TYPE Perspective
PUBLISHED 30 June 2025
DOI 10.3389/fenvs.2025.1643879

OPEN ACCESS

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RECEIVED 09 June 2025
ACCEPTED 16 June 2025
PUBLISHED 30 June 2025

CITATION
Slaveykova VI (2025) Navigating Earth's biogeochemical dynamics: Integrating elemental cycles, anthropogenic pressures and planetary boundaries.
Front. Environ. Sci. 13:1643879.
doi: 10.3389/fenvs.2025.1643879

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.

Funding

The author declares that no financial support was received for the research and/or publication of this article.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Generative AI statement

The author declares that no Generative AI was used in the creation of this manuscript.

Publisher's note

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