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What's ahead: navigating the future of environmental science

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What's ahead: navigating the future of environmental science

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Editorial: What's ahead: navigating the future of environmental science

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Editorial on the Research Topic
What's ahead: navigating the future of environmental science

The 21st century is a period of critical and substantial change for humanity, and unlike any other. At its beginning, the seriousness and consequences of continued fossil-fuel burning, and wilful destruction of the natural environment, to planetary heating and biodiversity loss was clear and unequivocal. A quarter of a century on, while awareness of the issue has been strengthened by science, and while technological, social and financial progress on some solutions has been made, the world is now 1.3 °C warmer than in pre-industrial times. The 2015 Paris Climate Agreement aimed "to limit global warming to well below 2 °C, preferably to 1.5 °C". In 2024, with an atmospheric CO_2 concentration of 423 ppm (in 2000 it was around 368 ppm), the annual temperature of our planet was measured at 1.55 °C, the first year to break the 1.5 °C mark, with the multi-annual global temperature set to surpass 1.5 °C within the coming decade unless greenhouse gas emissions are rapidly reduced (Bevacqua et al., 2025). Similarly, biodiversity loss and ocean health have plummeted in the last 50 years, due to mismanagement of land, over-fishing and the introduction of pollutants, and with the average size of wildlife populations dropping by 73%.

Regarding human existence and its future within a self-contained 'human world', as most people do, is a tragic mistake. Everything humanity requires to survive comes from the 'natural world', and by ignoring this, or taking it for granted, we damage our future prosperity and development (Siegert, 2016).

Our drive to "net-zero" greenhouse gas emissions is essential for our future, and this must be accompanied by the sustainable, non-destructive, and targeted extraction of resources, alongside increased recycling and repair, and decreased disposal of, and disregard for, waste. The 21st Century is a pivotal time for humanity. Will we continue on our present pathway or shall we transition, as science demands, to a sustainable future where humanity integrates harmoniously with nature?

In this Research Topic, we address this question by examining the future of a variety of themes and sectors within environmental science, to understand the damage that is now sadly unavoidable and what can be preserved and protected in the coming decades of this century.

Our cities, which now house around 60% of the global population, are essential as instruments of positive change, as they offer resource and service efficiencies to large populations. However, they also can lead to separation between our awareness of, and appreciation for, the natural world. As Haase points out, population density presents problems unique to cities in terms of pathogens as was so brutally exposed during the COVID pandemic of 2020-22. The future of cities is an important environmental issue. Careful building design, co-creation of green spaces with residents' needs, installation of utilities and services built for the future as well as for existing requirements, reductions in traffic, air pollution and waste, will be the hallmarks for success and wellbeing. The transformation can be driven, according to Haase through application of the "polluter pays" principle, which would firstly offer finances for necessary change and secondly lead to financial incentives for best practice. Several cities have started to adopt such practice, albeit written and explained publicly in other ways, to restrict congestion, to encourage shared heat and power systems, and to create shaded, water-retaining green shared spaces.

To understand how to solve the climate and biodiversity crises, and to prepare for the changes necessary, we require information to guide prioritisation and urgency. For this, environmental informatics and remote sensing is key (Kokhanovsky). While spaceborne and airborne remote sensing, with appropriate ground truthing and coupling with numerical models, has allowed unprecedented knowledge of environmental concerns and impacts, greater details are needed in key regions and across timescales. Kokhanovsky (2025) explains how a variety of next-generation satellites, operating within specific parts of the e/m spectrum, will ensure greater knowledge of environment change and the reasons behind it. For example, one of the most complex low-Earth orbit satellite systems is due for launch in 2025, enabling global coverage for climate monitoring and prediction until mid-century. Similarly, Biomass–an EU satellite working with a radar at UHF (~400 MHz), launched on 29 April 2025, aims to measure the carbon content of the world's forests for the first time. These and other satellite systems will mean a huge increase in data, needing rapid processing and analysis. The rise of machine learning and AI has been a crucial element in transferring satellite information into environmental knowledge and, hence, environmental informatics is likely to dominate scientific discovery in coming decades over spatial and temporal scales that have been challenging to deal with previously.

One clear example of humanity's misuse of the natural world is within the quality of soil. While essential for growing our food, there is a "mixed matrix" of human-caused problems such as heavy metals, pesticides, "forever chemicals" (such as per- and polyfluoroalkyl substances, PFAS) and microplastics (among others), that have led to widespread contamination of soil and the food grown from it. Chen et al. describe how advances in soil science can be used in future to remediate and protect soil quality. For example, novel biological agents are being developed to degrade persistent contaminants (Książek-Trela et al., 2025). Alongside such advances, policy and regulatory modification is necessary, making the role of national governance important, guided by international agreements such as the Stockholm Convention on forever chemicals, and essential to building positive change.

Ogunseitan also discusses pollutants but on systems other than those involving soil; including freshwater, air and the ocean. Again, forever chemicals have emerged as a huge issue in environmental toxicology, that is especially concerning with respect to the "natural planetary boundaries" of human development (Richardson et al., 2023), with evidence that we have already transgressed the safe operating zone for chemical pollution (Persson et al., 2022). The solution lies in the integration of science with political decision making and governance. Here, there are reasons to be both optimistic and concerned. As Zhao et al. (2025) point out, now is the time for greater stringency on protecting the natural word from toxins, but at the same time the recent reduction in funding to the US Environmental Protection Agency (EPA), and the deregulation of US environmental rules, testifies to a moment when science is being wilfully ignored by some powerful decision makers (Tollefson, 2025).

The environmental benefits of strong planning, governance and science-led decision making are becoming clear, however. Waring points to the rise of "regenerative agriculture," or agroecological farming, as an example of how local decisions on small holding farms (which produce over a third of the world's food, Lowder et al., 2021), through the better timing of specific crop planting and harvesting dependent on local conditions, reduction of pesticides and the creation of natural woodland areas (agroforestry), support both organic crop yields and biodiversity. The combination of ecological advice and farming practice is an exciting one for larger scale adoption, to maximise food production during times of extreme climate and weather conditions. While such adoption by large corporations is in early stages, in Europe at least it is interesting to note that most farmers are appreciative of, and motivated by, the desire to restore the natural world alongside farming practice (Markiewicz-Keszycka et al., 2025).

Moving to freshwater systems – the life and wellbeing of all lifeforms on Earth – climate change and poor human decisions have led to their neglect and underappreciation by governments and agencies. A good example is from the UK, where sewage discharge directly into rivers is at an all-time high due to extreme rain events and illegal actions (Ford et al., 2025). Arthington point to the application of firm governance solutions to freshwater systems such as the Emergency Recovery Plan (ERP) to tackle freshwater biodiversity loss (Tickner et al., 2020), and which has widespread support from freshwater scientists. However, some caution is needed, especially in the application of governance measures to areas and regions that are presently poorly understood in terms of the system specifics that drive ecological processes. That said, with climate change providing less to, and the growth in human population requiring more from, already pressured freshwater systems a level of 'rethinking' is required. An example lies in social-ecological resilience and 'rehabilitation' to restore natural freshwater systems and make them better able to resist the pressures being observed and measured. "Nature-based solutions" (such as the restoration of wetlands) is a good example, and when coupled as part of "integrated" water resources management, such an approach is promising for addressing the trade-offs between human and ecological water requirements.

It is clear that local solutions play an important role, when multiplied, in solving global environmental challenges. At the global scale, we should be aware that the integration of physical, biological and chemical systems dictates how the natural environment responds when stressed by humans. This biogeochemical integration has become a key component of environmental science (Slaveykova). As we look ahead, fossil fuel burning and the climate heating that results – if left unsolved – will play an increasing driver of biogeochemical changes. Within the nine Earth system processes with "safe operating spaces" Rockström et al. (2023), biogeochemical flows of nitrogen, phosphorus and carbon have emerged as being severely stressed (Richardson et al., 2023). While we have discovered and understood a lot about biogeochemical flows and processes, much remains to be known, especially for allowing better integration with numerical modelling to guide predictions and, from that, policy advice. Here, the use of AI is an emerging field in biogeochemistry, especially in consideration of how forever chemicals and plastics are transferred across natural domains.

In summary, 21st century environmental science is at the forefront of the climate and biodiversity crises. Pressure on natural systems is evident from increasing temperature and extreme weather events, as well as from politically/financially-motivated reductions in environmental protection, and through counter narratives to climate change action from some political fields. That said, among the areas and systems covered in this Research Topic, a number of returning themes have emerged that offer promising advances. The first is in new technology to better measure and understand natural systems, such as from bespoke satellites and by the increasing need for data assessment via AI. Another is the growing support for climate action and protection of our natural world among practitioners such as farmers and the general public. We neglect and misuse the natural environment at our peril. Failure to act now will make it increasingly difficult to solve in years to come; hence this has become a major intergenerational issue, with the voice of the young and consideration of the future necessarily becoming more important in decision making.

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Planetary boundaries for recalcitrant materials and toxic chemical pollutants: specifications for sustainable safe operating zones

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Announced as “the greatest and most consequential day of deregulation in U.S. history,” 12 March 2025 marks the retreat of the United States Environmental Protection Agency from remedial and preventive policies that were informed by decades of consequential research in environmental science and public health. The USEPA administrator boasted further: “We are driving a dagger straight into the heart of the climate change religion to drive down cost of living for American families, unleash American energy, bring auto jobs back to the U.S. and more.” The retreat threatens science-based regulations that have commanded the attention of researchers, policymakers, healthcare providers, non-governmental stewards of environments and ecosystems, and the general public. An example of such regulations targets mercury pollution, perhaps the only toxic chemical for which a specific UN action, the Minamata Convention, is dedicated. The linkage of mercury emissions to coal combustion as a source of energy that also drives climate change and particulate matter pollution that transcends national boundaries to cause diseases worldwide implies that the adverse impacts of USEPA’s retreat will not be borne only by the US population, but also by the global human population and wildlife. The retreat from progressive agendas on environmental sustainability is not unique to the US. Note the European Commission’s relaxation of reporting rules in the 2025 Competitiveness Compass. We may very well witness a “race to the bottom” as other countries sacrifice environmental regulations in pursuit of corporate profits.

KEYWORDS
environmental pollution, planetary boundaries, safe operating zones, toxic chemicals, recalcitrant materials

The scope and scale of urgent challenges in a turbulent environment

Announced as “the greatest and most consequential day of deregulation in U.S. history,” 12 March 2025 marks the retreat of the United States Environmental Protection Agency from remedial and preventive policies that were informed by decades of consequential research in environmental science and public health. The USEPA administrator boasted further: “We are driving a dagger straight into the heart of the climate change religion to drive down cost of living for American families, unleash American energy, bring auto jobs back to the U.S. and more.”

(United States Environmental Protection Agency, 2025). The retreat threatens to erase a broad range of science-based regulations that have commanded the attention of researchers, policymakers, healthcare providers, non-governmental stewards of environments and ecosystems, and the general public (Ogunseitan, 2023a). An example of such regulations is the one that targets mercury pollution, perhaps the only toxic chemical for which a specific United Nations Convention, The Minamata Convention on Mercury has been dedicated (Ogunseitan, 2017). The linkage of mercury emissions to coal combustion as a source of energy that is also a driver of climate change and respirable particulate matter that travel across national boundaries to cause diseases worldwide implies that the adverse impacts of USEPA's retreat will not be borne only by the US population, but also by the global human population and wildlife. The retreat from progressive agendas on environmental sustainability is not unique to the United States. Similar moves are noted in the European Commission's relaxation of reporting rules in the 2025 Competitiveness Compass (European Commission, 2025). We may very well witness a "race to the bottom" as other countries and regions sacrifice environmental regulations in the pursuit of competitive advantage regarding new natural and unsustainable resources to keep up with the technological revolution enabled by artificial intelligence and corporate financial profits. The retreat also comes at a time when research is intensifying to characterize the impacts of emerging toxic environmental pollutants such as microplastics (Singh et al., 2022) and recalcitrant "forever chemicals" such as per- and polyfluoroalkyl substances (PFAS) (Fenton et al., 2021; Wilson and Ogunseitan, 2017), and complex material mixtures present in hazardous electronic waste (Ogunseitan, 2023b). Government funding for research in environmental science may be scarcer in the US over the next 4 years, but this need not stop the creativity of the international scientific community in the pursuit of the most pressing question for this and future generations: How can we keep recalcitrant materials and toxic chemicals used in international commerce within the safe operating zones of planetary boundaries?

The concept of planetary boundaries provides a framework for understanding the limits within which humanity can safely inhabit Earth (Rockström et al., 2009). Among these boundaries, toxic chemical pollution has emerged as a critical concern, with far-reaching implications for human health, ecosystem integrity, and global environmental stability. The complexities of transgressing the planetary boundary for toxic chemical pollution and environmentally-recalcitrant materials is a major challenge for scientists and for those dedicated to the translation of research results into policies that protect human populations and planetary health. Exploring the specifications necessary for establishing and maintaining a safe operating zone is an ambitious and necessary endeavor.

Evidence suggests that humanity has already transgressed the safe operating zone for chemical pollution (Landrigan et al., 2018; Persson et al., 2022). The proliferation of synthetic chemicals, many of which are persistent and bio-accumulative, has led to widespread contamination of ecosystems and organisms worldwide. Some key indicators of this transgression include the ubiquitous presence of microplastics in marine and freshwater environments, as well as in the food chain, and in human tissues including the brain, the detection of persistent organic pollutants in remote areas, including the Arctic and deep ocean sediments, the decline of insect populations, partially attributed to pesticide use, and the bioaccumulation of heavy metals and other toxicants in apex predators and human populations. (Nihart et al., 2025; Pasquini et al., 2024). These indicators and ecosystem sentinels underscore the urgent need for a comprehensive approach to managing chemical pollution and defining safe operating zones.

Figure 1 depicts some of the adverse consequences of indiscriminate use of toxic chemicals and recalcitrant materials, the ultimate undesirable outcome of transgressing planetary boundaries being species extinction and ecosystem collapse at local and global scales. Rethinking fundamental research approaches, including translational science and multidisciplinary remediation technologies is necessary to establish sustainably safe operating zones for existing, new, and emerging chemicals and materials. Research priorities should align with knowledge of toxicological modes of action. Chemicals known to target phylogenetically-conserved physiological processes and reproductive fitness are likely to have broad spectrum impacts on biodiversity and can potentially lead to local extinction of species. For example, despite the well-documented toxicity of lead (Pb) and its compounds, it continues to be a major environmental risk factor for humans and other organisms. Lead has no known use in biological systems, and it interferes with the function of aminolevulinate dehydratase, a phylogenetically-conserved enzyme that is essential for the synthesis of pigmented biomolecules including hemoglobin and chlorophyll (Ogunseitan et al., 2000). Lead poisoning affects a third of the world's population of children and leads to nearly 1 million premature deaths annually, and 1 US$ trillion in lost economic potential (Global Alliance on Health and Pollution, 2025).

Future opportunities for understanding the planetary boundary for chemical pollution

The planetary boundary for chemical pollution is unique among the nine identified boundaries due to its diverse and pervasive nature. Unlike boundaries such as climate change or ocean acidification, which can be quantified using specific metrics like atmospheric CO_2 concentrations, chemical pollution encompasses a vast array of substances with varying impacts on different environmental compartments. The interplay between toxicology, pollution, and the environment continues to shape global ecosystems and human health. As the urgency to address ecological degradation mounts, a focused exploration of critical questions, policy frameworks, and innovative solutions becomes indispensable. Chemical pollution includes persistent organic pollutants (POPs), heavy metals, plastics, and emerging contaminants such as pharmaceuticals and nanomaterials. Individually, these pollutants can have long-lasting effects on ecosystems, biodiversity, and human health, but we have not really grasped their collective impacts through complex pathways and synergistic interactions. It is also necessary to pursue a better understanding of the ripple effects of pollution, including how it exacerbates climate change, disrupts food chains, and contributes to health disparities. Without an urgent, integrative approach, the consequences may become irreversible. One of the primary challenges in addressing the chemical pollution boundary is the difficulty in quantifying a single, comprehensive metric. Unlike other planetary boundaries, there is no universally accepted threshold for chemical pollution beyond which Earth system functioning is

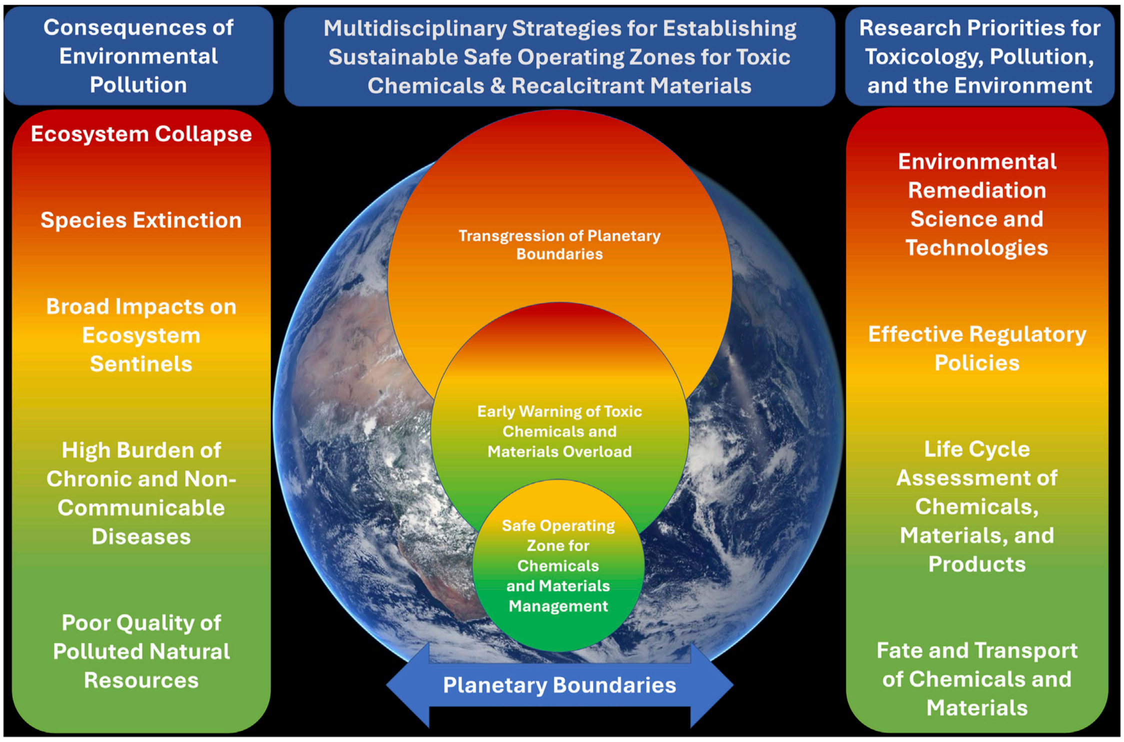

FIGURE 1
Schematic diagram of planetary boundaries including thresholds for safe operating zones of toxic chemicals and recalcitrant materials, early warning zones, and transgression of these boundaries (Middle Panel). The adverse consequences of environmental pollution become more severe with increasing production, use, and disposal of toxic chemicals and recalcitrant materials, leading progressively from depreciated quality of natural systems to ecosystem collapse (Left Panel). The roadmap for research priorities in toxicology, pollution, and the environment extend from creating active inventories, fate and transport studies, remediation technologies, and preventive regulatory policies. A collaborative multidisciplinary framework of research is necessary to support initiatives such as the circular economy to stay within or regain the safe operating zone for toxic chemicals and recalcitrant materials. Satellite image of Earth is from NASA (https://images-assets.nasa.gov/image/GSFC_20171208_Archive_e001016/GSFC_20171208_Archive_e001016~large.jpg?w=1920&h=1080&fit=clip&crop=faces%2Cfocalpoint).

significantly altered. This complexity arises from the diverse nature of chemical pollutants, their varying persistence and toxicity, and the intricate web of interactions within ecosystems. Several theoretical and empirical approaches to quantify these boundaries are reasonable, including the total mass of chemicals released into the environment, the number of novel entities introduced into the biosphere, the concentration of specific indicator chemicals in various environmental compartments, and the overall toxic load on ecosystems and human populations. Each of these approaches has its merits and limitations, highlighting the need for a multifaceted integrative approach to understanding and managing chemical pollution, and the establishment of rigorous specifications for safe and resilient operating zones that account for the complexity and diversity of chemical pollutants.

Future research in this direction needs to support a broad-ranging infrastructure including the establishment of a comprehensive inventory of chemicals in use, their production volumes, and potential environmental and health impacts. This inventory should be regularly updated and include emerging contaminants. Risk assessments studies should consider not only individual chemicals but also their potential synergistic effects and long-term consequences, and such studies should be aligned with global monitoring networks to track the presence and concentration of key chemical pollutants in various environmental compartments. These networks should cover air, water, soil, and biota, with a focus on both urban and remote areas to capture the full extent of chemical pollution. In addition to chemical monitoring, effect-based approaches using biomarkers in sentinel species can provide early warnings of ecosystem stress due to chemical pollution. This approach can help capture the cumulative effects of multiple pollutants and their interactions. Transitioning to a circular economy model and promoting green chemistry principles are crucial for reducing the introduction of harmful chemicals into the environment. This includes designing chemicals and products for easy recycling, minimizing waste, and prioritizing the use of less toxic alternatives. Enabling a circular economy also demands setting clear, science-based targets for reducing the overall chemical footprint of human activities. These targets should consider both the quantity and toxicity of chemicals released into the environment and be regularly reviewed and updated based on the latest scientific evidence. Implementing comprehensive lifecycle assessments (LCA) for chemicals and products can help internalize the environmental costs of chemical pollution and incentivize cleaner production methods. However, LCA methods also need further development particularly in the assessment of composite materials such as metallic alloys, and in the modelling of future scenarios. The integration of Artificial Intelligence tools with LCA could be transformative in this direction, particularly for exploring the interactions between chemical pollution and other planetary boundaries, such as climate change and biodiversity loss (Singh and Ogunseitan, 2022). Implementing these specifications for safe operating zones faces several challenges. These include the economic interests of the chemical industry, the lack of data on many chemicals' environmental impacts, and the difficulty of addressing legacy pollutants already present in the environment.

Integrative solutions

How can we comprehensively assess and mitigate the long-term impacts of emerging pollutants on ecosystem structures, functions, and services, including dependent human population health? Transgressing the planetary boundary for toxic chemical pollution poses a significant threat to Earth system functioning and human wellbeing. Establishing and maintaining a safe operating zone requires a comprehensive, multifaceted approach that addresses the complexity of chemical pollution. By implementing robust monitoring systems, promoting sustainable chemistry practices, strengthening international governance, and fostering public awareness, we can work towards reducing our chemical footprint and safeguarding the planet's life-support systems for future generations. The challenge of chemical pollution exemplifies the interconnected nature of global environmental issues and underscores the need for systemic, transformative changes in how we produce, use, and manage chemicals and materials. As we navigate the Anthropocene, our ability to operate within the safe boundaries of chemical pollution will be crucial in determining the long-term sustainability and resilience of both human societies and the Earth system as a whole.

Given the transboundary nature of chemical pollution, strong international governance mechanisms are necessary. Such mechanisms should be built to resist the uncertainty of national political turbulence such as the retreat of the USEPA from effective regulations and evidence-informed policies. This includes harmonizing chemical regulations across countries, implementing and enforcing global treaties on chemical management, and establishing mechanisms for rapid response to emerging chemical threats. The absence of standardized thresholds for emerging pollutants leaves many toxic chemicals and recalcitrant materials unchecked in commerce and international supply chains. Additionally, policies frequently focus on individual pollutants without accounting for their cumulative and synergistic effects. This fragmented approach undermines comprehensive mitigation efforts. Governments and international bodies must adopt adaptive, science-driven frameworks that integrate real-time data and predictive models. Collaborations between policymakers, scientists, and industry stakeholders can enhance the relevance and enforceability of regulations. Furthermore, fostering global agreements to monitor and mitigate cross-boundary pollution will ensure cohesive action in addressing shared environmental challenges.

The coming decade is likely to bring a host of challenges. Climate change will act as a force multiplier, intensifying pollution's effects and complicating toxicological studies. Unless we invent innovative research approaches, methods, and capacity to meaningfully interpretate disparate results, the rapid proliferation of synthetic chemicals and recalcitrant nanomaterials will outpace our ability to understand their long-term impacts. The convergence of toxicology, pollution, and environmental challenges demands immediate, coordinated action. By addressing burning questions, closing policy gaps, preparing for future hurdles, and fostering innovative strategies, the scientific community can navigate this critical juncture with resilience and excellent research skills. The path forward hinges on collaboration, adaptability, and a commitment to safeguarding our planet for future generations. Let this be a clarion call to unite science, policy, and community in the pursuit of a sustainable, equitable, and thriving world.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

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OO: Formal Analysis, Methodology, Validation, Conceptualization, Project administration, Investigation, Writing – original draft, Writing – review and editing, Resources, Visualization.

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Soil pollution and remediation: emerging challenges and innovations

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This perspective addresses the critical issue of soil pollution, exacerbated by rapid urbanization, intensive agriculture, and climate change, which introduces a complex mix of contaminants such as heavy metals, pesticides, per- and polyfluoroalkyl substances, and microplastics into the soil. These pollutants pose severe risks to environmental health and agricultural productivity by altering soil functionality and contaminant mobility. This perspective summarizes innovative monitoring and remediation technologies, including advanced sensors and bioremediation strategies, that enable real-time detection and effective management of soil pollutants. The integration of artificial intelligence and machine learning offers significant advancements in predicting and managing soil contamination dynamics. Furthermore, the perspective discusses the challenges and future directions in soil pollution research, particularly the need for robust policy frameworks and international cooperation to effectively manage and mitigate soil contamination. Emphasizing a multidisciplinary approach, this study calls for enhanced global standards, public engagement, and continued scientific research to develop sustainable solutions for soil remediation and to ensure the protection of vital soil resources for future generations.

KEYWORDS

soil pollution, soil remediation, extreme weather, pollution sensor, environment policies

Introduction

Soil pollution, driven by rapid urbanization, intensive agriculture, and industrial expansion, represents a critical environmental concern (Zhang et al., 2023; Roy et al., 2022). The mixed matrix of pollutants in soils, such as heavy metals, pesticides, pharmaceuticals, per- and polyfluoroalkyl substances (PFAS), and microplastics, poses significant risks to soil health and agricultural productivity, complicating remediation efforts (Maddela et al., 2022; Liu et al., 2024). Climate change further affects soil pollution dynamics, altering pollutant behavior, mobility, and environmental fate (Biswas et al., 2018). Concurrently, advances in analytical methods, sensors, and artificial intelligence present opportunities for precise and real-time monitoring and management of soil contamination (Fan et al., 2022; Aniagor et al., 2022). This paper examines recent advances in understanding soil contaminants, the impact of extreme climate-induced changes on pollutant dynamics, and innovative technologies for pollution monitoring, assessment, and remediation. Furthermore, it explores integrated policy frameworks, social-economic initiatives, and education efforts for protecting soil resources, aiming to guide future research, policy development, and global collaboration.

Emerging challenges

Soil co-contamination with inorganic and organic pollutants, along with particle matters is increasingly common due to complex industrial activities and the reuse of waste materials (Bian et al., 2024). Understanding these interactions is challenging since coexisting pollutants can alter each other's physicochemical behavior and toxicity, subsequently affecting the effectiveness of soil remediation strategies (Nie et al., 2024; Zeng et al., 2024). For example, combined metals, organic contaminants (such as petroleum, pesticides, pharmaceuticals, and PFAS), or microplastics can exacerbate toxicity beyond individual effects or enhance each other's mobility and persistence in the soil matrix (Deng et al., 2017; Kastury et al., 2023). Current soil pollution studies primarily focus on a single pollutant or a group of similar pollutants; thus, improving knowledge of pollutant interactions is critical for risk assessments and effective remediation.

Extreme weather conditions, including temperature fluctuations, flooding, and drought, significantly affect the fate and transport of soil contaminants. Elevated temperatures can increase the volatilization of pollutants (e.g., mercury or polycyclic aromatic hydrocarbons), promoting their atmospheric transport and deposition (Chételat et al., 2022; Gbeddy et al., 2020). Flooding alters soil physicochemical conditions, mobilizing contaminants previously bound to soil matrices and significantly increasing pollutant mobility (Ciszewski and Grygar, 2016). Additionally, intense rainfall events accelerate contaminant leaching, potentially altering transport patterns of pollutants (Stuart et al., 2011). Drought concentrates contaminants and enhances soil oxidation, which may shift redox-sensitive species and alter organic pollutant transformation pathways (Zhang and Furman, 2021). Due to the increasing frequency of extreme weather events, future research should integrate climate variables into soil pollution migration models.

Rapid urbanization and intensified agriculture introduce soil to a wide range of contaminants, thereby disrupting soil health and its ecological functions (Chen, 2007; Li et al., 2018). Urban sources like industrial emissions, road dust, construction materials, and waste disposal contribute contaminants such as heavy metals, hydrocarbons, PFAS, and hazardous particles (Goonetilleke et al., 2017; Sager, 2020; Yao et al., 2024). Agricultural practices add significant loads of pesticides, herbicides, synthetic fertilizers, and veterinary pharmaceuticals, which accumulate in soil over time (Yan et al., 2022). These contaminants pose risks to human health through direct exposure, bioaccumulation in food chains, and groundwater contamination (Baweja et al., 2020). Innovative approaches are needed to prevent soil pollution amid sustainable urbanization and agricultural intensification.

Innovative monitoring and remediation technologies

Advanced sensing technologies enable specific, real-time detection of soil contaminants such as molecularly imprinted polymers, aptamers, microbial biosensors, and microelectromechanical systems-based arrays (Shah et al., 2023). Integrated with wireless platforms, these tools support continuous monitoring, timely data delivery, and informed mitigation strategies for stakeholders (Tsakiridis et al., 2023). Recent advances in sensor technology for monitoring soil contaminants are characterized by breakthroughs in microfluidics, miniaturization, and multiplexing techniques. Microfluidics enables precise control of flow and reaction conditions, thus promotes sample processing efficiency (Aryal et al., 2024). Miniaturized sensors allow for portable or field-deployable detection for *in-situ* monitoring with reduced field sampling and laboratory analysis (Satish, 2024). Multiplexed platforms are cost-effective and designed for the simultaneous detection of multiple pollution (Coskun et al., 2019). These innovations are driving the development of next-generation sensors for scalable soil pollution monitoring.

Artificial Intelligence (AI) and advanced statistical methods represent emerging tools for tackling the complexity of soil pollution dynamics (Wani et al., 2024). Deep-learning algorithms, such as convolutional neural networks, analyze high-dimensional sensor data and hyperspectral images for soil pollution identification and spatial mapping (Wang et al., 2024). Machine learning approaches, such as random forests, support vector machines, and gradient-boosting models, have been applied in modeling source attribution or soil contaminant distribution (Wei et al., 2019; Sakizadeh et al., 2017; Wang et al., 2020). Additionally, advanced geostatistical techniques, such as Bayesian hierarchical modeling and kriging interpolation, provide frameworks to quantify uncertainties and predict contaminant transport at large scales (Wang et al., 2023; Boente et al., 2019). Future research should integrate AI-driven analytical workflows for proactive pollution management.

Advances in bioremediation are revolutionizing soil remediation efforts using biological agents to degrade persistent contaminants such as PFAS (Ye et al., 2017; Lee et al., 2025). Recent studies have utilized engineered microbial strains, which can defluorinate PFAS under anaerobic conditions, significantly reducing PFAS toxicity and persistence (Smorada et al., 2024). Phytoremediation research has led to a new direction using genetically engineered plants with enhanced detoxifying enzymes for the degradation of broader organic pollutants (Abhilash et al., 2009). To enhance bioremediation of soil contaminants, future research should explore targeted genetic improvements in plants and microbes, along with the optimization of metabolic pathways for pollutant degradation with emphasis on field-scale validation.

Policy and regulatory developments

Strengthening global regulatory standards is critical for effectively managing soil pollution, particularly for contaminants with transboundary impacts, such as airborne heavy metals, persistent organic pollutants (POPs), or PFAS. International agreements, like the Stockholm Convention on POPs and the United Nations Environment Programme (UNEP)'s guideline for PFAS, emphasize global cooperation for managing traditional and emerging contaminants in soil. (Cheng et al., 2023; Fiedler et al., 2022). However, substantial gaps remain due to a lack of unified guidelines and consistent monitoring protocols for pollutants globally. Future policymaking should enhance global standards and cooperation frameworks to improve the capacity to manage the risks associated with transboundary soil contamination.

Evidence-based policymaking for soil pollution control requires the integration of regulatory decisions with scientific data. Recent examples include the European Union's Soil Strategy for 2030, which incorporates data from large-scale monitoring programs and advanced risk assessment methodologies, and the U.S. EPA's evolving guidelines on PFAS, informed by ongoing toxicological and environmental research (Panagos et al., 2022). Leveraging machine learning and data analytics for predictive scenario modeling, current research data enable risk forecasting to support policy-related decision-making processes. Future research efforts should focus on improving the transparency and accessibility of scientific data, enhancing collaboration, and developing adaptive policy frameworks that can incorporate new scientific insights rapidly.

Public engagement and education are crucial for soil pollution prevention and management. Recent community science projects, such as citizen-led microplastic monitoring campaigns, have demonstrated that informed community participation can enhance data collection capabilities and increase public awareness (Sinha et al., 2024). By combining science with community outreach, "SoilSHOP" initiative led by the U.S. Agency for Toxic Substances and Disease Registry empowers individuals to take action and reduce exposure risks in their own environments (Saikawa et al., 2023). Future outreach efforts should prioritize developing accessible educational resources encouraging community participation for collaborative approaches toward sustainable soil management.

Soil contamination reduces agricultural productivity imposes significant social and economic burdens, exacerbating social inequalities (Martinho, 2020). Economically, soil pollution contributes to substantial losses, land devaluation, and high remediation costs (Graves et al., 2015). Future research should prioritize incorporating socio-economic vulnerability indicators into pollution risk assessment frameworks, that could enhance the equitable pollution control policies, thus better protecting vulnerable communities. Economic modeling quantifies the long-term economic benefits of soil protection and pollution management should also be emphasized to reinforce the soil remediation investment.

Conclusion

Co-contamination, extreme weather events, rapid urbanization, and intensified agriculture pose significant challenges for protecting soil resources. These challenges highlight the importance of integrating advanced monitoring technologies, precise analytical tools, and science-based policies. Embracing sustainable practices combined with enhanced global standards and targeted bioremediation can effectively manage soil contaminants and facilitate restoration. Addressing socioeconomic impacts, actively promoting and engaging local communities, and continuous collaboration among scientists, policymakers, and the public remain essential for protecting soil resources and promoting soil health.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HC: Writing – original draft. BG: Writing – review and editing, Conceptualization. YL: Validation, Writing – review and editing, Conceptualization, Supervision.

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What's ahead: navigating the future of environmental science in and around cities in post-pandemic times

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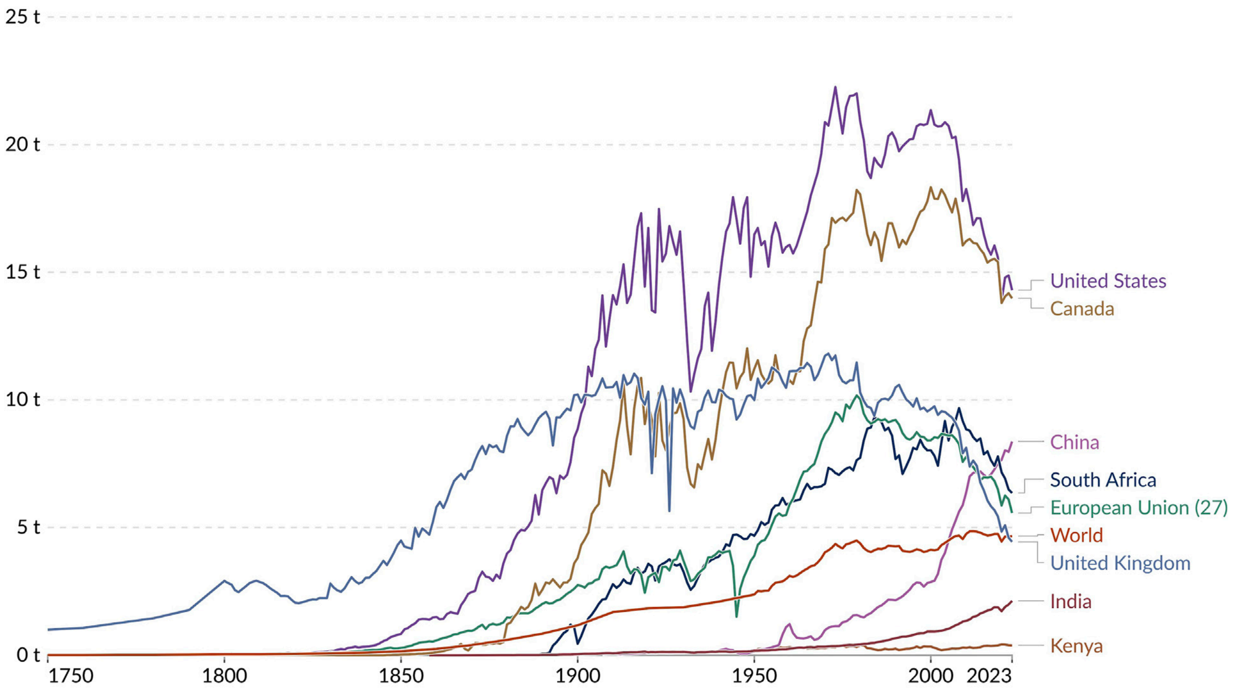
urban, social-ecological systems (SES), future research, climate change, biodiversity, human health

It is evident that the planet is experiencing a series of ecological crises, manifesting in the form of temperature rise, ocean warming, biodiversity loss and natural disasters. This phenomenon has been further emphasised by the World Meteorological Organization's designation of 2024 as a 'year of extremes' having a direct impact on many people and societies globally. Therefore, it has perhaps never been more topical to quote Shakespeare's Hamlet: "The world is out of joint.". This sentiment captures the uncertainty surrounding the ability to meet the established targets of the Paris Agreement, namely, the 1.5- and 2-degree limits on global warming (Figure 1). In particular, the ongoing loss of biodiversity has significant ramifications for the resilience of our ecosystems, including urban ones, which are vital for responding to and recovering from disturbances associated with global warming (Andersson et al., 2022; Kowarik et al., 2025).

Concurrently, and which only appears to be independent at first glance, since the 2010s, there has been in addition an observable rise in autocratic politics and a partial rejection of democracy as a societal model, owing to the evident distrust many people have in its ability to address the global challenges reported above. Only 45% of the world's population lives in a democracy, with 39% under authoritarian rule, and 15% in hybrid regimes that combine electoral democracy with authoritarian tendencies (Economist Intelligence Unit, 2025). The coronavirus pandemic has reinforced and accelerated these prevailing trends (Haase, 2021; Otto and Haase, 2021). Chief amongst these is the erosion of trust amongst younger generations in state support and social promises for the future, a phenomenon that is particularly evident in Western democracies.

What does this have to do with the most urgent question in the research field of social-ecological urban systems, and why does it need to be answered immediately? Because this question must be something like this: How do we address the global risks outlined above? How do we get a sustainable and socially balanced transformation off the ground that is geared towards the 1.5-degree target, that allows for the co-existence of humans and nature and thus the survival of all species, and that fairly distributes the benefits and burdens for us humans, to address the global risks outlined above, in particular the most vulnerable among us? What is more, because cities and their urban social-ecological systems are not the only answer, but a decisive one!

Why? Cities are the places where meanwhile most of the global population resides. It is anticipated that they will continue to experience growth in terms of both population and importance in the future: Mid-2024 approximately 4.8 of the more than eight billion people worldwide lived in towns or cities. This represents almost 60% of the global population. By 2030, this figure is set to reach 60% (Democracy Index, 2024). Urban areas are the locations of over 60% of all universities, functioning as pivotal centres of innovation and international



Data source: Global Carbon Budget (2024); Population based on various sources (2024)
OurWorldinData.org/co2-and-greenhouse-gas-emissions | CC BY

1. Fossil emissions: Fossil emissions measure the quantity of carbon dioxide (CO_2) emitted from the burning of fossil fuels, and directly from industrial processes such as cement and steel production. Fossil CO_2 includes emissions from coal, oil, gas, flaring, cement, steel, and other industrial processes. Fossil emissions do not include land use change, deforestation, soils, or vegetation.

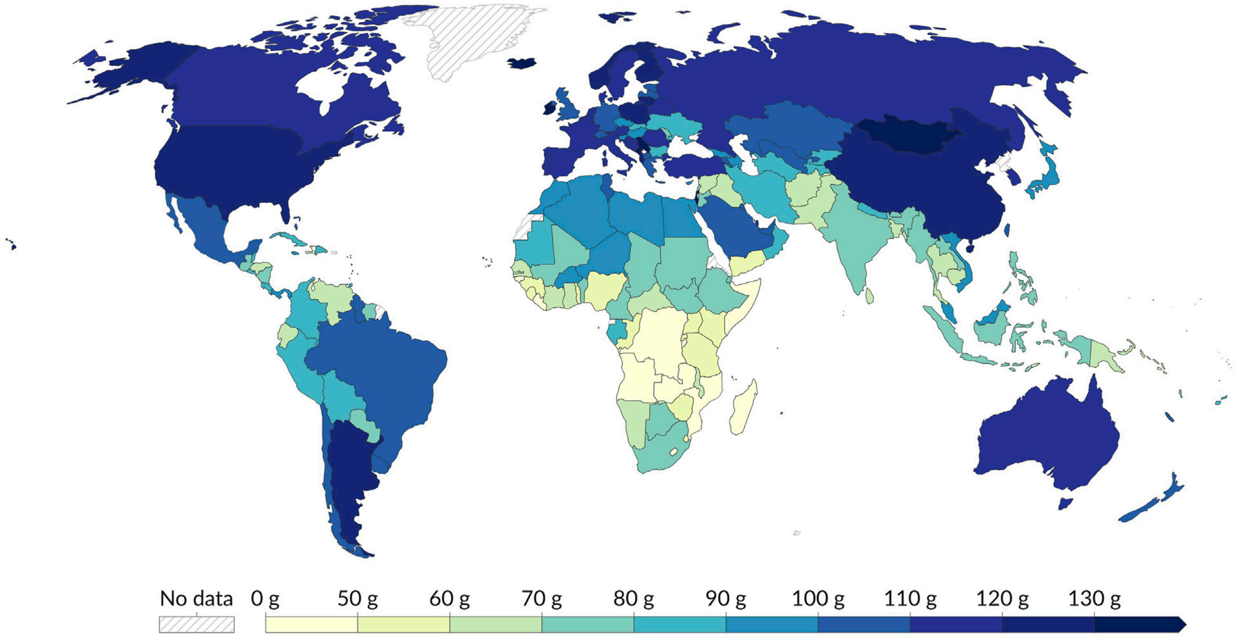
FIGURE 1
Per capita CO_2 emissions as carbon dioxide (CO_2) emissions from fossil fuels and industry. Land-use change is not included (Ritchie, H. et al., 2023; our world in data).

intellectual thought. Urban areas are further characterised by the proximity of humans to nature, as well as a high density of built, technological, social, economic, and green-blue matter and processes (Elmqvist et al., 2021). These characteristics are associated with a high level of complexity, termed the 'urban metabolism', and the potential for high resilience, attributed to high diversity and proximity to resources.

However, both density and proximity can also be problematic in terms of spillovers and vector jumps when not fully understood or ignored, as evidenced by the emergence of pathogens such as the SARS-CoV-2-II virus in 2020, the Zika virus in Brazil in 2016, and more recently monkeypox and Ebola, as well as a measles outbreak in the USA in 2025 (Haase, 2021). Furthermore, it is imperative to consider larger spatial contexts and to conduct research in these contexts to really capture the most urgent questions to be solved for urban systems. To illustrate this with a prominent example, the dramatic retreat of inland glaciers since 2000, which may be geographically distant from most cities, is particularly relevant given the imminent approach of tipping points in water supply to urban catchments that depend directly on meltwater, rivers and inland reservoirs.

At the same time, the complex social-ecological system of the city addresses numerous challenges and contentious scenarios daily. These include mutations and adaptation in the natural part of the system, as well as a transient equilibrium of human-related interests. However, the societal part of the system also features a continually expanding array of conflict resolution methodologies. In essence, cities function as substantial living laboratories, tasked with grappling with predicaments such as climate change and biodiversity loss, which they contribute to, in addition to mitigation and adaptation. It is imperative to harness these attributes when contemplating a global transition towards enhanced sustainability and the attainment of the 1.5-degree target (Andersson et al., 2022).

It is imperative that future research on socio-ecological systems in urban areas increasingly focuses on the systematic analysis of the emergence, progression, and resolution of complex problems along the lines of human-nature interaction, explicitly combining qualitative and quantitative approaches in a triangular fashion. The system responses are just as complex as the systems themselves; if we want to understand how transformation "happens", we must research responses from all angles (McPhearson et al., 2025, in press). This necessitates the utilisation of contemporary satellite-based remote sensing and earth observation techniques, the exploration of niches for urban flora and fauna species in the field, and the comprehension of the diversity of urban living situations experienced by city dwellers and



Data source: Food and Agriculture Organization of the United Nations (2023); Food and Agriculture Organization of the United Nations (2024)

Note: Data measures the availability delivered to households but does not necessarily indicate the quantity of protein actually consumed (food may be wasted at the consumer level).

OurWorldinData.org/food-supply | CC BY

FIGURE 2
Daily *per capita* protein supply, 2022. Average daily *per capita* protein supply, measured in grams of total protein per day. (Roser et al., 2013; our world in data).

how these are linked to local and global economic and financial cycles (Wellmann et al., 2023).

What future challenges are anticipated in the coming decade, and how can the scientific community prepare to tackle them collectively–see from an urban systems' angle? Urban areas are set to encounter a plethora of challenges in the present and the future, including climate change, biodiversity loss, long-term sustainability, public health and equity, congestion and pollution, structural racism and civic engagement, and, in an ideal scenario, the enhancement of democracy. In order to address these challenges, it is imperative that future cities adopt a collaborative approach with their residents to identify and implement effective solutions. This collaborative effort is crucial to ensure the continuity and inclusivity of urban development (Buijs et al., 2024).

To connect directly here, what innovative strategies, collaborations, or technologies can be leveraged to address these burning questions and future challenges? It is essential that experience and knowledge from different sources are systematically analysed and brought together. This requires a broader positioning and the facilitation of a discourse on facts and data that is both broad and open. Recent decades have seen an increase in societal disparities (Haase, 2024), particularly following the dissolution of the socialist system in 1990 and the rise of neoliberalism in the 1990s. This phenomenon is not merely a consequence of policy; rather, it is a fundamental societal issue that has come to the fore. Existing and emerging societal gaps and drawbacks have the potential to hinder progress in addressing the aforementioned challenges.

In the domain of social-ecological urban research, there has been an excessive reliance on planners and environmental experts in public administrations and large NGOs as the predominant recipients or consumers of research outcomes. This practice has led to a situation where diverse urban society is underrepresented as the primary target audience. However, the increasing digitalisation of life offers significant opportunities to directly involve diverse urban society in research and in communication of outcomes. Through the co-creation of data, supported by Smartphone-based apps using the power of AI, for example, there is an opportunity to reaffirm both interest and faith in science and to prevent systemic knowledge on global change, climate hazards, and biodiversity loss from being confined to the ivory tower of science.

In its own interest, environmental and sustainability science should, especially in times of regression of the democratic and liberal social model, examine the reasons for the global rise of this autocratic, nationalist movement and the mistrust in climate, health and biodiversity research and the rise of green bashing. Moreover, social-ecological system's research of the 21st century should address issues of water supply, food (exemplified in Figure 2; Roser et al., 2013) and energy security and concerns about the cost of living in a more direct manner.

Furthermore, there is a necessity to explore how the values and objectives of global environmental governance can resonate with those who hold deep scepticism towards the prevailing international order. Urban social-environmental governance of the 21st century must reduce shortsightedness, cumbersome procedures, or the influence of interest groups and, at the same time, exploiting their inherent advantages (Haase, 2024). Examples of such advantages might include, as discussed above, the free flow of information, participation, or accountability (Buijs et al., 2024). As previously referenced, the climate and biodiversity tipping points should be incorporated into the objectives of local and supra-regional policies, analogous to the SDGs. This would serve to more explicitly direct long-term framework laws, and focus deliberative mini-publics or hybrid mosaic governance (Buijs et al., 2024).

Finally, while not a counter-thesis to the aforementioned points, it is submitted that this perspective opens up a second, complementary line of thought. In accordance with Boone et al. (2014), the concept of "the city" may not be interpreted simply as a conventional spatial delineation. Rather, it is the urban lifestyle, termed "urban-ness" by Boone et al.—defined by the physical and functional characteristics that support and facilitate urban-like livelihoods, life styles, connectivity, and places—that necessitates transformation and should, as a filter and enabler, be positioned at the core of the systematic, systemic, and integrative analysis of frontiers researchers on social-ecological urban systems.

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Environmental informatics and remote sensing: modern trends in studies of environment and multi-dimensional global change

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The future trends in studies of environment and multi-dimensional global change are presented.

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Current environmental problems related to the climatic changes, global temperature rise and anthropogenic pollution of atmosphere, ocean, rivers, lakes, soils and cryosphere are characteristic features of the multi - dimensional global change, which is the main feature of modern time. 2024 was the warmest year on the record (see Figure 1). If the trend shown in Figure 1 continues for the next decade, the multiple climate tipping points may be triggered (Armstrong McKay et al., 2022), which will lead to the increase of various hazard (fires, heatwaves and flooding) probabilities. The recent examples are fires in California (Madakumbura et al., 2025), devastating flooding in Valencia (https://edition.cnn.com/2024/10/30/world/video/spain-flash-flooding-ldn-digvid) and heatwaves in Europe (van Daalen et al., 2024). Currently, the world is heading toward 2°C–3°C of global warming by year 2100. The observed global warming leads to the increased speed of snow melting, the decrease in snow-covered area and snow duration, the increase in snow fragmentation (Gu et al., 2024), disappearance of glaciers, decrease in sea ice extent (https://seaice.uni-bremen.de/sea-ice-concentration/amsre-amsr2/time-series/), sea level rise, the degradation of the permafrost, catalyse widespread temporal turnover in biodiversity and intensification of various nonlinear feedbacks in the climate system including surface - atmosphere and aerosol - precipitation interactions (Swain et al., 2025). Two remote areas on our planet (Greenland and Antarctica) are characterised by the ice mass loss with possible abrupt changes (Siegert et al., 2023; Petrini et al., 2025), which may lead to the devastation in coastal areas around the globe. Our best and only way to protect these areas and the planet in a whole is decarbonize to net zero by 2050 (Siegert, 2024). Geoengineering efforts (Budyko, 1977; Crutzen, 2006) can not lead to the solution of the problem on the short time scale we face (till mid century). The environmental informatics or geoinformatics is an integrator of science, methods and techniques and not just the result of using information and software technology methods and tools for serving environmental engineering needs. Therefore, it plays a special and very important role in the modern environmental sciences. Clearly, without methods of the environmental informatics coupled with remote sensing, it could not be possible to prepare the results as shown in Figure 1, which are based on the huge databases and observational evidence. The record shown in Figure 1 confirms that we live in the epoch of rising temperatures. A part of current temperature records can be attributed to the natural factors such as the solar activity (see Figure 2). However, the oscillating total solar irradiance variation (Tchijevsky, 1970) can not explain the curve shown in Figure 1.

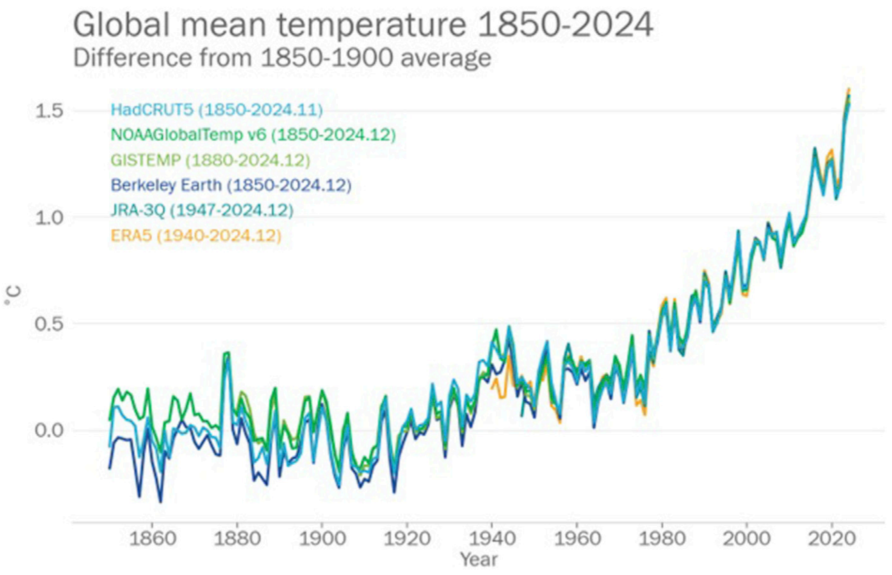

FIGURE 1
The temporal change of global mean temperature according to six different records (source: https://wmo.int/news/media-centre/wmo-confirms-2024-warmest-year-record-about-155degc-above-pre-industrial-level).

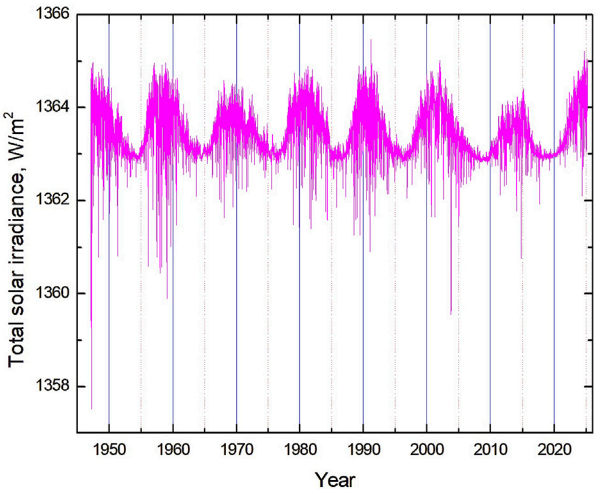

FIGURE 2
The daily variation of the total solar irradiance (Dewitte and Nevens, 2016; Dewitte et al., 2022).

Without doubt, one of the most important tasks of humankind at this stage is the preparation and implementation of measures to stop current warming trend. Otherwise, already in this century we may face disasters affecting not only flora and fauna but also humankind, especially in coastal areas, where the predicted sea rise is up to 1 m till 2100 (https://www.eea.europa.eu/en/analysis/indicators/global-and-european-sea-level-rise/observed-and-projected-change). The primary role in respect to climate change monitoring belongs to both ground-based and satellite remote sensing. The advanced spaceborne monitoring of our planet has been started a little more than half century ago. However, these efforts have already brought enormous progress in our understanding of atmosphere–underlying surface parameters and their temporal changes in conditions of current multi - dimensional global change (Kondratyev, 1998). Even more accurate and reliable results will be obtained by the mid-century with the planned launch of multiple satellite instrumentation operated in the UV, visible, NIR, SWIR and microwave regions of the electromagnetic spectrum including lidars, radars and hyperspectral instrumentation. The tremendous efforts put by the engineers and scientists in this direction can not be underestimated. In particular, The EUMETSAT Polar System–Second Generation (EPS-SG) and its Metop Second Generation (SG) satellites is one of the most complex and innovative low-Earth orbit meteorological satellites ever built. The system consists of two satellites working in tandem, each endowed with different suites of complementary instruments. Three successive pairs of Metop-SGA and Metop-SGB spacecraft will be deployed (from 2025), enabling full operational coverage and providing essential resource for climate monitoring, geoinformatics and global reanalysis till mid-century. The derived data will be used to inform policies and undertake actions to limit the negative effects of climate change on nature and humanity. The main features of the modern geoinformatics are the treatment of large amount of information (Big Data, e.g., coming from EPS-SG satellites), and the growing usage of the efficient computing, neural networks, and the Artificial Intelligence (AI) (Zhang and Zhang, 2022) including machine learning (Zhao et al., 2025), computational intelligence, data mining, and natural language processing (Bungartz et al., 2018). Taking into account resources put in these areas of research, a huge progress is expected in next decades leading to a better understanding of environment and its changes on various temporal and spatial scales, which is an important information for the decision makes and environment protection agencies worldwide. A special role in climate change studies belongs to the international cooperation and further development of the Global Climate Observing System (GCOS) (https://gcos.wmo.int/site/global-climate-observing-system-gcos) co-sponsored by the World

Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO), the United Nations Environment Programme and the International Science Council. The launch of the coordinated network of multiple geostationary satellites surveying the Earth as the whole at a given moment in time and the development of the self-organising satellite constellations, which enable satellites to autonomously cluster over Earth-surface targets (Mushet et al., 2015) is an important future exploration area. As it was underlined by Vernadsky (1926) a century ago, life is a geological force that changes Earth's landforms, its climate, and the contents of its atmosphere. It is time to take a part of this force related to human activities under control - long before time, when it is too late. In this way together human reason and scientific thought will continue to create the next evolutionary geological layer (Teilhard de Chardin, 1966; Vernadsky, 1991; Vernadsky, 2001). As said Teilhard de Chardin (1966), "The Age of Nations is past. The task before us now, if we would not perish, is to build the Earth".

Data availability statement

Requests to access the datasets should be directed to A. A. Kokhanovsky.

Author contributions

AK: Conceptualization, Writing – review and editing, Investigation, Methodology, Visualization, Writing – original draft.

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Safeguarding freshwater biodiversity and resilient social-ecological systems in uncertain futures

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Freshwater ecosystems and their diverse plant and animal communities are neglected, under-appreciated and threatened by the multiple interacting stressors of the Anthropocene era. Climate change is the most ominous threat on the horizon and freshwater ecosystems are particularly vulnerable. Climate change, multiple stressor syndromes and other uncertainties challenge freshwater restoration and conservation. This perspective presents a brief summary of major gaps in knowledge, governance and implementation that inhibit efforts to protect and restore freshwater biodiversity and offers guidance to address major gaps. The mission for freshwater science over the next decade is to leverage robust scientific knowledge, governance, funding and policy to inform freshwater restoration and conservation action plans (e.g., the Emergency Recovery Plan, GBF 30 × 30, SDGs, The Freshwater Challenge), and even to exceed their present targets, while simultaneously safeguarding resilient social-ecological systems and human wellbeing under climatic and other uncertainties.

KEYWORDS

biodiversity, freshwater ecosystem services, multiple stressors, climate change, rehabilitation, conservation, social-ecological resilience

Fresh water is life and wellbeing for all lifeforms on Earth (One Health[1]). People use and enjoy freshwater biodiversity and benefit from the ecosystem services provided by healthy aquatic ecosystems–food and other material goods, cultural services and environmental regulation (Lynch et al., 2023). Yet freshwater ecosystems and their diverse plant and animal communities are neglected, under-appreciated and threatened by the multiple interacting stressors of the Anthropocene era (Albert et al., 2021; Dudgeon and Strayer, 2025). Shameful statistics on freshwater biodiversity loss abound. One-quarter of decapod crustaceans, fishes and odonates on the IUCN Red List of Threatened Species[2] are threatened with extinction (Sayer et al., 2025), and many more species not yet assessed are likely to be suffering declining health and population losses. Prevalent threats driving population declines and species extinctions present a devastating catalogue (Reid et al., 2019; Tickner et al., 2020). Although there are many examples of restoration successes, typically but not always at local scales (e.g., Pander et al., 2015), land and water management systems are largely failing to address today's complex and spatially dispersed syndromes of

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[1] https://www.who.int/health-topics/one-health#tab=tab_1

[2] https://www.iucnredlist.org/

freshwater ecosystem degradation. Even our freshwater protected areas are poorly buffered against pressures within and external to their boundaries (Acreman et al., 2020). Climate change is dumping a further blanket of pressures on freshwater systems and already compounds multiple-stressor problems.

Since its inception in 2016, the Freshwater Science section of *Frontiers in Environmental Science* has set out grand challenges facing the field (Bunn, 2016; Arthington, 2021). The section promotes opportunities offered by the Sustainable Development Goals (SDGs)[3], the post-2020 Kunming-Montreal Global Biodiversity Framework (GBF)[4] and the 2021–2030 UN Decade on Ecosystem Restoration[5] to bring the linkages between terrestrial, freshwater and estuarine/marine biodiversity, ecosystem integrity and human health/wellbeing (One Health) into public prominence.

The GBF provides a vital policy setting and ambitious targets for the restoration, effective conservation and management of 30% of inland waters by 2030, with emphasis on maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people (CBD, 2022).

This long overdue recognition of 'inland water' ecosystems and the freshwater biodiversity crisis within a unique global policy has resonated widely. It is critically informed by the publication of a freshwater biodiversity Emergency Recovery Plan - ERP (Tickner et al., 2020) setting out six major priorities for global action and policy development to "bend the curve of freshwater biodiversity loss" including: (1) accelerate implementation of environmental flows; (2) improve water quality to sustain aquatic life; (3) protect and restore critical habitats; (4) manage exploitation of freshwater species and riverine aggregates; (5) prevent and control nonnative species invasions in freshwater habitats; and (6) safeguard and restore freshwater connectivity.

The ERP is supported by a suite of 'evidence-based roadmap' reviews to guide effective implementation of each action theme in diverse contexts around the world. Example reviews include accelerating environmental flow implementations (Arthington et al., 2024) and safeguarding and restoring freshwater connectivity within and among freshwater systems and their landscape and seascape surroundings (Thieme et al., 2024). These implementation reviews are also valuable for their clear enunciation of the many practical, societal and policy factors that enable (or inhibit) freshwater restoration and conservation actions in context (e.g., Twardek et al., 2021).

The ERP blueprint has received remarkable support from freshwater scientists, conservation practitioners and many other sectors with support growing apace. Might it prove to be the 'last best hope' for recovery and conservation of freshwater biodiversity globally? Dudgeon and Strayer (2025) hope so, but they caution that successful implementation of all ERP recommendations will require significant effort on emerging, overlooked or poorly understood topics. Their analysis of impediments to successfully 'bend the curve of biodiversity loss' offers many insights and a positive but tempered conclusion.

A recent exploration of major knowledge gaps in freshwater science, deficiencies of governance and legislation, and impediments to practical freshwater restoration and conservation is revealing (van Rees et al., 2025). Prominent gaps include patchy biodiversity inventory (e.g., taxonomic deficits, neglected ecosystems, geographic bias), unresolved multiple stressor and climate change interactions, limited monitoring and weak evidence of restoration and conservation outcomes, poor stakeholder and Indigenous participation in knowledge generation and collaborative management, and weaknesses in navigating trade-offs between water uses for societal development and priorities for freshwater biodiversity.

Every one of these gaps has the potential to influence our capacity to meet the 30 × 30 restoration and conservation targets of the Kunming-Montreal Global Biodiversity Framework, and related initiatives (van Rees et al., 2025). Furthermore, the deadline for achievement of GBF goals for all signatory countries and ecosystem types (see Keith et al., 2022) is frighteningly close.

Climate change is the most ominous threat on the horizon and freshwater ecosystems are particularly vulnerable. Shifting thermal and water quality/quantity regimes directly impact aquatic species and compound the impacts of other stressors on freshwater biodiversity and ecosystem services (Capon et al., 2021). Human population growth will vastly increase demands for fresh water and new water infrastructure, typically depriving aquatic systems of habitat, connectivity pathways and essential ecological cues. Uncertainty related to the societal and ecological implications of climate change combined with other threats means that our concept of ecosystem restoration to a former preferred (or near natural) state is often inappropriate, and rarely feasible, given the magnitude of changes and degradation of most of today's freshwater ecosystems, and the emergence of hybrid and novel ecosystems that support valued biodiversity (Erős et al., 2023). For example, our current practice of targeting environmental flows (e-flows) towards restoration of historic natural flow patterns (the 'natural flow regime paradigm') is shifting towards the goal of managing for social-ecological resilience in an adaptive management framework that explores trade-offs and embraces learning and adjustment of goals and practices as outcomes emerge over time (Poff et al., 2016; Poff, 2018).

Thoms and Fuller (2024) promote social-ecological resilience thinking, and "rehabilitation" as the preferred terminology for efforts to sustain and protect robust, diverse and functional freshwater ecosystems under situations of future environmental and sociological uncertainty. Future-proofing the freshwater Emergency Recovery Plan sets out options and opportunities to safeguard ecosystems against future environmental and sociological uncertainties and build ecosystem resilience to shocks and surprises (Lynch et al., 2024). Nature-based Solutions (NbS)[6] and Green or Natural Infrastructure address major societal challenges (such as flood and drought mitigation) and human wellbeing while simultaneously enhancing the biodiversity and resilience of ecosystems, their capacity for renewal and provision of services. Specific NbS can be qualitatively linked to several of the six

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[3] https://sustainabledevelopment.un.org/sdgs

[4] https://www.cbd.int/doc/c/409e/19ae/369752b245f05e88f760aeb3/wg2020-05-l-02-en.pdf

[5] https://www.decadeonrestoration.org/about-un-decade

[6] https://iucn.org/our-work/nature-based-solutions

conservation goals of the freshwater biodiversity Emergency Recovery Plan (Tickner et al., 2020) in win-win contexts (van Rees et al., 2023). However, applications of trade-off procedures (e.g., Thieme et al., 2021; Opperman et al., 2023) during NbS practice and biodiversity conservation planning are limited and warrant far more attention. van Rees et al. (2025) call for integration of conservation practice/ecological knowledge with Integrated Water Resources Management as a promising avenue for addressing trade-offs between human and ecological water needs. The broadest goals of Target three of the Global Biodiversity Framework relate to area-based conservation targets to achieve "ecologically representative, well-connected and equitably governed systems of protected areas", while "recognizing and respecting the rights of Indigenous peoples and local communities" (CBD, 2022). Biodiversity knowledge co-production and respectful engagement with stakeholders, Indigenous peoples and local communities will be critical to achieving these ambitious GBF conservation goals.

Leveraging robust scientific knowledge, governance, funding and policy to inform freshwater restoration and conservation action plans (e.g., ERP, GBF 30 × 30, SDGs, NbS, The Freshwater Challenge[7]), and even to exceed their present targets, while simultaneously safeguarding resilient social-ecological systems and human wellbeing under climatic and other uncertainties, is our outstanding mission for the next decade.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AA: Project administration, Investigation, Conceptualization, Writing – review and editing, Writing – original draft.

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[7] https://www.freshwaterchallenge.org/

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Navigating Earth's biogeochemical dynamics: Integrating elemental cycles, anthropogenic pressures and planetary boundaries

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Anthropogenic activities increasingly alter Earth's biogeochemical cycles, threatening the integrity and resilience of critical planetary systems. This perspective paper highlights the pivotal role of biogeochemical cycles in global sustainability challenges such as climate change, biodiversity loss, land degradation, and water scarcity, underlining feedbacks that exacerbate ecosystem degradation and diminish Earth's self-regulating capacity. Advances in integrated Earth system models demonstrate the necessity of capturing nutrient interactions to accurately predict ecosystem productivity and carbon sequestration, particularly under nutrient-limited conditions. The emergence of novel entities introduces unprecedented vulnerabilities to elemental cycles, with their long-term impacts and planetary boundary exceedances still poorly understood. These challenges, coupled with nutrient boundary exceeding and ongoing climate change, regional variability and nonlinear and cascading responses emphasize an urgent need for interdisciplinary research, enhanced monitoring, and robust regulatory frameworks, supported by advances in modeling, big data analytics, and artificial intelligence.

KEYWORDS

climate change, pollution, biogeochemical cycles, novel entity, planetary boundaries

Introduction

Understanding Earth as an integrated physical, chemical, and biological system, and the consequences of human-induced disturbances is at the core of modern biogeosciences (Steffen et al., 2020). Biogeochemistry deals with how elements circulate through the atmosphere, biosphere, hydrosphere, and lithosphere, sustaining life and regulating planetary processes. This understanding is increasingly vital as climate change and different anthropogenic pressures accelerate. The Biogeochemical Dynamics section of Frontiers in Environmental Science, launched in 2019, offers a dedicated platform for advancing knowledge on the complex interactions among biological, geological, and chemical processes (Slaveykova, 2019). As we progress through the 21st century, this multidisciplinary section stands at the forefront of disseminating cutting-edge scientific knowledge and impactful discoveries in the field of biogeochemistry to researchers, industry, policymakers, and the public worldwide. Wide spectrum of research topics spans from greenhouse gasses, such as methane cycling (McGinnis et al., 2023) to ecological risks posed anthropogenic particles (Mitrano et al., 2021), from distinct dynamics of biogeochemical cycling within wetland (Rezanezhad et al., 2020) to urban systems (Mitchell et al., 2023) and cold regions in transition (Rezanezhad et al., 2023).

But what's ahead signals growing concern: the integrity of Earth's biogeochemical cycles is increasingly threatened by anthropogenic activities, which are altering the natural flow, transformation, and storage of essential elements across atmospheric, terrestrial, and aquatic systems (Bertrand and Legendre, 2021; Ciais et al., 2014; Friedlingstein et al., 2025). These alterations have far-reaching consequences, intersecting with major global sustainability challenges, including climate change, land degradation, biodiversity loss, and water scarcity (Fletcher et al., 2024; Lenton et al., 2008; Lieu et al., 2025; Wang et al., 2024). Big data analyses confirmed widespread planetary decline but also highlight areas of resilience and recovery (Runting et al., 2020).

Climate change is both a driver and consequence of biogeochemical cycle disruption (Friedlingstein et al., 2025). As warming intensifies, interactions between the C, N, and P are expected to become more dynamic potentially reshaping ecosystem processes in complex ways (Luo et al., 2022; Menge et al., 2023; Zhang et al., 2020; Zuccarini et al., 2023). However, the direction and scale of these changes remain uncertain, as biogeochemical responses vary across systems (Cui et al., 2025). The interconnection of C, N, P, and other elemental cycles means perturbations can cascade, complicating predictions and management efforts (Gruber and Galloway, 2008). Simultaneously, *land degradation*, often exacerbated by unsustainable land-use practices, has led to altered soil nutrient dynamics and declining ecosystem productivity, further weakening biogeochemical resilience (Amelung et al., 2020; Burrell et al., 2020; Gibbs and Salmon, 2015). Biogeochemical imbalances also underlie the ongoing *global biodiversity crisis*. Imbalance of global nutrient cycles exacerbated by the greater retention of P over N potentially leading to biodiversity losses within lakes and algal blooms in downstream N-limited coastal zone (Wu et al., 2022). Nutrient enrichment from agricultural runoff, such as excess N and P, disrupts aquatic food webs and contributes to hypoxic zones and species loss in freshwater and coastal systems (Devlin and Brodie, 2023). Conversely, diverse plant and microbial communities' buffer against nutrient losses by enhancing element retention and recycling. They degrade the natural capacity of ecosystems to regulate essential and toxic elements, with cascading effects on climate, water quality, and food security. Preserving and restoring biodiversity—especially in soils—is critical for maintaining stable and resilient biogeochemical cycles. Moreover, *water scarcity and declining water quality* are deeply connected to alterations in the hydrological and geochemical cycling of both nutrients and pollutants, especially in regions undergoing rapid climate and land-use change (Akhtar et al., 2021).

What is the Earth capacity to support disruptions to biogeochemical cycles due to the anthropogenic activities without crossing critical thresholds? This is a key question in biogeochemical dynamics research because Earth's systems operate within finely balanced thresholds, and exceeding limits can trigger cascading effects (Rockström et al., 2024b). The planetary boundaries framework (Rockström et al., 2009; Steffen et al., 2015) identifies nine Earth system processes with proposed "safe operating spaces". This framework allows define safe limits for the elements of Earth's biogeochemical cycle and assess the stability of Earth's life-support system. Among the nine identified boundaries, biogeochemical flows of N and P, along with C (through climate change) cycle disturbance, have emerged as some of the most severely stressed (Richardson et al., 2023). These cycles underpin core ecosystem functions, such as primary productivity, soil fertility, and water quality.

Biogeochemical cycles are *tightly interconnected*, and their interactions critically shape ecosystem productivity and resilience. Yet many Earth system models still simulate these cycles in isolation, missing key feedback and nutrient co-limitations. Recent modeling advances, such as the dynamic land ecosystem model, show that coupling C, N, and P cycles significantly improves predictions of carbon sequestration, especially under phosphorus-limited conditions in tropical ecosystems (Wang et al., 2020). This emphasizes the need for integrated models that reflect the complex interdependencies among elemental cycles. Integrating micronutrient dynamics into Earth system models is also essential for accurately predicting ecosystem responses to global change. In marine systems, nutrients like Fe, Mn, Zn, and Co are vital for phytoplankton and carbon cycling (Tittensor et al., 2021) but are often underrepresented. Modeling shows that climate-driven changes, such as ocean stratification, can disrupt micronutrient availability and affect primary production (Bian et al., 2023).

Biogeochemical dynamics is characterized by non-linear interactions, feedback loops, and cross-scale processes, which represent a challenge for predictive ecological modeling (Jones et al., 2024). Traditional process-based models, while indispensable, often struggle to integrate high-dimensional, heterogeneous data streams in ways that capture emergent patterns across Earth system boundaries (Jones et al., 2024). In such context, artificial intelligence (AI) offers promise for tracking, pattern recognition, and forecasting (Gupta et al., 2023; Irrgang et al., 2021), as well as for quantifying safe operating spaces and helping reduce risks to human and planetary health (Rockstroem et al., 2023). This aligns with the One Health concept, which emphasizes integrated approach across environmental, animal, and human health (Pitt and Gunn, 2024). However, the full potential of AI in this field is still emerging. It was highlighted that transforming existing process-based models into neural network-based tools could enable predictive insights into key ecological processes, harnessing the full potential of the big data revolution (Alexandrov, 2025).

Recent inclusion of *novel entities*, including synthetic chemicals, plastics, pharmaceuticals, nanomaterials added a new dimension to biogeochemical "vulnerability" of the Earth system (Persson et al., 2022). For instance the persistence and global spread of four selected per- and polyfluoroalkyl substances (PFAS) in the atmosphere has led to the planetary boundary for chemical pollution being exceeded (Cousins et al., 2022). Unlike traditional pollutants, novel entities do not cycle through the environment in predictable or reversible ways, and their long-term impacts on global biogeochemical processes are still poorly understood. Their persistence and interactions with elemental cycles remain poorly understood and largely under-investigated. A recent study has demonstrated that the plastic pollution exacerbated all planetary boundaries (Villarrubia-

Gómez et al., 2024). Understanding the influence of novel entities on biogeochemical cycles remains thus a critical frontier in environmental science.

Together, the overshoot of nutrient boundaries and the rise of persistent *novel entities* signal that the planet's buffering capacity is nearing critical limits. Addressing these interlinked threats demands not only limiting excess nutrient flows but also investing in early detection, monitoring, and regulation of novel substances. Interdisciplinary research is urgently needed to define safe exposure thresholds and understand how these emerging stressors interact with global element cycles under accelerating climate change. Furthermore, very recent study revealed that even under optimistic scenario with strong environmental policy measures, critical boundaries, in particularly those related to climate change, biogeochemical cycles, and biodiversity, are projected to remain exceeded by 2050 due to systemic inertia and delayed responses (van Vuuren et al., 2025).

Recent advances have improved quantification of planetary boundaries, yet significant uncertainties remain, particularly regarding regional variability and nonlinear responses in coupled biogeochemical cycles (Schulte-Uebbing et al., 2022) and crucial to defining safe operating spaces that balance human development with Earth system stability (Gupta et al., 2023). Understanding these thresholds is essential for shaping effective environmental policies, guiding mitigation strategies, and building resilience in socio-ecological systems (Rockström et al., 2024a). Research emphasizes the link between societal tipping points and ecological tipping points and highlight the necessity of unified understanding of the Earth by integrating physical components (atmosphere, cryosphere, land, ocean, lithosphere) with human and social processes (Lam and Rousselot, 2024). Bridging science and policy require integrated nutrient monitoring systems, institutional reform to enable cross-sector collaboration, and inclusion of social sciences to leverage behavioral change. Strengthening local governance is also essential for equitable, context-specific solutions. However, translating this knowledge into effective governance remains a major challenge (Rockstroem et al., 2023). Governance tools for integrating land use, water management, and climate action are still fragmented. Integrated policy frameworks and technology-enabled monitoring, such as AI and satellite tools, are critical for real-time tracking of nutrient flows and emissions. Additionally, stronger regulation of novel chemical entities is needed to prevent accumulation and long-term ecological harm.

Looking ahead, biogeochemical cycles will encounter multifaceted and interdependent challenges necessitating integrative scientific and policy approaches. While current understanding acknowledges that Earth's capacity is finite and under strain, there is urgent need for *more spatially resolved, process-based insights*. The biogeochemistry community is actively working on refining models, identifying thresholds, and providing actionable knowledge to avoid irreversible ecological change. The forthcoming decade represents a pivotal period for advancing scientific understanding and policy implementation to prevent ecological overshoot and to navigate toward sustainability.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

VS: Writing – review and editing, Writing – original draft, Investigation, Project administration, Conceptualization.

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Turning the tide–why cities can be both drivers of climate change and biodiversity loss, and leaders in tackling them

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Preface. This perspective uses the key features of the “city” system to prevent the triad of climate, biodiversity and socio-economic inequality crises from worsening. In other words, global change key drivers know how to make things better. The perspective discusses the idea of cities as both a cause and a solution to planetary challenges, such as climate change, biodiversity loss and socio-environmental as well as health inequalities. Unlike many other articles on urbanisation as a driver of environmental problems, this article does not focus exclusively on this role. Instead, it links urbanisation to its tremendous potential to both cause and solve these environmental problems, drawing on the enormous innovative and communicative talent inherent in cities and urban societies. It offers a fresh, serious yet optimistic look at the role of cities in the global race to prevent critical tipping points for a broad urban-focused audience.

KEYWORDS

urban system, cities, climate change, tipping points, transformative change, responsive policies

Fundamental changes ahead challenging an increasingly urban world

As our planet undergoes fundamental changes, the stability of social and economic structures is also being called into question. Whether climate change, species extinction or socio-economic inequality, critical thresholds have been reached everywhere (Tomalka et al., 2024). And these thresholds are closely interlinked, spatially and functionally: When we think about the threat to habitats for all species—humans, plants and animals. In order to effect a change in the prevailing circumstances, it is primary imperative that we implement wide-ranging and fundamental societal transformations. That means we have to ameliorate the egregious disparities in wealth, education and income. Above all, it is essential to engage in open and conflict-inclusive communication about these urgently needed transformations. This communication must address both the change-related losses (Reckwitz, 2024) suffered and the options for (re-)gain involving an application of the broad and reliable body of knowledge we have. Here is both, an inventory and a perspective on how this can be achieved which ultimately places cities as decisive units or entities at the centre. In other words, this polemic sets out the argument that in particular cities and their urban populations are capable of exerting a significant influence on these fundamental changes, namely all—climate change, biodiversity loss and socio-economic inequities. This way, they could serve as frontrunners in the fight against the consequences of the causes, and the causes themselves, which they themselves generate, i.e. to a certain extent to be against one's own way. If we let them.

But first things first.

Our earth is heading towards several critical turning points

Our globe is a complex, constantly evolving system. Any changes are therefore largely irreversible, which means that there is no way back to the *status quo ante*: Even if global warming were to be reduced to 1.5 °C again after exceeding critical limits, a collapsed (tropical or other) forest will not be able to re-develop in a climate-shaping way. And a dead coral reef will not simply rise again. What is more, persistent multiyear droughts develop into a growing threat to nature and humans, especially in densely populated urban areas (Chen et al., 2025). Neither the North Pole would most probably not freeze over again, nor the increased sea level would not return to pre-industrialisation levels or the year 2015 of the 1.5-degree Paris Agreement for several millennia. Thus, novel coastal landscapes, including urbanized areas and coastal cities, will inevitably emerge. And not just in the lower latitudes, but everywhere. And most likely even faster in Europe than in other regions of the world, which would entail a dramatic sequence of loss and gain with a very concrete physical manifestation, namely in terms of space and place (van Oldenborgh et al., 2009). Numerous scientific studies warn that the global climate system and the rapidly declining biodiversity could be put into a state in which they irretrievably lose their stability as a result of human impact (Lenton et al., 2023). Many elements of the earth system can initially buffer external influences, are then stressed, but still appear stable and unchanged. At some point, however, it becomes too much, a threshold value is reached and one more drop causes the proverbial barrel to overflow. Then a tipping point is passed, not yet to be confused with an ecosystem or societal turn (see Hillebrand et al., 2023, for biodiversity and ecosystem change; Bentley et al., 2014; Milkoreit, 2023, for social system change and social tipping points).

Cascades of feedback

Typical characteristics of a tipping point are accelerated changes after a threshold has been crossed, which are often self-reinforcing due to feedback effects. The development can then neither be stopped nor controlled until a completely different, more stable and often irreversible system state is reached, to which both, society and the economy, must then adapt. The new system states could fundamentally change the living conditions on our planet - with potentially devastating consequences for humanity and its societies (Dombrowsky et al., 2024), especially in its concentrated form in cities. The probability and depth of such a system transformation are characterised by feedback loops and tipping points in the Earth system. If, for example, the planetary boundary of species and biodiversity loss is exceeded, other tipping points also shift and the system as a whole becomes more sensitive and fragile (Rockström et al., 2024). It can, therefore, happen that the crossing of one system boundary influences others and also contributes to boundary crossings there: For example, it makes the risk of zoonoses and pandemics more likely (Rupasinghe et al., 2022).

The positive feedback of the tipping points and the resulting domino effect is known as the tipping cascade. The more the planetary boundaries are exceeded, the closer we come to this tipping cascade. The planetary boundaries, such as the changing climate, biodiversity and ecosystem integrity, not only define ecological thresholds, but also have profound and potentially irreversible effects on the socio-economic fabric of our societies, again, in particular of our core settlement areas, the cities: If wheat and maize no longer grow due to climate conditions in Central Europe, if the irrigation of agricultural crops becomes impossible due to, at least temporary, water shortages, if fruit and other foods no longer thrive due to a lack of pollinators, i.e. insects, if climate-related healthcare costs in cities become so high that healthcare systems collapse, then there is a risk of widespread societal collapse, spatial segregation and fortressing and, inescapable, deep conflicts ahead as we experienced during the corona crisis (Armocida et al., 2020). It is almost impossible to predict exactly when the ecological limits will be exceeded or when critical species diversity levels will be undercut, and trophic systems will collapse, partly because these types of feedback loops are not yet fully integrated into climate models, just as little as social feedback (Rockström et al., 2024). The current plans to reduce emissions on the one hand and to protect biodiversity. On the other, may therefore not be sufficient to adequately limit future global warming and the loss of habitats and biodiversity.

Societies and their social and economic as well as cultural systems are once again an order of magnitude more complex, making it difficult to predict societal reactions and conflicts. However, the importance of reduction and adaptation processes as well as protective measures for the non-human living world can hardly be overemphasised. Recent studies show that the ecological and social 'tipping point risk' increases with every tenth of a degree above 1.5 °C of global warming, and even faster with an increase of over 2.0 °C (Emmerling et al., 2024), which is already exceeded today. At the same time, recent health studies show that humans have been adapting to global warming since the middle of the 20th century. Thus, the effects of heat on morbidity and mortality have been progressively reduced when cold related deaths are also included (Pintor, 2024). However, it is not possible to predict when the limits will be reached.

Tipping is an ongoing property of the system

Thresholds and tipping points exist in ecosystems and biodiversity systems, but also in our (post)modern (neo)liberal economic and social systems, including cities. They may have different origins, but in all cases, it is difficult to predict either their exact location or their timing. The fact that they have been crossed is usually only realised afterwards, when it is too late. One such tipping point was reached in the financial crisis of 2008, at first glance an economic feature, at second glance an urban economic feature, when the first major bank collapsed, the fragility of financial market structures became apparent and the entire financial industry had to be rescued by the state, which had previously often been demonised. Other tipping points were the oil and gas price crises of the 1970s and 2022, which led to a far-reaching restructuring of the energy system. The most impressive political tipping point was the collapse of the Soviet Union and the socialist pact system 35 years ago, triggered by economic and social upheaval, similar to the French Revolution more than 200 years ago. The former created an enormous path dependency with violent consequences such as the war in Yugoslavia or Russia's current war of aggression against Ukraine (D'Anieri, 2023). Not to be forgotten at this point is the Arab Revolution in the 2010s, which most likely among others had climate change-related triggers, namely persistent drought (Kaniewski et al., 2012). Today, there is a looming threat of systemic change, if it has not already become apparent, in the so-called 'illiberal democracies' and under the leadership of far-right political parties. The fundamental objective of politics must therefore not be to allow events to run their natural course until the established limits are reached and then intervene (if such intervention is indeed possible). Instead, the fundamental objective of politics must be to maintain a safe distance from the danger zone and to prepare adequately for the inevitable crises that will arise. And here we can and must draw a connection to climate change, the loss of biodiversity and the resulting increasing incidence of vector jumps between animals and humans, but also between wild animals and farm animals.

Society has immanent momentum when embracing its ambivalence

We are already so close to the tipping points of the Earth system that the targeted creation and activation of positive tipping points to redirect economic and social trends are the only realistic option for limiting systemic risk (see Snizhko et al., 2024, for the Ukraine under war). This requires political action and societal mobilization, broad scope for understanding and judgement including ambivalent views, changes in behaviour and norms building on this, and, at the end, considerable financial investment and technological innovation (Hernandez et al., 2024). The electricity sector in many countries has recently passed the tipping point of cost parity for renewable electricity generation. However, the momentum of decarbonisation has so far been held back by billions in subsidies for fossil fuels, which therefore urgently need to be reduced (Østergaard et al., 2022). In addition, measures to avoid energy-intensive activities and to shift to less energy-intensive activities, i.e. sufficiency policy, are still lacking. However, there will not be a revival of coal and nuclear power, but the pure futile endeavours to achieve this may cost time and money, which will then be sorely lacking for climate protection. Worse still is the example of proxy decisions at the COP16, the United Nations Biodiversity Conference, in Cali, Colombia, in Pusan, South Korea, or Lisbon, Portugal, at the failed plastic waste summits, all in 2024 or 2025: Most visible in Cali, token progress was celebrated by recognising the core role of indigenous peoples in biodiversity conservation, as if this decision had made any effective contribution to mitigating the current loss of biodiversity (Euronews, 2024).

To explain what I mean, let's look at just one example: The most important political measure would be the introduction and enforcement of strict sector-specific limits and targets that force technical and organisational innovations and have a knock-on effect on other sectors - creating positive tipping points. This opportunity was offered by the Climate Protection Act with its sector targets but was removed due to a lack of interest and assertiveness on the part of several European governments, for example. Instead, the survival of the fossil fuel industry is being ensured by conservative ministries across the continent through technical sham solutions such as CCS (CO_2 capture and storage) at a cost of billions.

This example makes clear, that both necessary scale and speed of change can only be achieved with sufficient public consent and acknowledging societal ambivalences (Haase and Dushkova, 2024): Instead of reducing participation rights with fast-track laws, the public should be involved in the relevant decision-making processes and a clear understanding, on the one hand. Enormous opportunities, above all saved lives, improved health and wellbeing, better jobs, clean and cheap energy, as well as the risks and losses of rapid change, on the other. Crisis preparation and climate adaptation, together with honest communication that does not conceal the burdens of transformation but offers help to the socially vulnerable and low-income households in particular, are necessary not only to avoid overburdening institutions. For successful transformative change, there is also a restoration of the damaged credibility of politics and government action needed (Hernandez et al., 2024). Listening to the concerns of citizens, exchanging viewpoints between different peer groups, looking for solutions together and keeping promises strengthens democracy and removes one of the strongest current obstacles to transformation, the rise of right-wing radicalism (Jylhä et al., 2020).

Avoiding ecological tipping points by respecting planetary boundaries is of central importance for the continued existence of our civilisation and of nature itself. To achieve this, far-reaching social and economic changes are needed that develop sustainable economic systems, strengthen socio-environmental distributional, procedural and interactional justice (Low, 2017) and improve international cooperation, namely transformations that can only become effective in time through positive tipping points (Everall et al., 2024).

To turn the tide according to the polluter pays principle—the role of cities

The accumulation and manifestation of collective and individual experiences of permanent change including gain and loss of, on the one hand, and unequal access to natural resources and biodiversity is a subject that has been the focus of much scholarly attention (Temper et al., 2015). As demonstrated in this text, cities and urban societies are frontrunners in several senses. Firstly, they now concentrate almost 60% of the world's population (UN-Habitat, 2025). Secondly, they are among the main causes of the processes of climate change and biodiversity loss discussed here. At the same time, cities are frontrunners in driving, experiencing and negotiating change: Cities are subject to a material transformation of their (non)-built substance, which takes place either disruptively through human-made wars, place-based ecological disasters or authoritarian urban redevelopment. Or cities force an incremental process of creative destruction through societally, economically or politically motivated renewal (Kılkış et al., 2024).

However, losses that are inextricably linked to these dynamics are experienced, remembered and dealt with in divergent ways in urban areas. And Reckwitz (2024) speaks here of individual losses or perceived declines as well as those specific to society as a whole or income classes ('decline' of the middle class's which is definitely most pronounced in cities). Consequently, cities function as the social arenas for the discursive negotiation and narrative processing of experiences of loss and gain that arise as a result of transformations in demographic, social, political and environmental factors, including climate change and biodiversity. The narratives and memories associated with these experiences find their systemic and spatial expression in the city and beyond (the peri-urban). And it is precisely the role of cities and urban societies as co-creators of crises and losses as well as the sites of their negotiation for the future to crosslink these thoughts to what was said above about current biodiversity loss *"…to make use of diverse sources of information to better account for the diverse relations between people, other species and the ecological, social, cultural, economic, technical and increasingly digital structures that they are embedded in"* (Andersson et al., 2024; p.813).

In consideration of this background, the analysis of how experiences of loss, in more general, for example, when cities shrink, when cities get flooded or when cities loose its nature and biological diversity, are addressed and processed in their spatial narratives (e.g. mourning, nostalgia, protest, *etc.*) becomes a central element for comprehending late modern urban development and pivotal for any future of and in cities facing global change. An examination of the urban conditions of loss illuminates both the heterogeneous losses in the city and at the same time how cities deal with it, adapt or negotiate fundamental changes and ultimately implement them. These fundamental transformations affect and can rely on the whole urban system including social structures, identities, communicative processes of conflict, negotiation or compromise, and their spatial, urban natural, semi-natural designed and built forms of expression.

Utilising the polluter-pays principle and the polluter-pays responsibility wisely but imperatively would offer a realistic opportunity to prevent or at least mitigate the global tipping points, discussed in the first part of this perspective, be they of climate, biodiversity or inequality nature. The protection of planetary boundaries is therefore not at all only an environmental or ecological necessity, but also a social and political one, in order to secure a sustainable and more just future for all. Therefore, it is no longer a question of intellectual subjunctive but of practical imperative that cities, as the centre of life for almost 60% of the world's population, should be given a leading role in international decision-making on sustainable development, and not just nation states. Existing networks include the UNESCO Global Network of Learning Cities (GNLC) and the C40, a global network of nearly 100 mayors from leading cities who are united in acting against the climate crisis. They have large potential to drive greater sustainability and transformative change than has been realised so far.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

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Next generation of domestic wastewater management

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The next generation of wastewater management must go beyond centralised treatment to meet emerging environmental and regulatory demands. This study explores source separation as a complementary strategy that enables the tailored treatment of greywater, urine, and faeces. By decentralising processes and recovering resources, especially nutrients and energy, new systems can reduce greenhouse gas emissions and nutrient loads on existing infrastructure and receiving environments. Innovations in urine concentration and fertiliser production demonstrate the feasibility of turning waste into valuable products. A paradigm shift towards source-separated sanitation is essential for climate neutrality and staying within planetary boundaries.

KEYWORDS

recycling, source separation, sanitation, resource recovery, urine

Following the implementation of waterborne sewer systems, the development of wastewater treatment plants has progressed in stages to increasingly focus on mitigating environmental pollution and removing harmful substances. These developments have focused on centralising wastewater treatment with the value of a large scale. Treatment plant processes have been optimised to efficiently remove targeted pollutants in an energy-efficient process. The next stage in the development of centralised treatment plants is the removal of micropollutants driven by the update of the EU Urban Wastewater Directive (EU 2024/3019). The updated directive will further enhance nitrogen and phosphorus removal. At the same time, many municipalities are striving to decrease their environmental impact, with waste and wastewater management playing an important role. The focus is on decreasing emissions of greenhouse gases with the aim of becoming carbon-neutral; this also affects wastewater treatment plants with restrictions on treatment processes and chemical input. Each of the above factors lead to an increased need for further advances in the functions and operations of treatment plants by improving current processes and developing new ones.

The major objective of wastewater treatment is still pollution prevention. However, in some cases resource recovery is included as a component. The two main resources that are recovered are energy and phosphorus. Energy is recovered both as heat from incoming water and as methane production from carbon in the sludge. The recovery of phosphorus is relatively simple as it is easy to separate and recover, especially when the full sludge is recycled. When the sludge is incinerated, the recovery is somewhat more challenging but still manageable (Nilsson et al., 2025). Technologies are being developed to recover phosphorus from wastewater sludge by different types of extraction (Ottosen et al., 2022). Nevertheless, a sole focus on phosphorus recovery still requires large volumes of chemicals and energy.

One alternative to centralised wastewater treatment is to move in the same direction as solid waste management. Over the last 30 years, Europe has gradually introduced an increasing number of different waste fractions—both domestic waste and producer responsibility schemes (Arkady et al., 2024). Sweden currently sorts domestic waste into

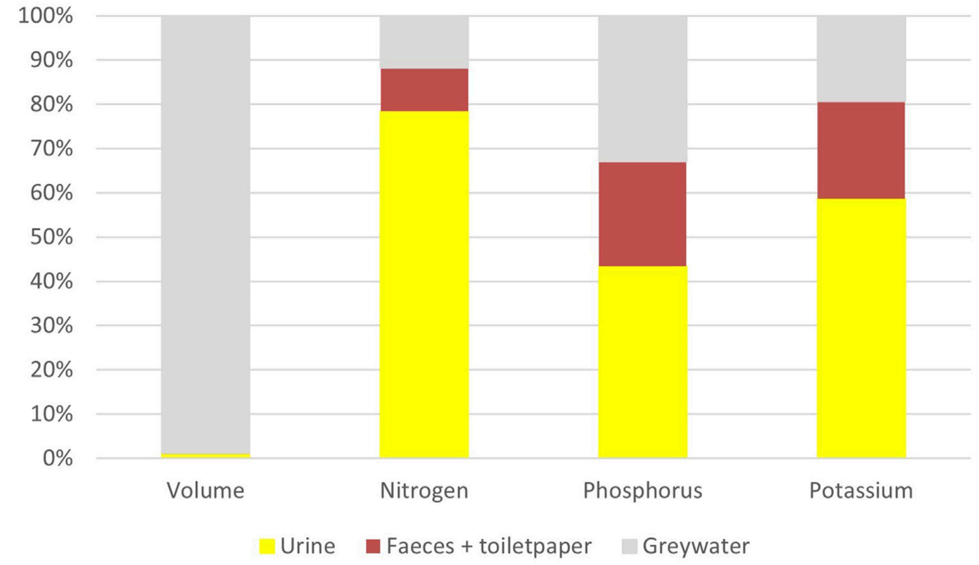

FIGURE 1
Distribution of volume and plant nutrients in urine, faeces + toilet paper, and greywater (Vinnerås et al., 2006).

eight fractions at home, in addition to textiles. Over ten more fractions under producer responsibility, such as batteries and used nicotine products, are supposed to be collected at central collection points.

In the wastewater sector, source separation could complement centralised domestic wastewater treatment systems. Moving some of the treatment closer to the source could decrease the need for several complicated and costly improvements of current centralised treatment systems. To some extent, this has already started with industrial wastewater and wastewater from carwash facilities (Rubí et al., 2009). There are still challenges in moving household wastewater towards source separation, as legislation is largely based on centralised wastewater treatment. Policies are also based on current wastewater management systems, making the introduction of complementary systems challenging. For instance, introducing source separation places pressure on individual to invest in the system and ensure the correct management and use of all products. In contrast, households connected to the central sewer only pay for the connection and are not responsible for anything more than assuring that the pipe is connected to the municipal sewer line at the edge of the property and paying the required connecting fees.

When looking at domestic wastewater fractions, we often divide them into three fractions by volume: greywater, urine, and faeces (Figure 1). Greywater is the fraction containing the majority of energy, both in the form of biodegradable carbon (COD, or KWh per person and year) as well as in the form of heat (kWh per person and year). Urine is the fraction containing the majority of plant nutrients, as it reflects elements taken up by the body, together with the main proportion of consumed pharmaceuticals. The concentration of heavy metals is very low, especially when looking at non-essential heavy metals. For the smallest fraction, faeces, the concentrations of plant nutrients are similar to those in urine but with lower plant availability, as the elements are either bound in organic biomass or, in the case of P, are precipitated as metal phosphates. The concentration of heavy metals is somewhat higher, and the risk of pathogens is considerably higher. Instead of mixing these fractions directly, they could be managed separately in accordance with their composition and then used as resources. Urine and faeces could be ingredients for blending as suitable fertilisers, together with other fertiliser products (Perez-Mercado et al., 2024). The challenge with most circular fertilisers is that the water content is too high for efficient fertilisation while it is too low and is often applied at the wrong time to support the need for irrigation. To reach an efficient circular fertiliser system, the nutrients need to be concentrated and be minimally diluted in water.

Currently, many cities have problems with their wastewater piping system, as it combines water from several sources. Furthermore, ageing systems need to be repaired and replaced, or systems serving a declining population may become oversized. When introducing a source-separation system, the most convenient approach today is not to centralise the piping but to decentralise treatment and then tap into other urban transport systems to handle the concentrate as one extra fraction of solid waste (Aliahmad et al., 2025). Integrating wastewater fractions into solid waste management will be challenging, as it is a major paradigm shift compared to the earlier mentality of increased piping and an end-of-pipe solution for every form of waste and wastewater.

Research on source separation is growing in relation to research on wastewater treatment (Aliahmad et al., 2022). Nevertheless, the proportion of research related to this topic is small in comparison to conventional sanitation. Current research into on-site wastewater management is focused on local water reuse mainly from greywater and fertiliser production from urine only or the mixed toilet fraction. The driving forces behind these local solutions differ significantly from those related to capacity limitations in existing wastewater systems, where new domestic customers would result in an overload of the current sewer system. Other challenges are related to overloading the sewage treatment plant with nutrients. In contrast, reducing nutrient loads could result in a better nitrogen–carbon balance for improved nitrogen removal.

In the context of greywater treatment, the predominant technologies are conventional systems based on filtration and membrane processes. These systems are typically implemented at the local scale to produce reclaimed water for non-potable applications, either within buildings, using dual distribution networks for potable and non-potable water, or externally, such as for landscape irrigation (Buehler et al., 2025).

For blackwater, the technological development is either low-tech sanitisation and reuse of the full fraction as fertiliser in agriculture or a technology more or less similar to conventional wastewater treatment with aerobic biodegradation combined with the precipitation of phosphorus and stripping of ammonia nitrogen (Kjerstadius et al., 2015). For low-tech systems, sanitisation is long-term storage longer than 6 months, in accordance with WHO guidelines. By using ammonia-based treatment, where the function of uncharged ammonia is utilised for sanitisation, the treatment time can be significantly shortened, and the end-product will be of higher hygienic quality. A combination of intrinsic and added ammonia raises the pH of the material. With a pH above 8, a proportion of the ammonia will be found in uncharged form. As the effect of the sanitisation is based on the presence of uncharged ammonia, the treatment time will be regulated by factors of pH, temperature, and total ammonia nitrogen concentration. The higher any of the three parameters, the more efficient the sanitisation process (Magri et al., 2015).

The main development in source separation technologies are new urine concentration systems. The key in this technology is to remove the water fraction from the solutes in the urine and then use the concentrate directly as fertiliser or as the main ingredient in fertiliser production (Larsen et al., 2021). It is a new technology that is expanding from an initial focus on urine treatment collected at events to now also being implemented at full scale in office buildings and at football stadiums. There are two main technologies that have been developed in parallel: the partial nitrification of hydrolysed urine (Larsen et al., 2021) and stabilisation of the urine by raising the pH above 10 or lowering it below 4 (Vasiljev et al., 2022; Simha et al., 2023). This is then followed by water removal either by vacuum distillation or convective drying. Two different fertiliser products have been produced and are available on the market. One is Aurin, a liquid fertiliser with a concentration factor 5 of urine, which is mainly intended for household use but has been tested in agriculture as well. The second is Granurine, a solid fertiliser with a concentration factor 20 that is intended for use in agriculture. Creating commercial fertilisers with a strong market potential can be the driver for pollution prevention by resource recovery.

The research and development of these treatment technologies show that it is possible to transfer a wastewater fraction into a fertiliser product that is valued by farmers (Simha et al., 2017). By doing this, we can achieve multiple gains ranging from local reduction in nutrient load to the wastewater treatment plant to global impacts on biogeochemical flows of nitrogen and phosphorus that are presently far outside recommended planetary boundaries (Rockström, 2025).

In conclusion, adopting a fraction-based approach to wastewater management, similar to solid waste sorting, offers significant environmental and resource recovery benefits. By separately treating greywater, urine, and faeces, we can tailor treatment processes to their specific compositions, reduce nutrient loads on centralized plants, and produce valuable fertiliser products. This shift requires updated legislation, supportive policies, and increased investment in research and infrastructure. Embracing decentralized and source-separated systems is essential for meeting climate neutrality goals and staying within planetary boundaries for CO_2 emissions and biogeochemical flows of nitrogen and phosphorus.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

BV: Writing – original draft, Writing – review and editing.

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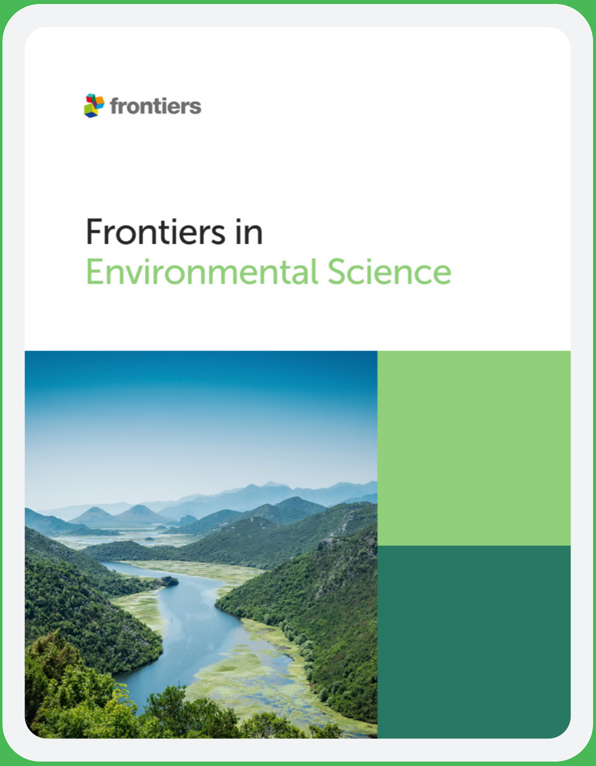

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