**World Journal of Environmental Biosciences**
Available Online at: **www.environmentaljournals.org**

**Volume 14, Issue 2: 88-97**

https://doi.org/10.51847/SNJfMp0pbS

**ISSN 2277- 8047**

# From Local Pollution to Planetary Boundaries: Reframing Environmental Contamination through Multi-Scale Systems Reviews

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**ABSTRACT**

*Environmental contamination has long been addressed primarily at local scales, focusing on site-specific pollution events and their immediate ecological and human health impacts. However, the escalating complexity of global environmental challenges necessitates a reframing of contamination through multi-scale systems perspectives, extending from local sources to planetary boundaries. This narrative review synthesizes recent literature to explore how local pollutants aggregate and interact across scales, ultimately influencing Earth's system limits as defined by the planetary boundaries framework. We examine the conceptual evolution of planetary boundaries, highlighting updates that underscore the transgression of multiple thresholds due to anthropogenic activities. Key themes include local-scale contamination sources such as industrial emissions and agricultural runoff, their escalation to regional transboundary issues, and their culmination in global phenomena like climate change and biodiversity loss. Employing systems thinking, we review integrative approaches that model multi-scale dynamics, including nutrient pollution in river systems and volatile organic compounds apportionment. Case studies on persistent contaminants like microplastics and per- and polyfluoroalkyl substances (PFAS) illustrate how local actions reverberate globally, often amplifying Earth system interactions. Challenges in data integration, modeling uncertainties, and policy alignment are discussed, emphasizing the need for holistic frameworks to achieve sustainability within safe operating spaces. By reframing contamination through multi-scale lenses, this review advocates for interdisciplinary strategies that bridge local remediation with global governance, fostering resilient environmental management in the Anthropocene. Ultimately, the objectives are to highlight gaps in current understanding and propose pathways for future research that integrate systems reviews to prevent further planetary boundary transgressions.*

**Keywords:** *Planetary boundaries, Environmental contamination, Multi-scale analysis, Systems thinking, Transboundary pollution, Sustainability*

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**Received:** 29 March 2025
**Accepted:** 19 July 2025

## INTRODUCTION

The Anthropocene epoch denotes a transformative period in Earth's history in which human activities have emerged as a dominant force shaping planetary systems, rivaling or exceeding natural processes in scale and intensity (Zhou *et al*., 2022). Industrialization, urbanization, and intensified resource extraction have profoundly altered atmospheric composition, biogeochemical cycles, land use patterns, and biodiversity. These changes have rendered environmental disturbances increasingly complex, nonlinear, and trans-scalar, such that localized human actions now propagate through interconnected Earth systems to generate regional and global consequences. In this context, environmental contamination can no longer be understood as a series of isolated incidents; rather, it represents a systemic phenomenon embedded within coupled socio-ecological systems.

Historically, scientific inquiry and environmental governance have addressed contamination primarily through localized lenses, focusing on discrete sources such as industrial effluents, mining operations, agricultural runoff, or accidental chemical spills (Lu *et al*., 2025). Regulatory frameworks and remediation strategies have accordingly been designed around site-specific risk assessments, emission thresholds, and jurisdictional boundaries. While these approaches have achieved notable successes in reducing acute exposures and improving local environmental quality, they often fail to account for the mobility, persistence, and cumulative effects of contaminants once released into the environment. Pollutants frequently transcend spatial and temporal boundaries via atmospheric circulation, riverine transport, ocean currents, and food webs, thereby linking local emissions to distant ecological and human health impacts (González-Pleiter *et al*., 2021). This disconnect between the scale of environmental management and the scale of environmental processes—commonly described as a scalar mismatch—has become increasingly apparent as global environmental change accelerates.

The limitations of localized contamination frameworks are particularly evident when viewed through the lens of planetary boundaries, a conceptual framework developed to define a safe operating space for humanity within Earth's biophysical limits (Richardson *et al*., 2023). Planetary boundaries emphasize that Earth system processes operate within threshold ranges, beyond which abrupt and potentially irreversible changes may occur. Recent assessments reveal that humanity has already exceeded six of the nine proposed boundaries, including those associated with climate change, biosphere integrity, land-system change, and the proliferation of novel entities such as synthetic chemicals and plastics (Rockström *et al*., 2023). These transgressions highlight how cumulative local activities—each seemingly manageable in isolation—aggregate to destabilize global systems. Environmental contamination, therefore, must be reconceptualized not merely as a local or regional concern, but as a key driver of planetary-scale risk.

Against this backdrop, there is a growing need for integrative, multi-scale perspectives that explicitly connect local pollution dynamics to global Earth system thresholds. This review seeks to address this gap by synthesizing literature published between 2019 and 2025 to examine how environmental contaminants move across spatial and organizational scales, interact with biogeochemical cycles, and contribute to the transgression of planetary boundaries. By reframing contamination as a systemic, cross-scale phenomenon, this work aims to advance a more holistic understanding of environmental risk and to inform governance strategies capable of operating effectively in the Anthropocene.

Systems thinking has emerged as a critical analytical framework for reframing environmental contamination in the context of complex, interconnected Earth systems. Rather than treating environmental components as discrete or linear entities, systems thinking conceptualizes ecosystems, socio-economic structures, and technological processes as dynamic networks characterized by interdependence, nonlinearity, and feedbacks across spatial and temporal scales (Voulvoulis *et al*., 2022). Within such systems, contamination is not merely the result of isolated emissions but an emergent property arising from interactions among multiple drivers, including land-use change, industrial metabolism, governance structures, and consumption patterns. This perspective enables a more comprehensive understanding of how small-scale perturbations may cascade through environmental systems, producing disproportionate and sometimes irreversible outcomes at regional or global levels.

Recent syntheses in global environmental health and sustainability science increasingly advocate for systemic interventions that target underlying structures rather than symptomatic outcomes (Mahaffy *et al*., 2019). These reviews emphasize the importance of identifying feedback mechanisms, tipping points, and leverage points—strategic nodes within a system where targeted interventions can yield transformative change. For instance, nutrient pollution management has evolved from localized mitigation efforts toward integrated, multi-scale modeling approaches that link catchment-level nutrient loading with regional hydrological processes and global biogeochemical cycles (Strokal *et al*., 2019). Such models enable the anticipation of downstream effects, including coastal eutrophication and hypoxic zones, illustrating how agricultural practices in one region may influence distant marine ecosystems. Similarly, studies of urban expansion within megaregions demonstrate that localized land-use decisions, when aggregated across rapidly urbanizing landscapes, drive broader environmental impacts such as altered climate patterns, biodiversity loss, and increased resource demand (Yang *et al*., 2022). These examples underscore the value of systems-based approaches in capturing cross-scale linkages that conventional analytical frameworks often overlook.

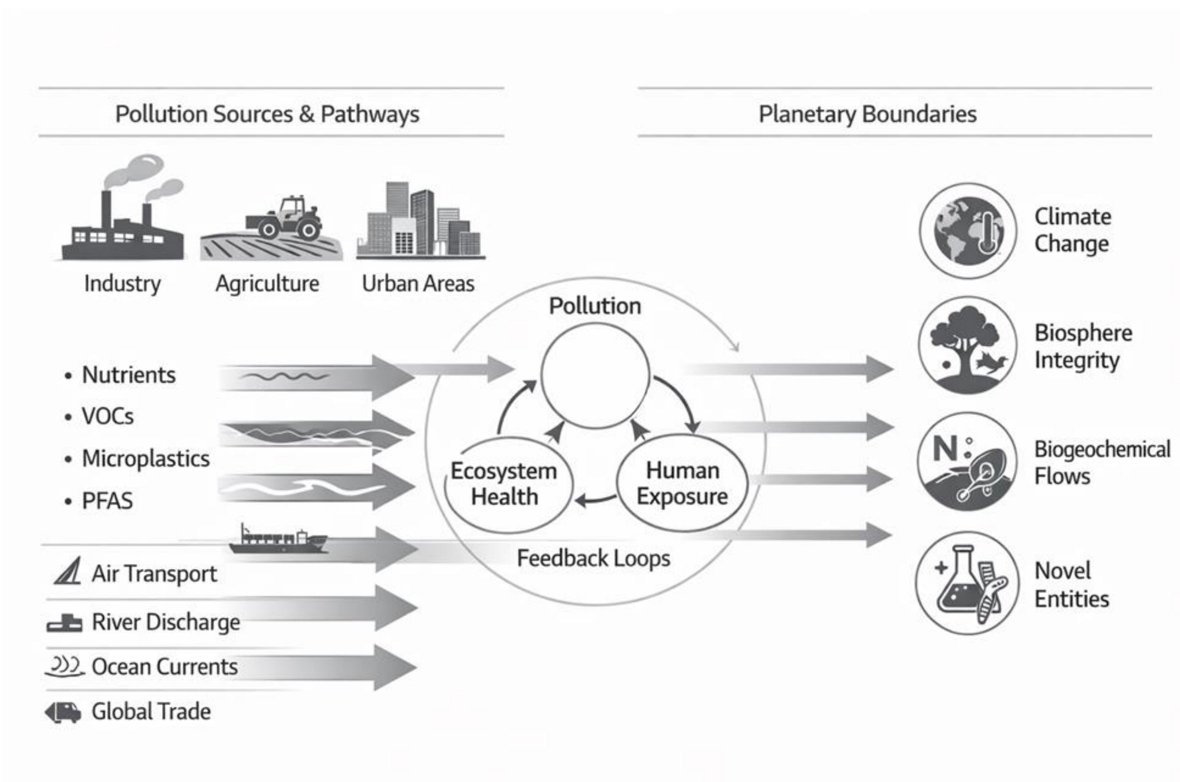


**Figure 1.** From Local Pollution to Planetary Boundaries: A Multi-Scale Systems Framework

Building on this systems-oriented perspective, the objectives of this review are threefold. First, it aims to synthesize thematic insights from recent literature to elucidate how environmental contamination operates and interacts across local, regional, and global scales. Second, it seeks to examine systems-based methodologies—such as integrated assessment models, network analysis, and multi-scale monitoring frameworks—that facilitate the integration of heterogeneous data and processes across scales. Third, the review identifies key challenges and opportunities associated with applying systems thinking to environmental governance, particularly in the context of achieving sustainability within the limits defined by planetary boundaries. By drawing on peer-reviewed research, this review offers a narrative intended to inform both policy development and future scientific inquiry, advocating for a shift away from fragmented, site-specific responses toward coordinated, planetary-scale strategies. Such a reframing is increasingly essential in light of compounded pressures arising from population growth, intensifying industrialization, and climate variability, all of which heighten the risk of exceeding Earth's safe operating spaces (MacLeod *et al*., 2021; Zhang *et al*., 2024).

*Local-scale environmental contamination: sources, pathways, and immediate impacts*

At the local scale, environmental contamination typically arises from discrete, identifiable sources whose impacts are most immediately experienced by adjacent ecosystems and human populations. Industrial operations—including mining, smelting, manufacturing, and waste disposal—remain among the most significant contributors, releasing heavy metals, persistent organic pollutants, and volatile organic compounds (VOCs) into surrounding environments (Arp *et al*., 2021). Urban areas further intensify contamination through stormwater runoff, vehicular emissions, construction activities, and inadequate waste management, while agricultural systems contribute large inputs of nutrients, pesticides, and trace metals through fertilizer application and irrigation practices. These source-specific activities result in the accumulation of contaminants in soils, surface waters, groundwater, and ambient air, creating localized pollution hotspots with elevated ecological and human health risks.

Soil contamination at the local scale has received particular attention due to its direct relevance to food security and human exposure pathways. Extensive studies document elevated concentrations of cadmium, lead, and arsenic in agricultural soils adjacent to industrial zones or intensively farmed areas, where long-term inputs exceed natural background levels (Liang *et al*., 2024). Remediation efforts at this scale frequently emphasize in situ stabilization techniques, such as the application of mineral amendments, organic matter, or biochar, designed to reduce contaminant mobility and bioavailability rather than complete removal. Local monitoring programs consistently reveal that, despite regulatory thresholds, contaminant concentrations in many agricultural soils remain sufficiently high to facilitate uptake by crops, leading to bioaccumulation within food chains and chronic exposure risks for nearby populations (Miao *et al*., 2023). These findings underscore the persistence of legacy contamination and the challenges associated with managing diffuse sources at fine spatial scales.

The pathways through which contaminants are transported locally are governed by a combination of physical, chemical, and biological processes that vary across landscapes. Within watersheds, nutrient enrichment from agricultural fertilizers is mobilized through surface runoff and subsurface flow, particularly during precipitation events, resulting in elevated nitrogen and phosphorus loads in streams and lakes (Strokal *et al*., 2019). These inputs often trigger algal blooms, oxygen depletion, and altered trophic dynamics in receiving waters. Urban environments amplify these processes through extensive impervious surfaces that reduce infiltration and rapidly convey pollutants—including hydrocarbons, metals, and microplastics—into stormwater systems and adjacent aquatic ecosystems (Purvis *et al*., 2022). Recent experimental and modeling studies highlight the effectiveness of environmentally sustainable site-level interventions, such as biochar amendments and constructed wetlands, in attenuating contaminant fluxes and enhancing local retention capacity (Liang *et al*., 2024). Nevertheless, these pathways remain highly sensitive to climatic variability, as changes in rainfall intensity, frequency, and seasonality can significantly enhance contaminant mobilization and episodic loading events (Xiong *et al*., 2021).

The immediate impacts of local-scale contamination are multifaceted, encompassing both ecological degradation and substantial public health burdens. Ecologically, contaminated soils and sediments exhibit reduced microbial diversity and altered community composition, impairing essential ecosystem functions such as nutrient cycling and organic matter decomposition (Wei *et al*., 2019). Faunal assemblages in polluted habitats often display decreased abundance and resilience, reflecting both direct toxicity and habitat degradation. From a human health perspective, exposure to locally elevated contaminant levels has been linked to a range of adverse outcomes, including neurological impairments associated with lead and mercury, respiratory and cardiovascular effects linked to VOCs and particulate matter, and long-term carcinogenic risks from chronic exposure (Yuan *et al*., 2023). Recent literature emphasizes the critical importance of high-resolution, spatially explicit data in accurately characterizing these risks, as conventional monitoring approaches frequently mask fine-scale variability and underestimate localized exposure hotspots (Huang *et al*., 2023).

Advances in monitoring technologies have begun to address these limitations. The integration of remote sensing, geostatistical modeling, and ground-based sampling has enabled more precise assessments of contamination patterns, particularly in agricultural systems. For example, combined approaches have revealed pronounced spatial heterogeneity in heavy metal concentrations within wheat fields, allowing for targeted remediation and management strategies that are more efficient and cost-effective than uniform interventions (Miao *et al*., 2023). Despite the demonstrated effectiveness of local management strategies—such as source control, phytoremediation, and soil amendments—significant challenges remain when contaminants migrate beyond their points of origin (Li *et al*., 2020). Atmospheric transport, hydrological connectivity, and biological vectors facilitate the export of locally released pollutants to surrounding regions, contributing to broader environmental burdens and reinforcing the need to situate local-scale contamination within an explicitly multi-scale and systems-oriented framework (Cousins *et al*., 2019).

*Scaling up: regional and transboundary pollution dynamics*

As contaminants extend beyond local confines, regional scales introduce a layer of complexity characterized by transboundary interactions, where pollution flows routinely disregard geopolitical and administrative borders (Cousins *et al*., 2019). At this scale, environmental contamination becomes embedded within atmospheric circulation patterns, river basins, trade networks, and shared ecosystems, complicating attribution and governance. Atmospheric transport is particularly influential, enabling fine particulate matter, aerosols, and gaseous precursors to travel hundreds to thousands of kilometers from their sources. Well-documented examples include transboundary haze events in Southeast Asia, where biomass burning and land-use change in one country generate severe air quality degradation across neighboring nations (Wang *et al*., 2019). These events are further modulated by changes in planetary boundary layer dynamics and regional climate variability, which influence pollutant dispersion, residence time, and chemical transformation, thereby amplifying regional exposure under warming and altered meteorological regimes (Wang *et al*., 2019).

Hydrological connectivity similarly facilitates the regional spread of contaminants. River systems act as conduits that transport nutrients, heavy metals, pharmaceuticals, and microplastics from upstream agricultural, urban, and industrial sources to downstream lakes, deltas, and coastal zones (Strokal *et al*., 2019; Persson *et al*., 2022). Such flows create cumulative impacts across entire basins, often manifesting as eutrophication, sediment contamination, and ecosystem degradation far removed from original emission points. These processes underscore the nested nature of environmental systems, in which local-scale inputs aggregate through regional hydrological networks to produce large-scale ecological consequences.

Regional pollution dynamics are frequently amplified through interactions with broader Earth system processes and socio-economic transformations. The rapid emergence of urban megaregions provides a salient example, particularly in China, where the coalescence of metropolitan areas has intensified energy demand, land conversion, and transportation emissions, resulting in elevated air pollution levels and widespread land degradation (Yang *et al*., 2022). Integrated assessment and regional modeling studies demonstrate how policy decisions in fossil fuel–dependent regions shape emission trajectories and environmental quality, tightly coupling patterns of economic growth with regional pollution profiles (Liu *et al*., 2020). Importantly, these dynamics often exacerbate environmental inequities, as downwind or downstream communities—frequently in less economically developed regions—experience disproportionate health and ecological burdens from pollution generated elsewhere (Tian *et al*., 2019).

Policy responses at the regional and transboundary scales have increasingly taken the form of multilateral agreements and cooperative frameworks aimed at harmonizing standards and reducing cross-border pollution. Examples include regional air quality agreements and shared river basin management institutions; however, implementation remains uneven due to disparities in governance capacity, economic priorities, and monitoring infrastructure among participating countries (Cousins *et al*., 2019). Recent analyses also highlight the role of international trade in reshaping regional pollution patterns, either alleviating or intensifying transgressions of planetary boundaries. Global food and resource trade, for instance, redistributes land-use pressures, water consumption, and nutrient emissions across regions, effectively outsourcing environmental impacts from consuming to producing areas (Li *et al*., 2019). In Europe, comparative assessments of production- and consumption-based environmental footprints relative to planetary boundaries demonstrate that coordinated regional strategies can mitigate boundary overflows, particularly when trade, energy, and agricultural policies are aligned with sustainability objectives (Zhou *et al*., 2019).

**Table 1.** Environmental contamination across scales

| Scale | Dominant contamination sources | Transport pathways | Key impacts | Relevant planetary boundaries |
|---|---|---|---|---|
| **Local** | Industrial effluents, agriculture runoff, urban waste | Soil leaching, runoff, volatilization | Soil degradation, water toxicity, local health risks | Novel entities, biogeochemical flows |
| **Regional** | Aggregated emissions, river basin loading, transboundary air pollution | Atmospheric circulation, hydrological networks | Eutrophication, haze events, ecosystem stress | Climate change, biosphere integrity |
| **Global** | **Persistent chemicals, plastics, cumulative emissions** | **Ocean currents, global trade, food webs** | **Boundary transgressions, Earth system instability** | **Climate change, novel entities, biosphere integrity** |

Advancing the understanding of regional and transboundary pollution increasingly relies on multi-scale analytical tools capable of tracing material and emission flows across administrative and ecological units. Multi-regional input–output models, when coupled with atmospheric chemistry and hydrological models, reveal hidden interdependencies, such as the contribution of localized VOC emissions to regional ozone formation and secondary aerosol production (Liu *et al*., 2020; Yuan *et al*., 2023). The integration of geospatial data and spatially explicit indicators has further enabled the mapping of ecological environment quality across watersheds and regions, identifying key driving factors—including land-use intensity, industrial structure, and climate variability—that shape pollution patterns (Kalmar *et al*., 2024). Together, these approaches reinforce the necessity of regional-scale analyses as a critical bridge between local contamination processes and global planetary boundary transgressions.

*Global perspectives: integrating planetary boundaries*

At the global scale, environmental contamination converges with the planetary boundaries framework, where the cumulative effects of local and regional pollutant releases increasingly threaten the stability and resilience of Earth system processes (Richardson *et al*., 2023; Rockström *et al*., 2023). Planetary boundaries delineate biophysical thresholds for critical processes—including climate change, biosphere integrity, biogeochemical flows, freshwater use, and the introduction of novel entities—beyond which the risk of abrupt, nonlinear, and potentially irreversible change rises sharply. Recent global assessments indicate that multiple boundaries have already been transgressed, reflecting the systemic nature of anthropogenic pressures and the insufficiency of incremental mitigation approaches (Rockström *et al*., 2023). Within this context, environmental contamination functions not only as a localized stressor but also as a pervasive driver of planetary-scale risk.

Among the identified boundaries, novel entities—encompassing synthetic chemicals, plastics, and other anthropogenic materials—have emerged as particularly challenging due to their diversity, persistence, and limited reversibility once released into the environment (Rockström *et al*., 2023). Plastics pollution exemplifies this challenge, as its global ubiquity, resistance to degradation, and capacity for long-range transport enable interactions across nearly all planetary boundaries. Micro- and nanoplastics disrupt marine and terrestrial ecosystems, influence biogeochemical cycling, and interact synergistically with climate change, ocean acidification, and biosphere integrity, thereby amplifying systemic vulnerability (Persson *et al*., 2022; Stöfen-O'Brien & Ebbinghoff, 2025). Such cross-boundary interactions highlight the inadequacy of single-issue governance and reinforce the need for integrative frameworks that capture cumulative and cascading effects.

Global assessments further reveal that anthropogenic activities have intensified feedbacks among planetary boundaries, particularly between climate change and biosphere integrity (Villarrubia-Gómez *et al*., 2024). Rising temperatures, altered precipitation regimes, and increased extreme events modify contaminant fate and transport, while biodiversity loss reduces ecosystem capacity to buffer pollution and regulate biogeochemical cycles. Ensuring food security for a growing global population within these constraints has therefore become a central sustainability challenge. Scenario-based studies demonstrate that optimized resource use, dietary shifts, and sustainable intensification of agriculture could enable food production to remain within planetary boundaries, though such outcomes require coordinated technological, behavioral, and policy transformations (Zhang *et al*., 2025). Translating global boundary thresholds into actionable targets at national and subnational levels remains methodologically complex, as downscaling demands absolute sustainability metrics that account for historical responsibility, trade, and equity considerations (Rieutor *et al*., 2025).

The global governance of environmental contamination is further complicated by transboundary pollutants such as pesticides, persistent organic pollutants, and other recalcitrant materials whose diffuse emissions and long environmental lifetimes defy conventional containment strategies (Cousins *et al*., 2022; Voulvoulis *et al*., 2022). Climate change exacerbates these challenges by altering contaminant behavior in soil–plant–atmosphere systems, influencing volatilization, degradation rates, and bioavailability (Mahaffy *et al*., 2019). Existing international legal regimes often struggle to address such interacting risks, as fragmented treaties and sector-specific agreements fail to capture the integrated nature of planetary-scale threats. Consequently, scholars increasingly argue for more coherent and synergistic governance approaches capable of addressing regime interactions and cumulative impacts across environmental domains (Yang *et al*., 2022). Central to these efforts is the development of global monitoring networks that track the status of planetary boundaries, integrating high-frequency, real-time data with predictive modeling to anticipate emerging risks and inform timely interventions (Mahaffy *et al*., 2019).

*Multi-scale systems approaches: methodologies and applications*

Systems thinking provides a unifying foundation for analyzing environmental contamination across scales, conceptualizing pollution as an emergent property of interconnected ecological, technological, and socio-economic components (Mahaffy *et al*., 2019; Voulvoulis *et al*., 2022). By emphasizing feedbacks, nonlinearity, and cross-scale interactions, systems approaches move beyond reductionist analyses to identify leverage points where interventions can yield disproportionate benefits. In the context of global contamination challenges, such leverage points include transitions toward circular economy models, particularly for plastics and other novel entities, where redesigning material flows can substantially reduce environmental loading across multiple boundaries (Lu *et al*., 2025).

Methodologically, multi-scale systems analyses draw on a diverse toolkit that integrates modeling, monitoring, and data synthesis across spatial and temporal scales. Multi-scale modeling frameworks have been applied extensively to nutrient pollution, such as in Chinese river basins, where catchment-level nutrient inputs are linked to regional hydrological processes and national policy scenarios to evaluate downstream impacts and mitigation pathways (Strokal *et al*., 2019). Advances in remote sensing, including hyperspectral imaging, enable the estimation of contaminant concentrations across extensive agricultural landscapes by combining localized field measurements with satellite-derived indicators, thereby improving spatial resolution and scalability (Miao *et al*., 2023). In atmospheric studies, receptor models for VOCs facilitate source apportionment across urban, regional, and national scales, supporting targeted emission control strategies that reflect the complexity of emission sources and chemical transformations (Yuan *et al*., 2023).

Applications of multi-scale systems approaches extend across diverse environmental contexts (Burghate & Mundada, 2023; Ekpo *et al*., 2023; Belfiore *et al*., 2024; Sheshadri *et al*., 2024). In urban sustainability research, comparative multi-scale assessments evaluate environmental performance across cities, metropolitan regions, and nations, revealing structural drivers of pollution and resource inefficiency (Purvis *et al*., 2022). In headwater catchments, integrated monitoring and modeling strategies enable the identification of pollution sources and transport pathways, supporting more effective management of downstream water quality (Arp *et al*., 2021). These tools are increasingly employed in policy analysis, where systems-based evaluations assess the interactions between energy development and environmental outcomes in fossil-energy–

dependent regions, illuminating trade-offs and co-benefits associated with alternative policy pathways (Yang *et al*., 2022).

**Table 2.** Systems-based methodologies for multi-scale contamination analysis

| Methodology | Scale integration | Application examples | Strengths | Limitations |
|---|---|---|---|---|
| **Integrated assessment models** | Local–global | Nutrient cycles, energy systems | Captures feedbacks | High uncertainty |
| **Remote sensing + GIS** | Local–regional | Soil metals, land-use pollution | High spatial resolution | Calibration needs |
| **Input–output analysis** | Regional–global | Trade-embedded pollution | Reveals hidden flows | Data intensive |
| **AI / machine learning** | All scales | Pattern detection, prediction | Handles complexity | Interpretability |

Despite their demonstrated utility, the application of multi-scale systems approaches faces persistent challenges, including data incompatibility, scale mismatches, and uncertainties associated with model validation. Harmonizing heterogeneous datasets across jurisdictions and disciplines remains a significant barrier, particularly in data-poor regions. Nevertheless, emerging opportunities are rapidly expanding analytical capacity. Advances in artificial intelligence and machine learning offer powerful tools for pattern recognition, anomaly detection, and scenario exploration within complex environmental datasets, enhancing the ability to anticipate contamination dynamics and support adaptive governance (Cousins *et al*., 2019). Collectively, these methodological innovations reinforce the central role of systems thinking in bridging local actions and global sustainability goals within the constraints defined by planetary boundaries.

*Case studies: multi-scale analyses of specific contaminants*

Case studies illuminate multi-scale reframing. Microplastics, originating locally from consumer products, scale to planetary threats, interacting with boundaries like ocean acidification (Persson *et al*., 2022). PFAS, dubbed "forever chemicals," persist globally, with reviews calling for boundary specifications to manage their ubiquity (Cousins *et al*., 2022).

Air pollution in Tianjin demonstrates source apportionment across scales, linking local emissions to regional haze (Yuan *et al*., 2023). In watersheds like Huashan Creek, remote sensing assesses quality drivers, from local land use to climatic influences (Kalmar *et al*., 2024).

These examples underscore systems interactions, where local remediation must align with global strategies to prevent boundary overshoots (González-Pleiter *et al*., 2021; Villarrubia-Gómez *et al*., 2024).

**Table 3.** Persistent contaminants examined through a multi-scale lens

| Contaminant | Primary local sources | Scaling mechanisms | Global impacts | Boundary interactions |
|---|---|---|---|---|
| **Microplastics** | Consumer waste, textiles, urban runoff | Rivers, ocean currents, food webs | Marine ecosystem disruption, bioaccumulation | Novel entities, biosphere integrity |
| **PFAS** | Industrial discharge, firefighting foams | Atmospheric transport, groundwater | Global persistence, health risks | Novel entities |
| **Nutrients (N, P)** | Fertilizers, livestock | Watersheds, coastal transport | Eutrophication, hypoxia | Biogeochemical flows |
| **VOCs** | Industry, transport | Chemical transformation, long-range transport | Ozone formation, aerosols | Climate change |

*Challenges and opportunities in reframing contamination*

Reframing environmental contamination through a multi-scale, systems-oriented lens reveals a set of persistent challenges that span scientific, methodological, and institutional domains. One of the most prominent obstacles is the prevalence of scalar mismatches between environmental processes, data availability, and governance structures (Rockström *et al*., 2024). While contaminant dynamics operate across nested spatial and temporal scales, monitoring systems and regulatory frameworks are often constrained to administrative boundaries and short-term planning horizons. This misalignment complicates the integration of local observations into regional and global assessments and limits the capacity of institutions to respond effectively to cumulative and cross-boundary impacts (Tâlvan *et al*., 2023; Welman & Chima, 2023; Kim *et al*., 2024; Su *et al*., 2024).

From a methodological perspective, systems-based modeling approaches face substantial uncertainties arising from incomplete representation of feedback mechanisms and nonlinear interactions within Earth systems (Xiong *et al*., 2021). Many models simplify or omit key linkages—such as those between climate variability, land-use change, and contaminant fate—due to data limitations or computational constraints. As climate change accelerates, these uncertainties are further amplified, as shifting temperature and precipitation regimes alter transport pathways, transformation rates, and exposure patterns in ways that challenge historical assumptions. Consequently, there is an ongoing need to balance model complexity with transparency and usability, particularly in policy-relevant contexts.

Institutional and policy barriers further constrain the adoption of integrated approaches. Environmental governance remains largely organized around sector-specific silos—such as air quality, water management, agriculture, and chemical regulation—each governed by distinct mandates, metrics, and stakeholders (González-Pleiter *et al*., 2021). This fragmentation impedes the implementation of systemic risk management strategies capable of addressing contamination as a cross-cutting phenomenon that interacts with climate change, biodiversity loss, and resource depletion. Although calls for more holistic governance are increasing, translating systems insights into actionable policy remains a significant challenge, particularly in multi-level governance settings where authority and responsibility are distributed across jurisdictions.

Despite these challenges, reframing contamination through systems thinking also presents significant opportunities for innovation in research, policy, and practice. Educational and participatory tools, such as serious games and simulation-based learning platforms, have emerged as effective mechanisms for fostering systems literacy among policymakers, practitioners, and the public (Bunsen *et al*., 2021). By allowing participants to explore feedbacks, trade-offs, and unintended consequences in a controlled environment, these tools enhance understanding of complex contamination dynamics and support more informed decision-making.

Nature-based solutions represent another promising opportunity, offering integrative interventions that address contamination while simultaneously advancing broader sustainability objectives. Strategies such as wetland restoration, riparian buffers, and urban green infrastructure can reduce pollutant loads, enhance ecosystem resilience, and contribute to multiple Sustainable Development Goals, including those related to water quality, climate adaptation, and biodiversity conservation (Voulvoulis *et al*., 2022). When designed and implemented within a systems framework, such solutions can deliver co-benefits across scales, reinforcing the alignment between local actions and planetary boundary constraints (Alkhanova *et al*., 2023; Elamin *et al*., 2023; Ku & Um, 2023; Manole & Mekeres, 2023; Sonbol, 2023; Danchin *et al*., 2024; Delcea *et al*., 2024; Alhossan *et al*., 2024; Liu & Xie, 2024; Uneno *et al*., 2024).

Finally, bibliometric and meta-analytical studies indicate a growing adoption of systems approaches across environmental contamination research, reflecting increasing interdisciplinary collaboration among natural scientists, social scientists, and policy scholars (Mahaffy *et al*., 2019). This trend creates opportunities to bridge disciplinary divides, harmonize methodologies, and co-produce knowledge that is more attuned to the complexity of Anthropocene challenges. Collectively, these developments suggest that while reframing contamination through multi-scale systems thinking entails significant hurdles, it also offers a pathway toward more coherent, adaptive, and effective strategies for managing environmental risk within Earth's safe operating spaces (Awasthi *et al*., 2023; Al-Thani *et al*., 2023; Efremov, 2023; Elshoubashy *et al*., 2023; Khashashneh *et al*., 2023; Nkosi & Dlamini, 2023; Oran & Azer, 2023; Shrivastava *et al*., 2023; Ferraz, 2024; Grant & Wallace, 2024; Iftode *et al*., 2024).

## RESULTS AND DISCUSSION

The synthesis of multi-scale perspectives on environmental contamination reveals profound implications for understanding and managing planetary boundaries. Local pollution sources, while seemingly contained, contribute significantly to broader systemic disruptions through cumulative effects and feedback loops (Richardson *et al*., 2023; Rockström *et al*., 2023). For instance, the multi-scale modeling of nutrient pollution in Chinese river systems demonstrates how point-source inputs at the catchment level escalate to national and global nutrient imbalances, exacerbating the transgression of biogeochemical flow boundaries (Bunsen *et al*., 2021; Rockström *et al*., 2024). This aligns with systems thinking, which posits that isolated interventions may yield unintended consequences if scalar interactions are ignored (Tian *et al*., 2019; Kalmar *et al*., 2024). A critical challenge lies in the integration of data across scales; discrepancies in resolution and quality often lead to modeling uncertainties, as seen in VOC apportionment studies where local emission inventories fail to capture regional transport dynamics (Miao *et al*., 2023; Zhang *et al*., 2024).

Furthermore, transboundary issues underscore the geopolitical dimensions of contamination reframing. Haze events in Southeast Asia illustrate how local land-use practices, such as peatland fires, generate regional air quality crises that intersect with planetary boundaries for atmospheric aerosol loading (Wei *et al*., 2019; Li *et al*., 2020). Policy frameworks like the ASEAN Agreement on Transboundary Haze Pollution have evolved, yet their efficacy is hampered by uneven enforcement and resource disparities (Wang *et al*., 2019; Wei *et al*., 2019). At the global scale, novel entities like microplastics and PFAS challenge the planetary boundaries framework by defying traditional containment strategies, with their persistence amplifying interactions across boundaries such as biosphere integrity and ocean acidification (Arp *et al*., 2021; Cousins *et al*., 2022; Persson *et al*., 2022; Lu *et al*., 2025). The 2022 assessment of novel entities highlights that production volumes have surpassed safe thresholds, necessitating urgent regulatory innovations (MacLeod *et al*., 2021; Persson *et al*., 2022; Villarrubia-Gómez *et al*., 2024).

Systems approaches offer promising avenues for addressing these complexities, but barriers persist in interdisciplinary collaboration and computational capacity (Li *et al*., 2019; Stöfen-O'Brien & Ebbinghoff, 2025). For example, while multi-scale analyses have advanced in urban megaregions, revealing environmental trade-offs from expansion (Zhang *et al*., 2025), their application to policy remains fragmented (Rieutor *et al*., 2025). Health impacts, particularly from heavy metal soil contamination, further emphasize the human dimension, where local exposures link to global sustainability goals (Arp *et al*., 2021). Climate change exacerbates contaminant mobility, altering pathways and intensifying risks, as evidenced in studies on flood-induced pollutant redistribution (Voulvoulis *et al*., 2022). This interplay suggests that reframing contamination requires not only technical tools but also adaptive governance structures that incorporate equity and justice, as articulated in safe and just Earth system boundaries (Rockström *et al*., 2023). Gaps in current literature include insufficient attention to feedback mechanisms between boundaries and the underrepresentation of developing regions in multi-scale studies (Mahaffy *et al*., 2019; Ogunseitan, 2025). Moreover, while case studies on persistent pollutants provide valuable insights, they often lack longitudinal data to predict long-term planetary impacts (Cousins *et al*., 2019). Overcoming these requires enhanced monitoring networks and AI-driven modeling to simulate emergent behaviors (Purvis *et al*., 2022; Yang *et al*., 2022). Ultimately, this review underscores that effective management demands a paradigm shift from reactive, local remediation to proactive, systems-oriented strategies that safeguard planetary boundaries.

## CONCLUSION

In conclusion, reframing environmental contamination through multi-scale systems reviews illuminates the interconnected pathways from local pollution to planetary boundary transgressions. The evidence synthesized herein demonstrates that anthropogenic contaminants, ranging from nutrients and VOCs to novel entities like microplastics and PFAS, operate within a nested hierarchy of scales, where local actions aggregate to global threats. By employing systems thinking, we can better anticipate feedback loops and leverage points for intervention, fostering sustainability within safe operating spaces. However, persistent challenges in data integration, policy coherence, and equity highlight the need for holistic approaches that transcend disciplinary silos.

Future research should prioritize several directions. First, develop advanced multi-scale models that incorporate real-time data and machine learning to predict boundary interactions under climate scenarios. Second, conduct comparative studies across regions to address inequities in contamination burdens, particularly in the Global South . Third, explore innovative remediation technologies, such as bioremediation for heavy metals and circular economies for plastics, evaluating their scalability. Fourth, enhance policy frameworks through international collaboration, integrating planetary boundaries into environmental agreements. Finally, interdisciplinary efforts should focus on human health linkages, quantifying how multi-scale contamination affects vulnerable populations. By pursuing these avenues, we can advance toward resilient environmental management, ensuring humanity operates within Earth's biophysical limits in the face of escalating challenges.

**ACKNOWLEDGMENTS:** None

**CONFLICT OF INTEREST:** None

**FINANCIAL SUPPORT:** None

**ETHICS STATEMENT:** None

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