direct and indirect impacts of pollutants can have negative consequences for biodiversity and ecosystem health (Köhler & Triebskorn, 2013). Currently, environmental assessment of chemicals focusses almost exclusively on three standardized and directly observable toxicity endpoints—survival, growth, and reproduction of individual organisms—selected for being closely linked to population trajectories and, hence, considered ecologically relevant. Indeed, many environmental pollutants are known or suspected to cause strong effects on these endpoints. For example, pesticide application can cause acute mortality in sensitive species (Berny, 2007; Grilo et al., 2020), while endocrine-disrupting chemicals can affect reproduction not only in humans but also in wildlife (Bernanke & Köhler, 2009; Marlatt et al., 2022).

However, besides the acute toxicity manifestations, subtle non-lethal effects, such as developmental malformations, physiological alterations, or behavioural changes may also exert significant impacts on both an individual's and the whole population's fitness in the natural environment (Brodin et al., 2014; Ford et al., 2021). As an example, exposure of European perch to a psychoactive antidepressant was shown to increase their overall activity, causing a higher predation risk (Brodin et al., 2013). In juvenile Coho salmon, low levels of copper also increased the fish's vulnerability to predators, but via a different mechanism, namely by decreasing its ability to detect and respond to chemosensory cues indicating predator presence (McIntyre et al., 2012). Zebrafish larvae were shown to smell the presence of certain insecticides in water and actively avoid contaminated areas, raising the question of whether chemicals can affect fish migratory behaviour as a result (Könemann et al., 2021). Similar effects can be expected to unfold in other animal species as well.

Furthermore, even in the cases where chemical exposure does not cause any visible effects on exposed organisms, energetic costs inflicted by chemical pressure may still need to be considered (Hamilton et al., 2017). That is, an organism that needs to expend a part of its resources to counteract chronic chemical exposure may not have enough resources to invest in other needs, most notably reproduction, which might decrease population viability over time (De Coen & Janssen, 2003). Lastly, the development of tolerance as a selective adaptation to chemical pressure may lead to a decrease in genetic and phenotypic diversity, and consequently, a reduced ability to withstand other types of stressors encountered in the future (Abdullahi et al., 2022).

Indirect impacts of pollutants, that is, impacts in the absence of direct chemical effects on the organism of interest, may only become visible in a certain ecological context, as they depend on specific interactions between different groups of organisms within and across species or trophic levels. For example, pollutants can change the trophic base for some organisms (Gessner & Tlili, 2016; Yamamuro et al., 2019) or disrupt social behaviours within an animal group (Michelangeli et al., 2022). In the two examples discussed above, where pollutants directly affected fish behaviour, and these behavioural alterations resulted in an increased predation risk for fish (Brodin et al., 2013; McIntyre et al., 2012), the co-occurrence of predators would be a necessary prerequisite for these direct effects of toxicants to manifest as adverse impacts. The end outcome, in this case, would thus depend on the interplay between direct and indirect influences, involving both the direct effect (behavioural alteration) and indirect effect (change in species interaction). Differential sensitivity of prey and predator species to toxicants is also a common phenomenon that can indirectly affect species dynamics across food webs and lead to changes in community structure (Hébert et al., 2021; Prosnier et al., 2015). Indirect effects of pollutants can also unfold through alterations in environmental microbiomes, as has been shown, for example, in the case of glyphosate (van Bruggen et al., 2021).

Of particular concern is the persistence of pollutants in the environment (Cousins, Ng, et al., 2019; Schaeffer et al., 2022). For example, PFASs remain in the environment for at least centuries after their initial emission, a property for which they are often referred to as "forever chemicals" (Cousins et al., 2022). Examples of other highly persistent organic chemicals include PCBs, halogenated dioxins, and a suite of first-generation synthetic insecticides, such as dichloro-diphenyl-trichloroethane (DDT) and lindane (Nizzetto et al., 2010). The use and release of such chemicals result in their global distribution (e.g., via long-range atmospheric transport), and a continuous increase of environmental concentrations of these substances, even in "pristine" ecosystems such as Arctic, Antarctic or high altitudes. As a consequence, any adverse impacts occurring on living organisms can be difficult, if not impossible, to reverse (Cousins et al., 2022; Wang et al., 2017). Many of these chemicals bioaccumulate, which means they tend to concentrate in living organisms compared with their surrounding environments such as water, soil, sediment, or air. Such chemicals can also be biomagnified within trophic chains, with top predators typically exhibiting the highest accumulated levels (Boisvert et al., 2019; McKinney et al., 2012). While some effects of these chemicals are already known (Desforges et al., 2018), other modes of impact and their consequences could yet be unknown. Such effects may manifest only after long-term exposure in the future, thus precluding the reliable estimation of these chemicals' risks based on currently available knowledge (Cousins, Ng, et al., 2019). For these reasons, several groups of highly persistent, bioaccumulative, and toxic (PBT) organic chemicals have been banned worldwide, notably under the Stockholm Convention on Persistent Organic Pollutants (POPs; Nizzetto et al., 2010). However, due to implementation

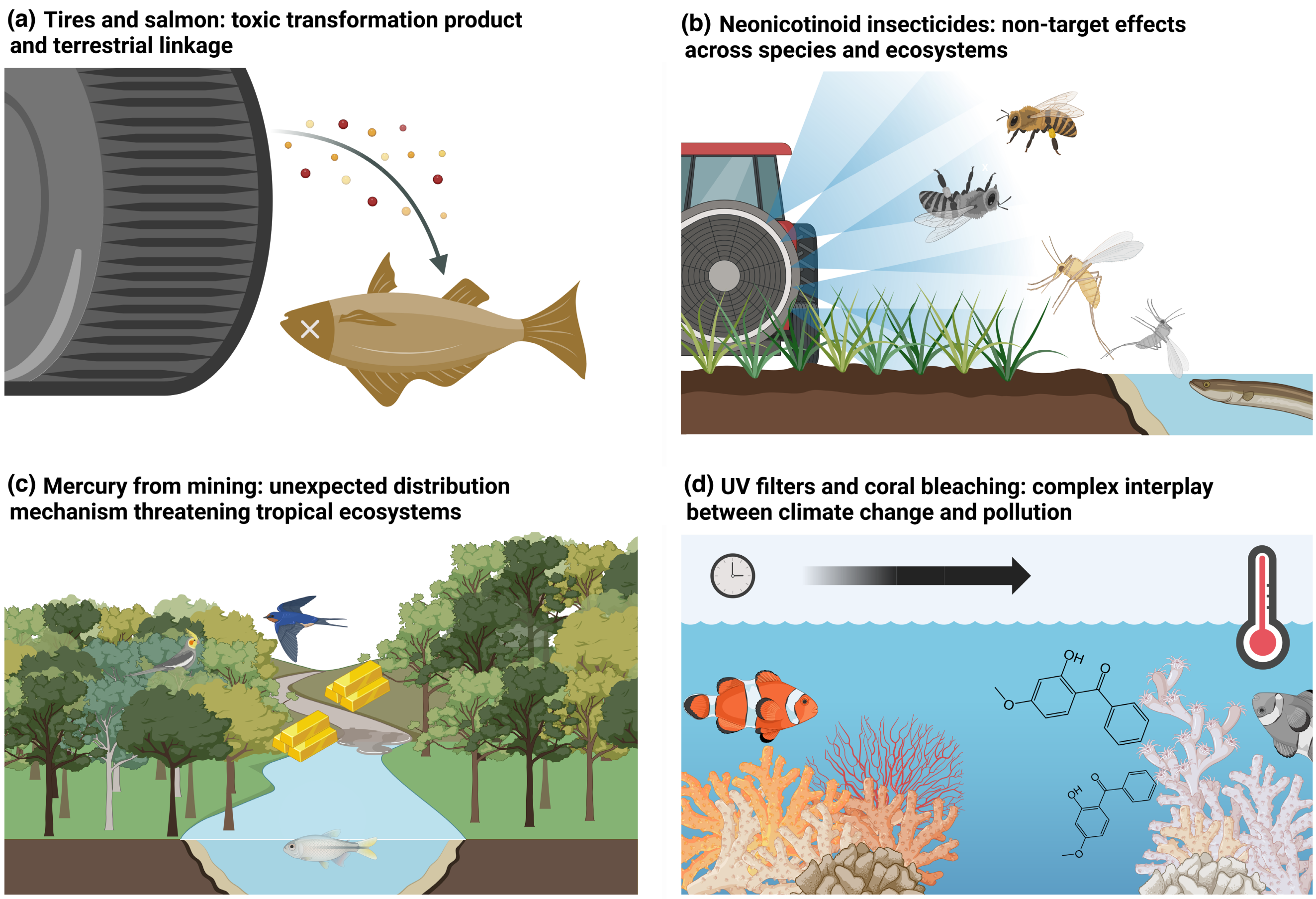


FIGURE 2 Examples of complex chemical impacts that were uncovered by interdisciplinary collaborations. Panel (a) In 2021, after spending over a decade investigating the high acute mortality of a particular salmon species, Pacific Northwest coho salmon, in urban creeks, researchers found that a globally ubiquitous tire rubber additive used as an antioxidant to decrease tire ageing can form a transformation product which is highly toxic to this species (Tian et al., 2021). Their discovery established a long-overlooked link coupling tire wear from terrestrial sources to effects in aquatic systems. Recently, researchers have also established a link between leachable tire wear additives and changes in microbial communities in coastal sediments (Ding et al., 2022), suggesting that tire wear additives can cause adverse effects for a wide range of taxa. Panel (b) Broad-spectrum neonicotinoid pesticides are still widely used in many countries worldwide (Klingelhöfer et al., 2022). They act by blocking synaptic transmission through interacting with nicotinic acetylcholine receptors (Main et al., 2018). While cases of acute poisoning are rare, exposure to low concentrations is of concern because of chronic sublethal effects and potential synergistic effects with other stressors (Hladik et al., 2018; Simon-Delso et al., 2015). Extensive adverse impacts on multiple non-target species have been documented, including not only honeybees but also many other non-target invertebrates in both terrestrial (Main et al., 2018; Pisa et al., 2015) and aquatic (Bartlett et al., 2018; Stepanian et al., 2020; Yamamuro et al., 2019) ecosystems. Massive declines in zooplankton were shown to disrupt food webs and, thus, lead to a reduction of fish populations as well (Yamamuro et al., 2019). Panel (c) Alluvial gold mining has caused mercury contamination hotspots in tropical ecosystems in South America (Asner & Tupayachi, 2016; Gerson et al., 2022) and South-East Asia (Yule et al., 2010), due to the tropical forests' exceptionally high capacity to accumulate mercury through air, leading to subsequent soil and water contamination via foliage exchange (Gerson et al., 2022; Teixeira et al., 2018). Because of its high biomagnification capacity, Hg concentrations tend to increase in organism at higher tropic levels (e.g., fish and birds). Mercury bioaccumulation in fish can be further worsened by forest fires which cause changes in the food web (Kelly et al., 2006). Mercury, especially after microbial methylation, is a neurotoxicant known to affect motor abilities and reproduction (Driscoll et al., 2013; Evers et al., 2008). By influencing top predators, it causes drastic deterioration of regional food webs (Bisi et al., 2012). Panel (d) Coral bleaching has been linked not only to increasing temperatures and ocean acidification (Ateweberhan et al., 2013; Hoegh-Guldberg et al., 2017) but also to oxybenzone, a UV filter chemical that is still widely used in sunscreen but is being banned in an increasing number of countries (Downs et al., 2022). Herbicides (Flores et al., 2021), nutrients (Donovan et al., 2020) and other chemicals can also contribute to coral bleaching (Ouédraogo et al., 2020). As climate change-related stressors and toxic chemical pressure jointly cause bleaching in the natural environment, their contributions need to be considered jointly when designing strategies to mitigate coral bleaching (Ouédraogo et al., 2020; Watkins & Sallach, 2021; Wear & Thurber, 2015).

difficulties and multiple exemptions under the convention, as well as their inherent persistence, POPs remain present in most ecosystems worldwide as legacy pollutants (Bogdal et al., 2013). Note that metals and metalloids are persistent and can also bioaccumulate and biomagnify (Córdoba-Tovar et al., 2022) as illustrated by mercury example in Figure 2c.

The challenge of managing the unexpected impacts of chemicals on non-target species, exposed through food chains or by other means, can also arise for non-persistent but continuously used chemicals, also referred to as "pseudo-persistent" substances. For example, the widespread use of the anti-inflammatory drug, diclofenac, for livestock has caused a near-extinction of vultures in the Indian subcontinent. Vultures turned out to be very sensitive to diclofenac and died *en masse* due to renal failure developed after receiving even small doses of the compound from feeding on carcasses of diclofenac-treated cattle (Green et al., 2004). The loss of vultures, in turn, leads to cascading effects such as an uncontrolled increase in insect populations and disease spread (Buechley & Şekercioğlu, 2016; Ogada et al., 2012). While vulture populations in India have been recovering following the ban on diclofenac, similar effects have begun unfolding in Europe where diclofenac has been approved for veterinary purposes since 2013 (Moreno-Opo et al., 2021). Additionally, diclofenac can also disturb aquatic ecosystems, with toxic effects documented for macrophytes, mussels, and fish (Joachim et al., 2021).

The impacts of chemicals can also be affected by non-chemical abiotic factors within a given ecosystem; thus, abiotic components such as temperature or pH of an exposed ecosystem can contribute to shaping the ecological consequences of chemical pollution (Rillig et al., 2021). On the one hand, they can influence the fate and behaviour of the chemicals involved (Cerveny et al., 2021). For example, high levels of UV radiation and elevated temperatures are known to decrease the stability of many chemicals by enhancing abiotic and biotic degradation (Schwarzenbach et al., 2002). Differences in pH affect the distribution behaviour and bioaccumulation of ionisable organic pollutants (Sigmund, Arp, et al., 2022) as well as the speciation and bioavailability of (organo)metall(oids) (Caporale & Violante, 2016). On the other hand, such abiotic factors are often stressors in and of themselves, especially for organisms that live on the edge of their distribution range, and thus, the combination of chemical pollution and other abiotic influences could result in drastic deterioration of an entire habitat (Zandalinas et al., 2021). Consequently, population vulnerability, community stability and ecosystem resilience under chemical pressure can vary depending not only on the types of chemicals but also on the characteristics of a particular ecosystem, including species composition, environmental conditions, and accompanying combinations of other stressors (Figure 3).

Chemical pollution can cause a decline in populations of various exposed species, or even an extinction of particularly sensitive species, and thus lead to a change in the structure and possibly functions of communities and whole ecosystems. Pollution acts via a multitude of pathways and mechanisms, which can unfold in a highly ecosystem-specific manner (Saaristo et al., 2019). Unfortunately, both the prospective and retrospective assessments of environmental risks of chemicals often fail to reflect this diversity of ecological contexts. In a prospective assessment, in-silico models, standardized laboratory tests and well-controlled field trials are used before a known chemical, such as a pesticide, is introduced into the environment. This is expected to allow for a reliable prediction of a chemical's environmental behaviour and resulting exposures and effects (Boivin & Poulsen, 2017). Standard tests for prospective assessments of risk

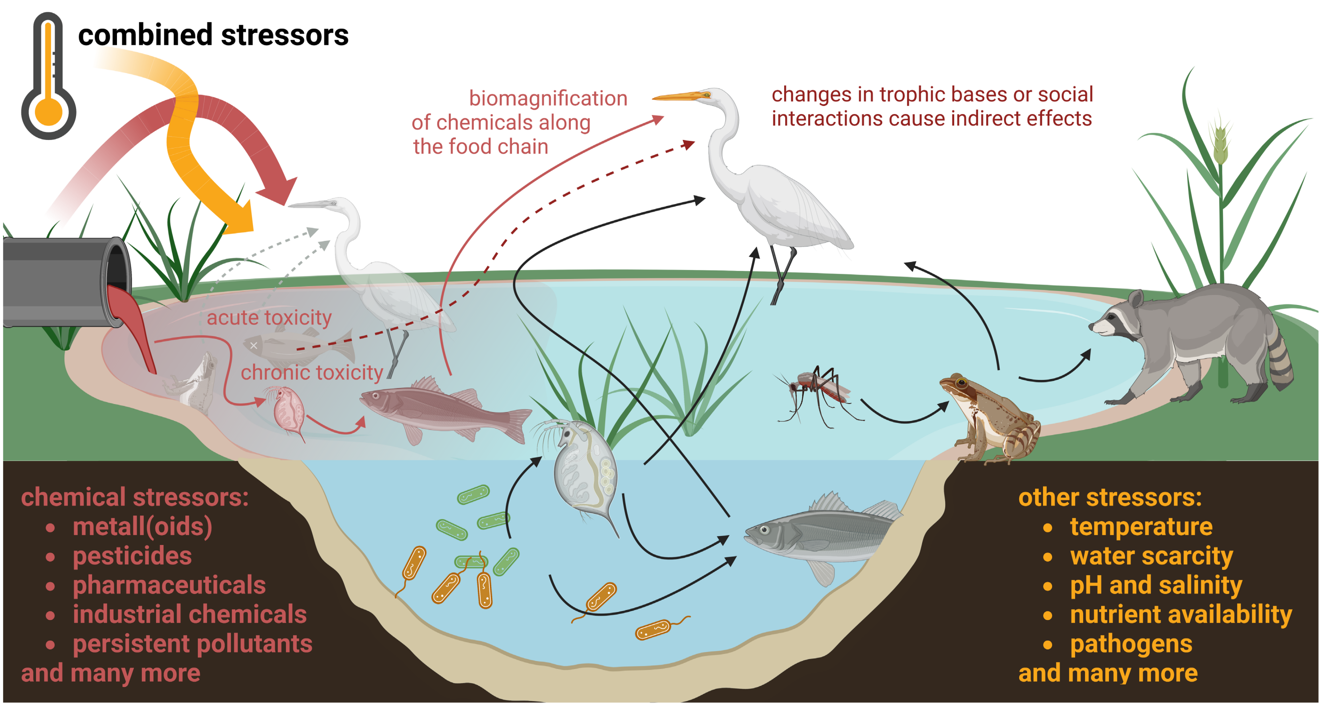


FIGURE 3 Combined effects of chemicals and other stressors on food webs. Chemicals can change existing food chains, be biomagnified via these same food chains and lead to direct toxic effects as well as indirect effects, for example, by affecting community interactions. Exposure to combined stressors (multi-stressors) such as chemical pollution and temperature can cause effects that can differ from those of a single stressor.

are, however, commonly performed with just a few species, which may not be sufficiently protective for the multitude of species present in the environment. Moreover, because of time and resource considerations, such assessments often focus on acute effects and individual chemicals. This gives only a poor reflection of the situation in the field, typically characterized by mixture exposures to low concentrations of chemicals over longer time periods. Retrospective assessments commonly focus on a few selected ecosystems to which known and/or unknown chemicals are expected to have been introduced previously. Their ecological status can be typically evaluated by combining chemical analysis and monitoring of standardized indicator species, as is done for example in the European Water Framework Directive (Posthuma, van Gils, et al., 2019). To date, ecosystems in mid- and low-income regions have been underrepresented in such analyses. Based on our discussion above and examples in Figure 2, currently applied approaches should be extended to enable better prediction of multi-species effects and chronic exposure outcomes. They should also consider the landscape context and ecological setting in which chemical pollution takes place, as a basis for providing adequate, solution-oriented options for environmental managers and policy makers (Schäfer et al., 2019). Importantly, extensive testing and implementation of appropriate control measures at present are mostly happening in high-income countries, and as a result, many of the standardized testing methodologies have been optimized to suit Northern ecosystems in particular. This again highlights the issue of resource inequality, which may have dire consequences for numerous hotspots of biodiversity located in the mid- and low-income countries.

4 | A SCIENTIFIC FIELD RIPE FOR DISCOVERY

Clearly, chemical pollution is an important factor exacerbating biodiversity loss worldwide. In line with that, in 2017 Bernhardt et al (2017) argued that ecologists need to recognize anthropogenic chemical pollution as a global change factor, next to CO_2 levels, temperature, and changes in water cycling, because (persistent) chemical pollutants will become distributed on a global scale. Notably, the diversity and quantity of chemical pollution are increasing at higher rates than other drivers of global change (Persson et al., 2022; Wang et al., 2020). Despite these trends, the fraction of pollution-focused ecology papers has remained very small compared with papers addressing other drivers of biodiversity loss and/or global change, as shown in our analysis of publications from the past 5 years (Figure 4).

One reason for the limited attention given to chemical pollution in the global change discourse may be that chemical pollution encompasses a wide variety of complex stressors that cannot be easily summarized by a single "one-for-all" parameter or endpoint, which is the case for other factors of global change such as global mean temperature or atmospheric carbon. The study of biodiversity loss, however, relies on a complex array of measures and metrics, thus suggesting that the biodiversity research community is ready for the challenge of chemical complexity as well.

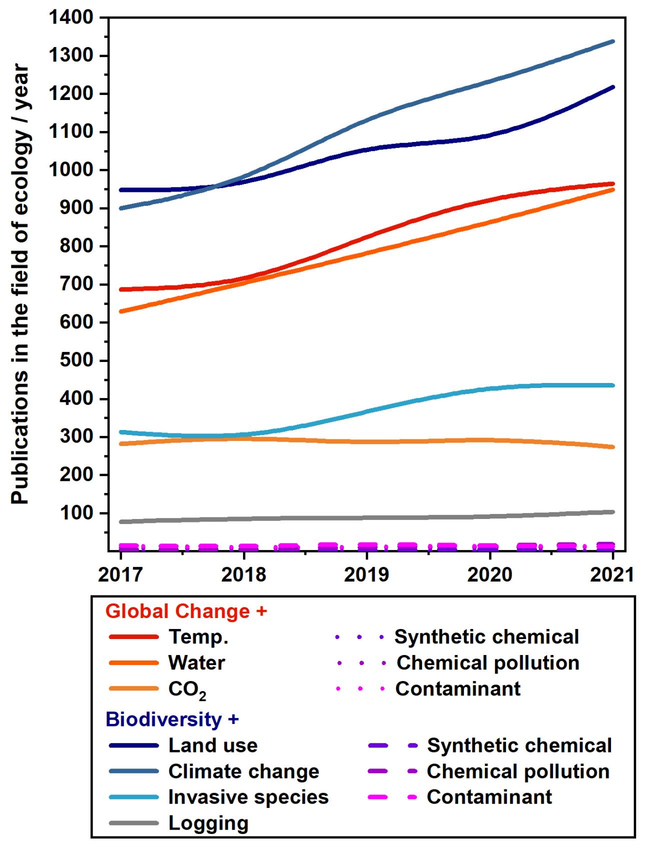


FIGURE 4 Chemical pollution as an underrepresented factor in the ecological literature. Results of Web of Science search for papers published in the period between 2017 and 2021 in the "ecology" category (as defined by Web of Science), related to "global change" + selected factors (Temperature, Water, CO_2) or pollution (represented by the terms "Synthetic chemical," "Chemical pollution," or "Contaminant"), or "biodiversity" + selected drivers for biodiversity loss (Land use, Climate change, Invasive species, Logging) or pollution (represented by the same terms). Land use and Climate change effects on biodiversity were the most intensively studied topics with over 5000 hits in total. In contrast, the search for chemical pollution amounted to less than 200 hits in total for the six search combinations shown.

Due to their scarcity, published studies to date have likely captured just a minuscule fraction of the multitude of chemicals contaminating the environment, thereby providing only a limited understanding of different physical states, environmental fate and transport, exposure patterns, modes of action and interactions between chemicals, organisms, and ecosystems (Kristiansson et al., 2021; Strempel et al., 2012). Part of the problem lies in the interplay of public attention on specific chemicals and research funders' preference for "hot topics" such as phthalates or microplastics, which severely limits the scope of chemical diversity that is being widely studied (Gould, 2015; Kristiansson et al., 2021; Sobek et al., 2016). This situation is further exacerbated by technical challenges such as the dearth of chemical standards for parent compounds and transformation products, which seriously hampers empirical research. Lastly, most of the current regulations and testing requirements imposed on chemical manufacturers may not provide sufficient information on environmental toxicity and ecological effects of chemicals (Karamertzanis et al., 2019; Saouter et al., 2019). Furthermore, whichever information is available is often not publicly accessible. As a consequence of these factors, most researchers and regulators continue to focus on a narrow selection of "fashionable," well-studied chemicals, while the general awareness and advancement of chemical pollution knowledge remain low.

Recently, the ecology community has embraced environmental DNA (eDNA) metabarcoding (Thomsen & Willerslev, 2015). In conjunction with modelling, this technique allows assessing biodiversity with less resource investment and with a much higher temporal and spatial resolution compared with the workforce-intensive and time-consuming conventional sampling approaches (Carraro et al., 2020). A broader and systematic application of this approach can enable the community to develop highly reliable quantitative parameters that can be used for in-depth comparative studies of biodiversity across scales. Similarly, the last decade has seen pivotal advances in environmental analytical chemistry with high-resolution mass spectrometry methods allowing the measurement of known and unknown chemicals at very low environmental concentrations (Schymanski et al., 2014). In the meantime, (eco)toxicologists have developed new approaches to assess the biological effects of chemicals and chemical mixtures (Brooks et al., 2020; Schuijt et al., 2021) and determine chemical pressures by using high-throughput bioassays (Krewski et al., 2020) combined with tools from analytical chemistry (Brack et al., 2016; Dong et al., 2020). Together with recent developments in data science (Wu et al., 2022; Zhu et al., 2014), these fields are ready to make the complex impacts of chemical pollution on biodiversity more tangible, and targeted investigations feasible. Based on their experience with intricate studies of biodiversity, ecologists are well equipped to venture into this new sphere of pollution ecology, which offers a whole universe of interactions and effects to explore.

5 | OPPORTUNITIES FOR THE COLLABORATIVE ROAD AHEAD

There are numerous examples where an improved understanding of the environmental effects of anthropogenic chemicals has been used to inform policy decisions or guide changes in industry practices (Cousins, Goldenman, et al., 2019; Eggen et al., 2014; Scheringer, 2017). Collectively, these developments have led to substantial progress in chemical management and environmental protection. Starting with the publication in 1962 of Rachel Carson's "Silent Spring," which spurred improvements in the management of organochlorine pesticides, ecotoxicologists have revealed environmental impacts of many further chemicals, some of which we have discussed in the text above and illustrated in Figure 2. Mitigation efforts that were initiated based on this knowledge have in some cases led to impressive successes in the restoration of biodiversity, such as the recovery of mollusc populations after the ban of the anti-fouling chemical tributyltin (Wells & Gagnon, 2020). However, for a significant proportion of anthropogenic chemicals and their environmental mixtures, knowledge and data remain limited. This is due not only to the large chemical diversity but also to the complexity of exerted effects and ecological interactions potentially affected. Therefore, to advance the assessment of chemicals' effects on biodiversity and ecosystems, broader collaborations between ecologists, environmental chemists, and ecotoxicologists are required.

The involvement of in-depth ecological expertise will enable ecotoxicologists to identify and overcome the existing shortcomings in their investigations. For example, this could help to find novel, ecosystem-relevant endpoints that can be used for screening chemical hazards, or contribute to the establishment of linkages between individual and population levels in adverse outcome pathways being developed to link molecular measures to population-level effects (Ankley et al., 2010; Groh et al., 2015). In turn, through consideration of environmental chemistry and ecotoxicology knowledge, ecologists may find better ways of designing comprehensive studies that address anthropogenic chemical pollution in a targeted manner. Close integration between monitoring efforts focused on chemicals and biodiversity would be crucial to enable a reliable establishment of clear links between exposure to particular chemicals or mixtures and the effects on biodiversity. Working together, scientists from these three disciplines could attain a more impactful understanding of chemical effects on the natural environment. This can help establish early warning systems for pollution-related regional biodiversity loss and/or ecosystem collapse, as well as identify novel strategies to thwart chemical pollution-associated biodiversity loss (Rillig et al., 2019; Schaeffer et al., 2016).

To efficiently address the multiple planetary crises threatening biodiversity, ecologists need to have all the necessary tools at hand, including those required for studying chemical pollution. Therefore, to increase expertise in chemical pollution, both environmental chemistry and ecotoxicology concepts should be included in curricula for ecologists and adjoined disciplines to allow students to obtain a broad overview, while gaining in-depth knowledge and practical expertise in specific disciplines (Schaeffer et al., 2009). One important tool already employed by both ecologists and ecotoxicologists is the microcosm/mesocosm experimental approach, which enables studies at a scale relevant to understanding ecological effects. These have been used and further developed over the last decades to answer increasingly sophisticated questions (Benton et al., 2007; Petersen & Hastings, 2001). At an even larger scale, pollution ecology could use experimental ecosystems such as the Canadian Experimental Lakes Area in Northwestern Ontario, Canada, to conduct ecosystem-scale experiments without needing to unethically jeopardize intact natural ecosystems (Bath, 2018).

Systematic collaborations between these three disciplines can be expected to generate novel and unexpected perspectives, research avenues, and paradigms. This interaction could, for instance, improve the development of management plans for protected areas, and to identify human activities that are likely to negatively influence biodiversity before the effects fully unfold. Such research may also help in determining tipping points in Earth's ecosystems. For example, with coinciding chemical pressure and pressures resulting from global warming, the continuous functioning of key ecosystems, including their capacity to sequester carbon (Rockström et al., 2021), could be jeopardized much earlier than expected.

A crucial task for environmental chemists and ecotoxicologists will be to inform ecologists about ecosystem-specific chemicals of concern, considering, for example, a chemical's preference to accumulate in the soil, water, or air (Lohmann et al., 2007). The potential for the existence of certain chemical effects of interest in a given ecosystem could also be assessed using bioassays performed on the mixtures of chemicals extracted from an environmental sample of water or sediments (Muz et al., 2020; Posthuma, Brack, et al., 2019). In this way, for example, the estrogenicity of the whole mixture could be assessed, without the need to separately measure and identify individual estrogenic chemicals, and the resulting value could be linked, for example, to the risks of reproductive disturbance among local fish populations. In addition, ecotoxicologists can contribute to the understanding of ecosystem health by using biomarker-based environmental biomonitoring in sentinel species caught in the wild (Triebskorn et al., 2002; Wernersson et al., 2015). In turn, ecologists can help ecotoxicologists to identify (more) suitable test organisms that are tailored to an ecosystem of interest, thus further increasing environmental relevance. In this way, a set of measurements to enable a targeted assessment of chemical pressure could be jointly developed and incorporated into ecological study designs. Collectively, mutual exchanges among these research communities, further supported by advances in computational biology and data science approaches, could allow developing truly innovative study designs providing the long-needed holistic insights into ecological effects of chemicals across scales and landscapes (Schneeweiss et al., 2023). In turn, this would support development of novel predictive tools that could help inform risk assessment and identify promising policy options. Figure 5 illustrates possible synergies between the disciplines, highlighting already existing seeds of joint methodology to build on.

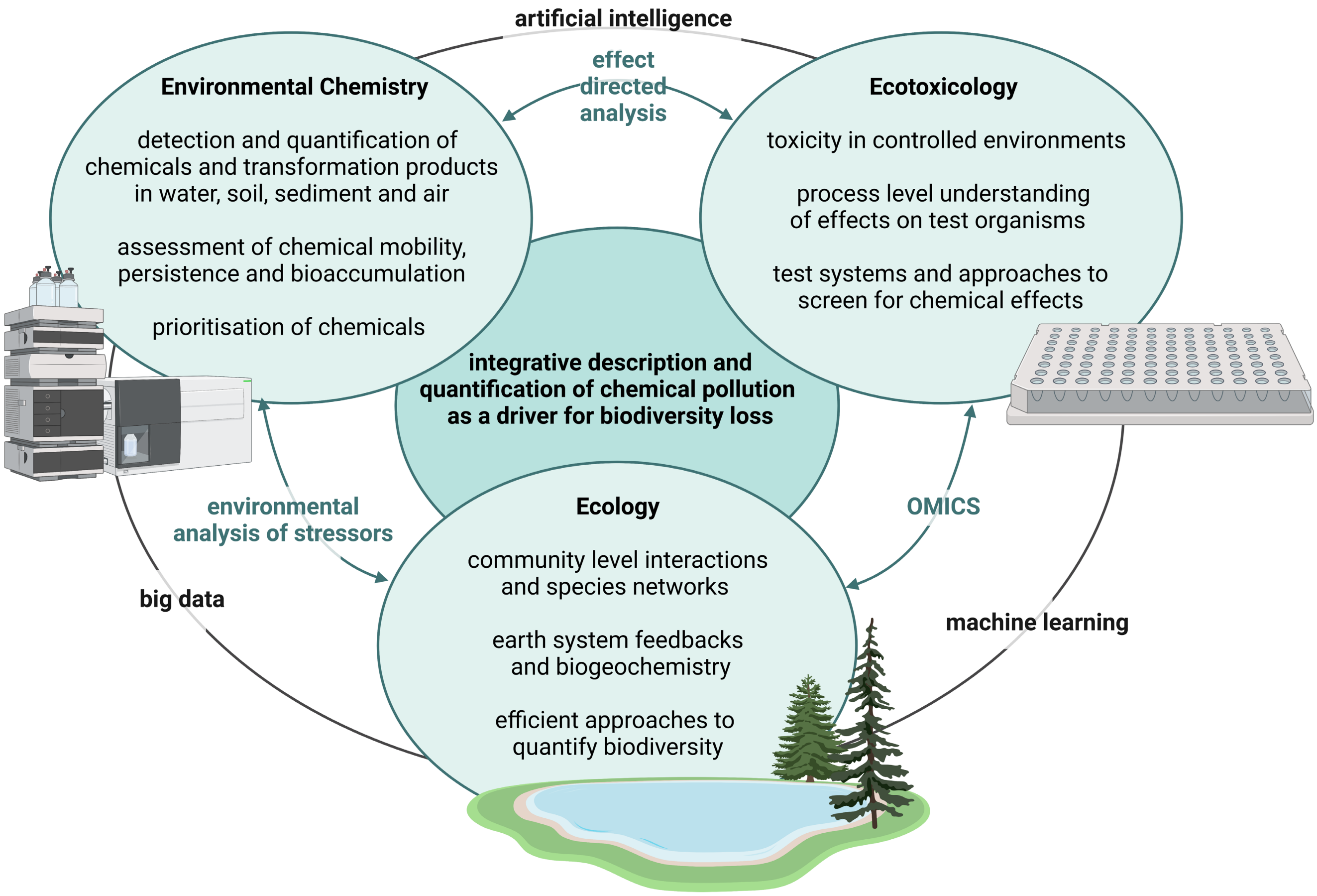


FIGURE 5 Opportunities for collaborations to elucidate the effects of chemical pollution on biodiversity. Key expertise and methods of single disciplines can complement each other to systematically disentangle the effects of chemical pollution on ecosystems and biodiversity in a truly interdisciplinary manner. Approaches from data science (black) are already applied in different contexts by all three disciplines and could facilitate a common FAIR (findable, accessible, interoperable, and reusable) workspace, while other approaches are already widely used by two disciplines (inner arrows in turquoise).While academic and funding institutions continue to favour specialization, that is, increasing the depth of knowledge within disciplines, the most efficient way to find solutions to our planetary challenges may lie in conducting true interdisciplinary research, requiring a certain degree of generalization to enable bridge-building across disciplines. To facilitate interdisciplinarity, both academic institutions and funding agencies need to expand the existing funding schemes or develop new ones to foster collaborations between ecologists and (other) environmental scientists in addressing chemical pollution as one of the major drivers of global biodiversity loss. Efficient ways for this interdisciplinary knowledge to be incorporated into regulatory and policy frameworks aimed at ecosystem protection are also needed and could build on such initiatives and reach out to social scientists and policy experts early on as well.

To facilitate interdisciplinary and cross-sectorial collaborations, as well as regulatory use, data on chemicals and biodiversity—derived both from public- and industry-funded research—need to become open, FAIR (findable, accessible, interoperable, and reusable), and easily translatable across disciplines (Wilkinson et al., 2016). To ensure interoperability, terminology, and language usage also need to be harmonized and/or translated between communities efficiently. The establishment of shared operating spaces accessible to different parties could further help to increase transparency and support mutually beneficial activities. An important first step in that direction could be the organization of recurring conference sessions to host ecologists at environmental toxicology and chemistry meetings, as well as offering a dedicated spot for ecotoxicologists and environmental chemists at ecology meetings.

6 | CONCLUSIONS

As discussed above, anthropogenic chemical pollution is a significant driver of biodiversity loss, acting through a multitude of direct and indirect effects on organisms and ecosystems. Ecologists and biodiversity scientists searching for effective solutions to mitigate and revert the ongoing crisis need to properly account for chemical influences in their work. Similarly, ecotoxicologists and environmental chemists should strive to integrate a holistic, ecosystem-wide perspective in their research. This can only be attained through interdisciplinary collaborations that seek to overcome the current siloes across research fields and study initiatives. Given recent methodological progress, conceptual developments, and computational advances, the time to seize the opportunity for such interdisciplinary collaborations is now. As biodiversity loss is accelerating at an unprecedented rate, the scientific community should respond to this worrisome trend through joint efforts addressing the threats to biodiversity posed by chemical pollution, together with other factors of global change. We encourage the readers to consider these needs and to reflect on how their individual contributions could support such collaborative efforts. We hope that the discussed examples will help spur further ideas and creative approaches to advance this collective goal.

AUTHOR CONTRIBUTIONS

The manuscript idea was conceived in discussion with all co-authors. GS and KJG wrote the first draft and finalized the manuscript in dialogue with other co-authors. All co-authors contributed ideas and content and have read and approved the final manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

The data used to create Figure 1 (Geographical differences in chemical releases across the globe) were taken from two publicly available reports, which are cited in the figure legend and referenced in the reference list of the manuscript. Specifically, these are (UNEP, 2018): UN Environment Programme (UNEP), 2018. Technical background to the global mercury assessment 2018, Narayana Press, Gylling, Denmark, https://www.unep.org/globalmercurypartnership/resources/report/technical-background-report-global-mercury-assessment-2018 and (UN-Habitat and WHO, 2021): United Nations Human Settlements Programme (UN-Habitat) and World Health Organization (WHO), 2021. Progress on wastewater treatment—Global status and acceleration needs for SDG indicator 6.3.1., UN-Habitat and WHO, Geneva, https://unhabitat.org/progress-on-wastewater-treatment-%E2%80%93-2021-update. The data used to create Figure 4 (Chemical pollution as an underrepresented factor in the ecological literature) are publicly available from Zenodo at https://doi.org/10.5281/zenodo.7745986.

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