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EDITORIAL

Safeguarding planetary boundaries: Challenges and response pathways for ecological security thresholds

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The stability of the Earth's system serves as the fundamental basis for the continuity of human civilization. The planetary boundaries framework, developed by scientists from the Stockholm Resilience Center and other institutions, delineates a well-defined ecological safe operating space for human activities by identifying nine key processes that have maintained Earth's stability over millennia. This framework indicates that breaching the critical thresholds of these processes will trigger irreversible global environmental disruptions, fundamentally jeopardizing the foundations of human civilization (Figure 1).

According to the latest 2023 assessment, six of the nine planetary boundaries have been transgressed.[1,2] Biosphere integrity (encompassing genetic diversity and ecosystem functioning) and climate change (reflected in atmospheric carbon dioxide concentration and radiative forcing) represent the core boundaries with the highest risk. Novel entities (including plastics, synthetic chemicals, and other anthropogenic substances) have been confirmed to be substantially beyond the safe threshold, emerging as the most severely exceeded boundary. Simultaneously, land-system change, disruption of biogeochemical flows (specifically the phosphorus cycle), and alteration of green water (soil moisture) have also clearly exceeded the safe operating limits.

These boundaries interact through complex biogeochemical cycles. Deforestation not only directly causes biodiversity loss but also diminishes the capacity of terrestrial carbon sinks and modifies regional precipitation patterns.[1,2] Global warming, in turn, further exacerbates anomalies in freshwater cycles and disrupts global nutrient cycling. This cascade effect means that transgressions of individual boundaries are generating domino effects, pushing the Earth's system toward an unpredictable state. Current response mechanisms face three profound constraints:

(i) Limitations in scientific understanding: Planetary boundaries demonstrate significant regional variations and temporal legacy effects. For instance, freshwater changes manifest with completely different critical characteristics in the Amazon Basin compared to the Yangtze River Basin, while the warming effects of carbon emissions require decades to fully manifest.
(ii) Structural deficiencies in global governance: Existing governance systems struggle to address synergistic effects between boundaries. Integrated solutions for climate change and biodiversity loss remain primarily theoretical, while fragmented jurisdictions among international institutions lead to disjointed policy response.[2]
(iii) Path dependence in socioeconomic systems: The global division of labor has created entrenched

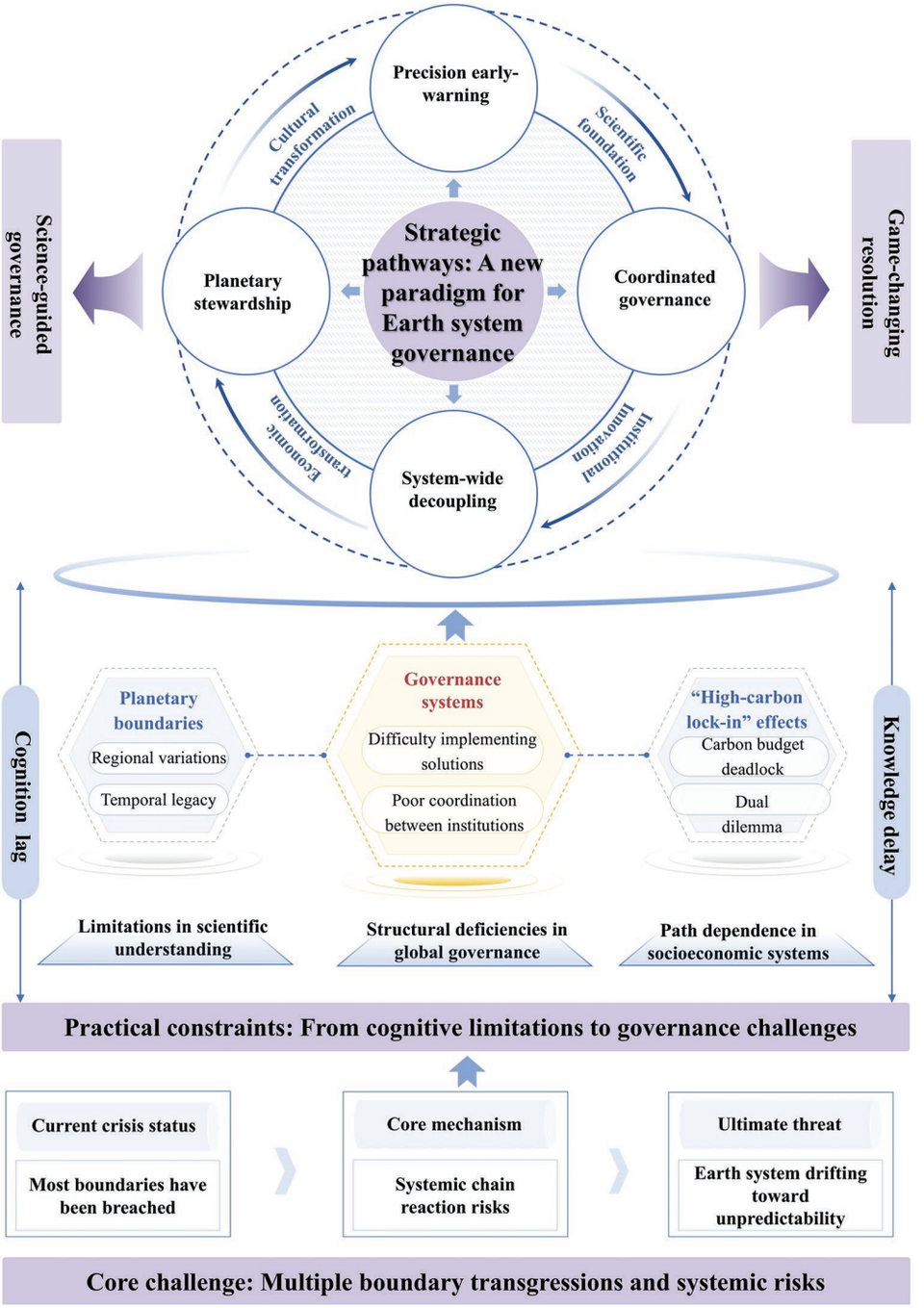

Figure 1. Schematic of the conceptual framework

"high-carbon lock-in" effects. Developing countries face pressure to accommodate polluting industries, while developed nations transfer emission responsibilities through carbon leakage, creating deadlocks in global carbon budget allocation under the Paris Agreement.[1]

Hence, safeguarding ecological thresholds requires the following systemic transformations:

(i) Establish a planetary boundaries early-warning platform: Integrate satellite remote sensing with *in situ* monitoring networks and develop advanced models of boundary interactions. Prioritize research on feedback mechanisms in biogeochemical cycles and establish regionally differentiated threshold systems to provide scientific foundations for precise governance.

(ii) Innovate global environmental governance architecture: Develop an international legal framework based on planetary boundaries, translating ecological thresholds into binding responsibility allocation mechanisms. Establish a Global Environmental Council to integrate governance functions currently dispersed among the United Nations Framework Convention on Climate Change, the Convention on Biological Diversity, and other institutions.[3]

(iii) Advance deep decoupling transformations: Implement systemic reforms across the "energy–materials–food" nexus: achieve renewable energy-dominated electrification in the energy sector; establish a complete lifecycle management in the materials sector through circular economy principles; and promote ecological intensification in agricultural production.[4]

(iv) Cultivate an Earth stewardship ethic: Incorporate planetary boundaries into national education systems and corporate decision-making processes. Develop consumption guidance mechanisms based on ecological footprint assessment and foster a new consensus around "high-quality development within safe operating space."

The planetary boundaries framework reveals a critical reality: the Earth system in the Anthropocene is approaching irreversible tipping points. Incremental technological solutions or non-binding commitments are insufficient to address this systemic crisis. Only by leveraging cutting-edge scientific guidance, implementing fundamental institutional innovations, and pursuing technological transformations can we reconfine human activities within ecological safety boundaries and secure the potential for civilizational continuity.[5] This constitutes both the ultimate test of global governance capacity and an essential developmental phase for humanity's maturation as a collective civilization.

Conflict of interest

Shaokun Li and Chengyun Zhou are part of the Editorial Board of the journal, serving as an Editorial Board Member and Editor-in-Chief, respectively. They declare no competing financial interests or personal relationships that could have appeared to influence the work reported in this editorial.

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