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Better integration of chemical pollution research will further our understanding of biodiversity loss

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Chemical pollution research should be better integrated with other drivers of biodiversity loss and the assessment of human impacts on ecosystems, to more effectively guide management strategies for biodiversity loss mitigation.

The erosion of biodiversity is among our biggest challenges, as we face the risk of losing close to one million plant and animal species within the coming decades[1]. Despite numerous and ambitious international agreements that have been reached over several decades, ecosystem degradation leading to biodiversity decline has continued – and even accelerated – in almost all domains of life across marine, freshwater and terrestrial systems[2]. Indeed, planetary integrity and ecosystem services are now at risk of irreversible changes, with severe consequences for human wellbeing[3]. The main drivers of global biodiversity decline include habitat degradation and loss caused by changes in land and water use, direct exploitation of organisms, climate change, invasion by non-native species and chemical pollution[4]. However, our understanding of these drivers, single and in concert, often seems to be too rudimentary to adequately guide mitigation strategies that would be compatible with human activities. Here we argue for better integration of chemical pollution alongside other drivers in research that assesses biodiversity impacts.

Decades of comprehensive ecotoxicological research and its inclusion in political and public agendas may convey the image that the environmental risks of chemicals are currently under control. Isolated but media-effective success stories contribute to this perception – for example, the recovery of bird of prey and vulture populations following restrictions on the use of DDT for insect control and diclofenac for cattle raising, respectively[5,6]. However, the true state of affairs is that the release of chemical pollutants into the environment has increased unabatedly during past decades, including a sixfold increase in global pesticide production between 1970 and 2010 (ref. 7). Currently, there are over 350,000 chemicals and mixtures of chemicals registered for production and use[8]. This emphasizes the enormous chemical diversity to which the environment may be exposed, with profound yet only rudimentarily understood consequences for living organisms, ecosystems and biodiversity.

Chemical pollution research is prolific but siloed

Rachel Carson's book *Silent Spring*, a seminal work from 1962 that warned about the environmental risks of chemical pollutants, marked the dawn of ecotoxicological research[9]. Since then, hundreds of thousands of scientific papers on chemical pollution have been published. We searched the scientific literature published between 1990 and 2021 to compare research conducted on chemical pollution with research on three other key drivers of global biodiversity loss: habitat degradation and loss, invasion of non-native species and climate change (detailed methods and search results are presented in Supplementary Information).

We found that most of the research on chemical pollution has been published in a notably low number of scientific journals (Fig. 1). These journals are primarily specialized ecotoxicological journals, in which papers on other drivers of biodiversity loss or biodiversity loss itself are rarely found. The comparatively low number of journals used to communicate chemical pollution research cannot be explained by low productivity in the field. On the contrary, there is a sharp contrast between the high number of papers produced on this topic and the narrow spectrum of journals in which these papers have been published (Supplementary Information), which suggests a high degree of encapsulation of the field. This stands in marked contrast to the publication patterns for climate change, habitat loss and invasive species, in which articles have been published in a broad range of journals – including prominent ecology publications (Fig. 1). Moreover, many of these journals have published work on more than one driver, directly on biodiversity loss or on both, which suggests strong connections among disciplines.

Thus, although research on chemical pollution has been prolific, it has so far primarily been conducted using a single-discipline approach

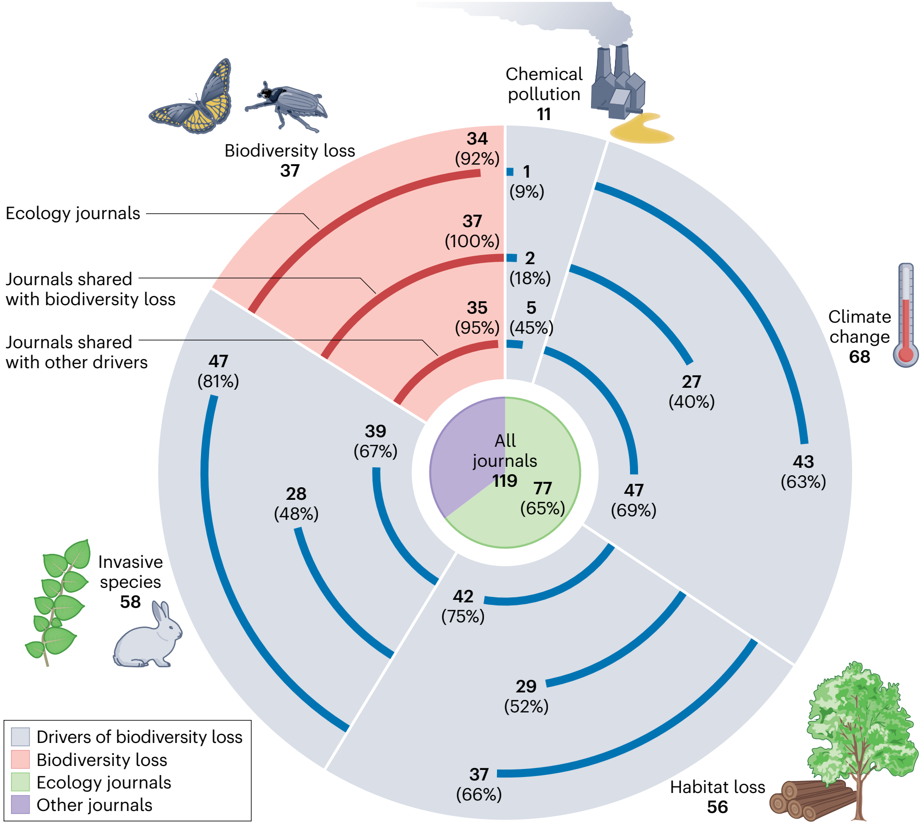

Fig. 1 | Chemical pollution research is isolated from the ecological literature. We searched for papers on four major drivers of ecosystem degradation and biodiversity loss, and on biodiversity loss itself, published between 1990 and 2021. From a total of 367 journals identified, we focused on the 119 most prolific journals, which accounted for 50% of the papers published on each topic. We found that, whereas reaching a 50% representation of papers published required 68 journals for climate change, 56 journals for habitat loss, 58 journals for invasive species and 37 journals for biodiversity loss, only 11 journals accounted for 50% of papers published on chemical pollution. Of these 119 journals, we classified 77 as ecology journals, but only one of the 11 journals that has published high volumes of chemical pollution research belonged to this category. By contrast, 34 of the 37 journals publishing more frequently on biodiversity loss and 47 of the 58 journals publishing more frequently on invasive species fell into this category. Similarly, only 2 of the 11 journals publishing more frequently on chemical pollution also published on biodiversity loss, and 5 published on other drivers of biodiversity loss; this overlap was considerably lower than for any of the other drivers we analysed. The bold numbers in the figure indicate the number of journals in each category, and the percentage values in parentheses show the proportion of those journals with respect to the total in each pie portion. Further details on the methods and results can be found in the Supplementary Information.

that has seldom included an ecological perspective. Consequently, scientific understandings of the ecosystem effects of chemical pollution remain limited[10]. Without the support of adequate science, conservation targets may be misguided[11]. If the effects of chemical pollution on biodiversity are to be elucidated and mitigated, there is a need to abandon scientific siloes and join forces as well as a need for expertise from a diversity of disciplines (including environmental chemistry, ecotoxicology and ecology)[12].

Advances in chemical pollution science and policy

Although good news in environmental issues is rare, we can identify at least two major positive developments in chemical pollution science and policy. The first development is that, despite scientific separation, ecotoxicology and ecology have both made substantial progress, and these advancements can be leveraged to make further strides in investigating exposure–impact relationships at the ecosystem level[13]. Decades of ecotoxicological research have produced a methodological arsenal to measure the effects of chemicals on biological entities[14]. Advances in analytical chemistry and big-data science allow the simultaneous detection of hundreds or thousands of known and unknown chemicals from environmental samples[15]. Novel high-throughput effect-based tools address specific modes of action and set up bridges between pollution and ecosystem impacts[16]. Concurrent advances in ecological theory, the proliferation of microevolutionary[17] and macroecological studies[18], the development of models to predict ecological risks of chemicals[19], technologies for remote environmental monitoring (for example, satellite-based[20]), and large-scale biodiversity sampling techniques (for example, environmental DNA[21]) all improve our ability to assess ecosystem integrity and biodiversity comprehensively. And the development of global scientific networks, open data exchange

Table 1 | Potential causes of disconnection between chemical pollution and ecological research and proposed actions to remediate this disconnection

Potential causes	Proposed actions
(1) Insufficient fundamental data. Knowledge of the chemicals present in nature is patchy and geographically imbalanced. The industry possesses substantial amounts of relevant data that are not made available to the scientific community. Additionally, there is a lack of information on the parameters that need to be fed into computational models to predict ecosystem effects.	• Systematically monitor chemicals in understudied ecosystems worldwide. • Increase funding for experimental and monitoring studies that generate new data. • Organize multisectoral workshops to promote cooperation among stakeholders. • Establish regulations that require industry to make relevant data publicly available.
(2) Overly technical and rigid study field. The study of chemicals and their effects on the environment has been historically dominated by the needs of the chemical industry. This has resulted in a proliferation of standardized protocols, organism and suborganism models primarily designed to inform the industry and managers for compliance with and enforcement of regulations. Often, however, these methods are relatively ineffective to examine effects on untested organisms (for example, microorganisms) and ecosystems.	• Create ecological test models and end points that capture higher levels of biological complexity, such as populations, communities and ecosystems. • Incorporate large-scale ecosystem-level assessments into regulations for safe chemical production.
(3) Complexity of ecosystem-level processes. Ecosystem-level processes are complex and occur at large temporal and spatial scales. The drivers of ecosystem change and biodiversity loss are interconnected. Consequently, the study of ecosystem impacts requires interdisciplinary collaboration (but see limitations identified in cause (4)), long study periods that exceed normal grant duration and large-sized infrastructure that is only available in a few research centres for a limited number of experimental replicates.	• Establish specialized departments and centres for ecosystem-level experiments (for example, equipped with experimental fields, mesocosms and climate change chambers). Consider settings that enable simultaneous assessment of different drivers. • Accept suboptimal experimental designs in complex, multi-stressor experiments, such as incomplete factorial designs, pseudoreplication or replication over time. • Use modelling techniques to better understand chemical impacts on ecosystems (but see limitations to models identified in cause (1)). • Establish specific funding mechanisms for long-term ecosystem study projects.
(4) Siloed structure of science. Interdisciplinary and transdisciplinary research is hindered by the siloed structure of science, with research groups, journals, funding and scientific meetings all following these siloes. Academic careers often depend on hiring and promotion rules that favour specialization and hinder collaboration between fields and with stakeholders outside of academia. Research agendas are often driven by discipline methods rather than standing problems. Different methods in environmental chemistry, ecotoxicology and ecology impede the identification of common research objectives. The historical self-identification of ecology with 'pristine' ecosystems and of ecotoxicology and environmental chemistry with 'polluted' ecosystems can further promote this separation.	• Publish special issues and journals focused on the ecological effects of chemical pollution to broaden publication options for research on this topic. • Organize joint conferences that involve ecological, chemical and ecotoxicological associations. • Organize multisectoral workshops that facilitate communication among researchers, policy-makers, industry and society stakeholders on chemical pollution issues. • Permit multiple first and senior authorships to acknowledge author contribution in large collaborative studies. • Develop unified theoretical frameworks for ecosystem processes and chemical pollution.
(5) Ineffective top-down measures. The increasing international recognition of the chemical crisis will promote management and regulatory action on chemicals through milestone advances, such as the establishment of a global science-policy panel on chemicals and waste. However, the direction of research projects is ultimately determined by individual researchers. For this reason, top-down measures may fail to increase the demand for ecological research on chemical pollution, unless they are accompanied by measures that raise the interest of researchers.	• Combine top-down measures with bottom-up incentives to research on ecological effects of chemical pollution, such as the actions proposed for causes (1) to (4).

and big-data processing technologies makes interdisciplinary integration possible.

The second development is that political awareness about the effects of chemical pollution on ecosystems and biodiversity is on the rise. With the European Green Deal and its 'Chemicals Strategy for Sustainability', the requirement to tackle chemical pollution and move towards a non-toxic environment has become one of the priorities of the European Union (the 'Zero Pollution Ambition'). Globally, the United Nations has identified the need to address chemical pollution and waste on a planetary scale, together with climate change and biodiversity loss. This led to the decision to establish a science-policy panel for the sound management of chemicals and waste, taken at the 5th United Nations Environment Assembly in Nairobi in March 2022 (ref. 22). This panel will seek to improve the interface between science and policy on global issues of chemical pollution, in the same way as the IPCC (Intergovernmental Panel on Climate Change) and IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) do for climate change and biodiversity, respectively. In December 2022, at the Conference of the Parties (COP15) of the Convention on Biological Diversity, the United Nations set a target to halve the use of nutrients, pesticides and highly hazardous chemicals by 2030 (ref. 23).

Steps to integration

Chemical pollution is a growing threat to life on Earth. However, although other drivers of global biodiversity loss have been readily embraced by general ecology, research on chemical pollution has remained predominantly technical, isolated from other disciplines and surprisingly disconnected from the assessment of biodiversity loss. It is now time to actively integrate advances in the different disciplines to produce science that effectively informs policy and management efforts. Yet, the lack of essential data, the intricate nature of ecosystem processes and specific characteristics of the field of study pose substantial challenges to achieving an interdisciplinary approach to chemical pollution research that integrates ecology (Table 1). To catalyse these changes, we propose a set of specific next steps (Table 1) that we hope may function as a guide for science policies and the scientific community.

Data availability

All data are publicly available from the sources cited in the Supplementary Information. Source data are provided with this paper.

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Author contributions

F. Sylvester, F.G.W. and H.H. conceived this work. F. Sylvester, V.L.L. and F.G.W. conducted the literature searches and data analyses with the help of S.F., K.J.G., J.J., S.J., F.L., R.O., J.P., M.P., S.S., M.S.-S. and F. Strobl. Writing was led by F. Sylvester with extensive input from H.H. Substantial contributions to writing and the direction of the manuscript were made by K.J.G., K.T., M.S., W.B. and J.J. Figures had substantial input from L.M.S., F.G.W, V.L.L., M.S.-S. and F. Sylvester. All other authors (M.B., L.B., C.B., B.B., J.C., P. Dierkes, P. Döll, I.E., E.J.N.H., T.H., S.K., H.K., D.M., T.M., J.O., S.U.P., G.J.S., J.F.S., A. Schlottmann, F. Schneider., E.S., F. Strobl, A. Sundermann, T.T., A.V., C.V. and R.W.) contributed to specific aspects and to further elaborate the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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