# Navigating Earth governance: A cybernetic and pragmatic pathway to digital twin Earth

Xin Li,[1,2,*] Jianbin Su,[1,3,*] and Shiwei Yuan[1]

[1]National Tibetan Plateau Data Center, State Key Laboratory of Tibetan Plateau Earth System, Environment and Resources, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

[2]University of Chinese Academy of Sciences, Beijing 100101, China

[3]State Key Laboratory of Climate System Prediction and Risk Management, Nanjing Normal University, Nanjing 210023, China

*Correspondence: xinli@itpcas.ac.cn (X.Li.); jianbinsu@njnu.edu.cn (J.Su.)

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Digital Twin Earth (DTE) stands at a transformative crossroads: evolve beyond sophisticated "digital mimicry" into a revolutionary planetary governance engine or remain confined to passive observation. We propose that DTE's transformative potential lies in integrating Human-AI synergy to enable proactive Earth governance through continuous intervention-feedback loops connecting real Earth systems, digital simulations, and policy implementation. This paradigm transforms passive environmental monitoring into active navigation of Earth's trajectory within planetary boundaries. While deliberate large-scale intervention carries inherent risks, the potential benefits—building systemic resilience against cascading environmental crises—substantially outweigh the drawbacks of continued passive evolutionary approach. We posit DTE as the high-fidelity simulation environment and AI as the core analytical intelligence within this dynamic governance loop, enabling human stakeholders to continuously design, test, implement, and refine governance strategies. We propose Digital Cousins as a pragmatic implementation pathway that balances scientific robustness with computational feasibility, offering targeted regional governance solutions. By operationalizing AI-powered DTE as an adaptive decision-making system, humanity can consciously navigate Earth's futures through integrated sensing, simulation, and policy implementation.

## INTRODUCTION

The convergence of extreme weather intensification, accelerating biodiversity collapse, and polar ice destabilization signals more than isolated environmental crises—these represent systemic symptoms of a planet operating beyond its safe boundaries. These cascading disruptions mark humanity's transition from the Holocene's relative stability into the Anthropocene epoch, where human activities fundamentally dominate planetary processes and multiple Earth systems approach potentially irreversible tipping points.[1] The planetary boundaries framework quantifies this stark reality, showing that critical thresholds for climate change, biosphere integrity, biogeochemical flows, and land-system change have already been crossed. Breaching these boundaries generates profound uncertainty and intensifies socio-ecological feedback, posing a fundamental challenge to conventional Earth management approaches.

In response, a fundamental paradigmatic shift is necessary, moving from reactive "Earth Management"—responding to changes after they occur—toward proactive "Earth Governance"—purposive interventions that actively guide Earth's trajectory within safe operating boundaries.[2] This transformation requires reconceptualizing humanity's relationship with Earth systems: from external managers to embedded navigators. While large-scale intervention might carry risks of unintended consequences, the alternative—a continued passive incrementalism leading to cascading system failures and further boundary transgressions—poses existential risks of far greater magnitude. However, such governance requires sophisticated navigation rather than simplistic control.

Digital Twin Earth (DTE) emerges as a potentially transformative technology in this context. Distinguished by continuous, bidirectional data flows between physical and digital realms, DTE represents far more than traditional static modeling approaches.[3] We argue that when strategically enhanced with artificial intelligence (AI) capabilities, DTE can evolve into a dynamic governance architecture that operationalizes continuous adaptation through Human-AI collaboration. By integrating real-time Earth system sensing, advanced simulation capabilities, and collaborative decision-making processes, an AI-powered DTE can transform abstract governance principles into concrete, implementable policy actions. However, bridging the gap between theoretical possibility and practical implementation remains the central challenge—one we address through strategic technological and institutional innovation.

## AI-POWERED DIGITAL TWIN: FROM SIMULATION TO PLANETARY GOVERNANCE

DTE, characterized by continuous, real-time data exchange between physical and digital realms, represents a paradigm shift in planetary modeling.[4] Global initiatives—from the European Union's *Destination Earth*[5] and *China's SDG Big Data Platform*[6] —demonstrate this ambition, unifying fragmented sensing data streams to achieve unprecedented predictive capabilities. However, when evaluated through a governance lens, even a theoretically perfect DTE reveals fundamental limitations. Its core function remains simulation and representation—generating high-fidelity forecasts of potential futures. While this capability is indispensable for understanding complex Earth systems, it is fundamentally passive—it can inform decisions but cannot autonomously generate or optimize interventions.

Integration with advanced AI frameworks fundamentally transforms these capabilities. Deep reinforcement learning enables policy optimization across multiple objectives, learning from both historical data and simulated futures to identify intervention strategies that maximize desired outcomes while minimizing unintended consequences.[4] Agent-based modeling captures the complex behaviors of diverse stakeholders—from individual farmers to multinational corporations—revealing how local actions aggregate into global patterns.[7] Large language models facilitate natural language interaction with complex Earth system data, democratizing access to scientific insights and enabling broader stakeholder participation.[8] Generative AI accelerates scenario exploration, creating synthetic but plausible future states thereby aiding in the identification of robust strategies across uncertainty ranges. These AI technologies work synergistically to enable continuous policy optimization, multi-stakeholder coordination, and anticipatory intervention before environmental crises fully manifest.

Central to this transformative vision is the intervention-feedback loop, an adaptive governance architecture that translates qualitative environmental management principles into quantifiable, iterative action within planetary boundaries (Figure 1). This framework moves beyond traditional linear policy cycles—problem identification, policy formulation, implementation, evaluation—toward continuous, adaptive processes that respond dynamically to Earth system changes. The process operates as a perpetual loop where policy initiatives are collaboratively developed by humans and AI, rigorously tested through high-fidelity simulations, carefully implemented in the real world, and continuously refined based on observed outcomes and emerging patterns.

To clarify its operational dynamics, this loop operates via three deeply interconnected components that function as an integrated system.

**Intervention design through human-AI synergy.** Strategic priorities and ethical guidelines are established by human stakeholders, reflecting societal values, cultural contexts, and political realities. AI systems then systematically explore the vast intervention space, generating novel policy combinations that humans might not conceive independently. For instance, in addressing urban heat island effects, humans might prioritize green infrastructure, while AI might identify synergistic combinations of albedo modification, strategic water feature placement, and adaptive building codes that amplify cooling effects. This collaborative process leverages human wisdom for value judgment and contextual understanding while harnessing AI's


**Figure 1. The AI-powered DTE governance framework** The framework illustrates a cycle of adaptive governance, operating as a continuous loop. Policy initiatives are developed through Human-AI synergy, which is underpinned by foundational pillars of technical innovation, ethical frameworks, and institutional architecture. These initiatives are then tested via simulation in DTE. The results fed back to the Human-AI synergy module to inform the final, human-led decision-making process and guide the formulation of targeted policy interventions (e.g., carbon dioxide removal, ecosystem restoration and climate adaptation) for real-world implementation. Crucially, the outcomes of this intervention are monitored via sensing, providing the necessary data feed to continuously update and ground-truth the DTE, thus closing the adaptive governance loop.

capacity for complex optimization and pattern recognition across massive datasets.[9] Ultimately, this synergy delivers a set of optimized and value-aligned candidate intervention schemes to DTE for rigorous ex-ante analysis.

Digital twin simulation for ex-ante analysis. Before real-world implementation, proposed intervention schemes undergo rigorous testing within the DTE environment. These simulations incorporate real-time data flows from satellite constellations, IoT sensor networks, and citizen science platforms, creating dynamic representations that evolve with actual Earth conditions. AI-driven analytics assess multi-scale impacts, from local ecosystem responses to global climate feedbacks, identifying potential tipping points, cascade effects, and unintended consequences. Uncertainty quantification techniques evaluate intervention robustness across parameter ranges, climate scenarios, and socioeconomic pathways. This comprehensive testing process transforms policy-making from untested assumptions into real-world validated solutions, reducing implementation risks while accelerating learning cycles.

Real-world implementation with adaptive feedback. Implementation proceeds through carefully monitored phases, with continuous sensing infrastructure tracking biophysical responses, social outcomes, and economic impacts. AI systems equipped with data assimilation techniques perform real-time diagnosis of divergences between simulated predictions and observed outcomes, distinguishing between natural variability, model uncertainties, and genuine anomalous events. Machine learning algorithms detect early warning signals of system transitions, enabling preemptive adjustments before crises materialize. Adaptive management protocols automatically trigger policy modifications when predetermined thresholds are crossed, ensuring rapid response to unexpected developments. This creates a learning system where each implementation cycle improves both model accuracy and intervention effectiveness.

To illustrate how this theoretical framework operates in practice, consider the complex challenge of large-scale afforestation initiatives aimed at carbon sequestration and biodiversity restoration. Traditional approaches might plant millions of trees based on static suitability maps, only discovering years later that changing precipitation patterns, pest outbreaks, or soil degradation compromise survival rates. In contrast, the AI-powered DTE approach begins with collaborative design combining indigenous knowledge, ecological science, and AI optimization to identify robust planting strategies. Simulations test these strategies across climate projections, incorporating factors like species interactions, hydrological impacts, and fire risks. During implementation, satellite monitoring tracks vegetation health, soil moisture, and carbon accumulation, while AI continuously adjusts species selection, planting density, and management practices based on observed outcomes. This adaptive approach ensures initiatives remain aligned with planetary boundaries while maximizing co-benefits for local communities and ecosystems.

## DIGITAL COUSINS: PRAGMATIC PATHWAYS TO GOVERNANCE

While the vision of a comprehensive, globally integrated AI-powered DTE system is compelling, its realization confronts formidable computational, theoretical, and institutional challenges. Earth's climate system alone involves interactions across scales spanning from millimeters (cloud droplets) to thousands of kilometers (atmospheric circulation), from seconds (turbulence) to millennia (ice sheet dynamics). Capturing these multi-scale processes at resolutions sufficient for local decision-making while maintaining global consistency would require computational resources exceeding current capabilities by orders of magnitude. Furthermore, the planetary boundaries framework itself operates at multiple spatial scales—while climate change is inherently global, land-system change and freshwater use manifest primarily at regional to local scales. These realities necessitate pragmatic implementation strategies that balance scientific robustness with computational feasibility.

To address these multifaceted realities, we propose a strategy that redefines the relationship between simulation and reality, inspired by the concept of *Digital Cousins* from robotics.[10] In its original context, a Digital Cousin is a virtual model that intentionally deviates from being an exact replica. Instead, it is designed to preserve the essential functions, or "affordances", of its real-world counterpart to solve a specific task. This stands in contrast to a digital twin, which strives for a comprehensive, one-to-one reconstruction.

We adapt and extend this function-first principle to planetary governance. A Digital Cousin Earth is not a scaled-down DTE, but a purpose-built model focused on solving a specific governance challenge. For instance, a Digital Cousin for a river basin would prioritize hydrological cycles and water allocation mechanisms over precise geological replication, embodying only the complexity needed to test water management policies effectively. This portfolio of specialized, problem-solving models collectively enhances our ability to govern the Earth without the immense overhead of universal simulation.

A prominent example is China's large-scale initiative to construct "digital twin river basins" for its major water systems. These are not exhaustive replicas of the entire river systems; instead, they function as purpose-built Digital Cousins focused on the critical affordances of flood forecasting, drought management, and optimal water resource allocation. By integrating massive real-time data streams with predictive models, these systems are designed to solve specific, high-stakes governance problems. This demonstrates that the most effective digital representations are not the most complete, but rather those best suited to their specific purpose. They serve as foundational proofs of the Digital Cousin strategy, establishing a pathway toward a constellation of specialized, AI-enhanced models that can actively and effectively govern regional Earth systems.

## BUILDING THE INTEGRATED FOUNDATION FOR DIGITAL TWIN EARTH GOVERNANCE

Operationalizing AI-powered DTE as a transformative governance engine requires more than technological innovation—it demands fundamental advances across technical, ethical, and institutional dimensions. These three pillars must develop synergistically, as weakness in any dimension undermines the entire framework's legitimacy and effectiveness. These foundational elements cannot develop in isolation; they must coevolve through iterative experimentation and social learning.

Technical innovation extends beyond raw computational power to encompass fundamental algorithmic advances. Causal discovery algorithms must distinguish correlation from causation in Earth system data, avoiding spurious relationships that could misdirect interventions. Physics-informed neural networks that incorporate conservation laws and Earth system constraints ensure AI recommendations remain physically plausible. Explainable AI techniques must render complex model decisions interpretable to policymakers and stakeholders, building trust through transparency. Federated learning approaches enable knowledge sharing across Digital Cousins while preserving data sovereignty and privacy. Finally, integration with cutting-edge Earth system science ensures the digital twin remains grounded in physical reality rather than drifting into abstraction.

Ethical frameworks must evolve from abstract principles to concrete mechanisms embedded within system architectures. Algorithmic auditing protocols systematically evaluate AI recommendations for biases that might disadvantage vulnerable populations or ecosystems. Procedural justice mechanisms ensure all stakeholders, particularly indigenous peoples, meaningfully participate in intervention design and evaluation. Value alignment techniques encode diverse ethical perspectives, from anthropocentric to ecocentric worldviews, enabling transparent negotiation of trade-offs. Human oversight protocols maintain meaningful human agency over high-stakes decisions while leveraging AI's analytical capabilities. Reversibility assessments evaluate whether proposed interventions can be undone if negative consequences emerge, incorporating precautionary principles into automated decision-making.

Institutional architecture requires unprecedented coordination. Transnational governance bodies must establish shared protocols for data exchange, model validation, and intervention coordination while respecting sovereignty and cultural diversity. Legal frameworks must evolve to address liability when AI-recommended interventions produce unexpected outcomes—who bears responsibility when an algorithm's climate intervention affects multiple nations? Financing mechanisms must mobilize resources for digital twin infrastructure while ensuring equitable access for developing nations. Science-policy interfaces must translate complex model outputs into actionable intelligence for decision-makers operating under time constraints and political pressures.

## CONCLUSION

AI-powered DTE stands at an inflection point that will determine whether it becomes a transformative instrument for Earth governance or remains an elaborate but ultimately passive monitoring system. The path forward requires bold vision tempered with pragmatic implementation, ambitious goals grounded in institutional realities. This evolutionary approach, exemplified by regional Digital Cousins, prevents the emergence of a "digital ivory tower"—sophisticated models divorced from real-world governance needs—while maintaining momentum toward the ultimate goal of integrated Earth system governance. By synchronizing advances across technical algorithms, ethical frameworks, and institutional architectures, we create a governance system that is both scientifically robust and socially legitimate.

Ultimately, a DTE enhanced with AI and guided by human wisdom offers not just a technological solution but a new paradigm for humanity's relationship with our planet. It transforms us from inadvertent planetary engineers to conscious Earth system navigators, capable of steering our collective trajectory within safe and just planetary boundaries. This vision—ambitious yet achievable, technological yet deeply human, global in scope yet regionally adaptive—represents our best hope for ensuring that Earth remains a thriving home for generations to come.

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## AUTHOR CONTRIBUTIONS

Xin Li conceptualized the study, developed the overarching framework, and led the manuscript preparation and revision. Jianbin Su contributed substantially to manuscript drafting and revision. Shiwei Yuan participated in the critical discussion of the work and contributed to manuscript revision. All authors contributed to the manuscript and approved the final version.

## DECLARATION OF INTERESTS

The authors declare no competing interests.