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Research Idea

A Generative Paradigm for Environmental Science: From Prediction to Immersive Scenarios for Participatory Stewardship

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Abstract

Humanity faces environmental crises on a scale that demands new scientific paradigms. While valuable, the application of artificial intelligence has largely been confined to a predictive role—a paradigm insufficient for the transformative action now required. We argue for a shift toward a generative framework, repositioning AI from an analytical tool to a facilitator of synthesis and communication. This perspective introduces a vision where advanced generative models, including text-to-video technologies, create dynamic, experiential simulations of designed ecosystems. This allows stakeholders to not only see a proposed design, but also to witness its potential dynamics, such as how a restored forest matures or how green infrastructure responds to climate events. Crucially, this approach empowers AI to act as a representative for non-human species, synthesizing data to visualize their needs. However, I emphasize the critical distinction between photorealistic visual rendering and rigorous biophysical simulation; the former must be grounded in the latter to avoid misleading outcomes. I critically examine the approach's inherent challenges, including the environmental footprint of these models, and argue for an indispensable "expert-in-the-loop" framework to guide and validate these powerful new tools. This paradigm shift has profound implications for

scientific methodology and public engagement, heralding an era where interdisciplinary teams leverage AI to visualize, deliberate, and collaboratively shape a resilient planet.

Keywords

Generative AI, Foundation Models, Environmental Science, System Design, Dynamic Simulation, Scientific Communication, Human-in-the-loop, Co-creation

Overview and background

The escalating scale of global environmental crises, from biodiversity loss to climate disruption, demands more than incremental improvements in our scientific methods; it calls for entirely new ways of thinking. Artificial intelligence has emerged as a powerful tool for managing these complex systems. Historically, its application has followed a predictive paradigm, evolving from remote sensing classification to complex forecasting models. These approaches, often relying on interpretable risk scores (Ustun and Rudin 2015), have significantly advanced our analytical capabilities. However, the advent of large-scale generative models represents a qualitative leap in AI's potential. As in other high-stakes fields like healthcare, this technology is moving beyond analysis to creation, prompting both excitement and critical ethical reflection (Ning et al. 2024).

Yet, environmental science remains largely confined to this predictive paradigm. This framework is fundamentally constrained when confronting a future with no historical analog, limiting us to a reactive stance. This perspective, therefore, proposes a generative framework, outlining how new AI capabilities can reposition the technology from an analytical tool to a partner in a facilitator of environmental stewardship (Fig. 1).

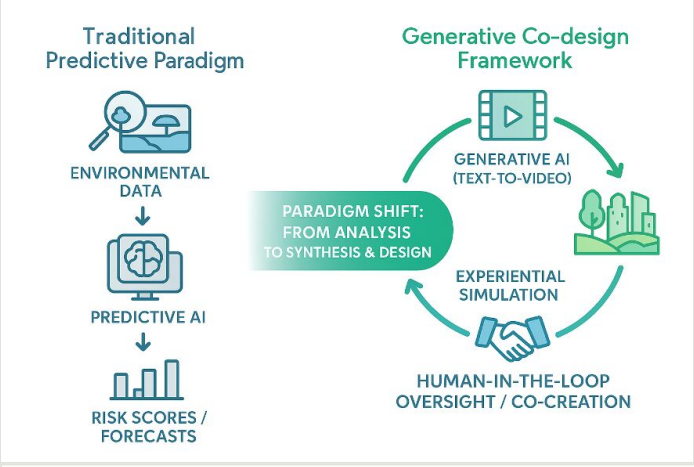

Figure 1. doi

Illustration of the proposed paradigm shift in environmental science.

The Generative Framework: Designing Across Environmental Systems

A generative framework reframes the central scientific question from "What will happen?" to "What system could we design to achieve a desired set of outcomes?". This approach leverages generative AI's synthetic capabilities to propose novel solutions across interconnected environmental challenges. In proactive conservation planning, instead of merely optimizing static reserve networks, a generative model could propose dynamic strategies, such as adaptive habitat corridors that reconfigure in response to simulated climate futures. Crucially, this allows AI to act as a representative for non-human species, synthesizing data on biodiversity requirements to propose scenarios that might otherwise be overlooked in human-centric planning. In ecological restoration, AI could design novel ecosystems for degraded lands, proposing assemblages of species with complementary functional traits optimized for future resilience. In sustainable urban design (e.g., Sedrez and Pitts 2025), it could generate integrated blueprints that weave functional ecological networks through the urban fabric, synthesizing biodiversity, infrastructure, and social equity goals. This moves beyond optimization towards genuine, systemic invention.

A New Frontier: "Dynamic Visual Hypotheses" with Video-Generative AI

The framework's potential culminates in its most transformative application: experiential simulation. The emergence of powerful text-to-video models like Sora (OpenAI 2024) signals a revolutionary capability to translate abstract decisions into dynamic visual narratives. We can now move from generating a static map of a restored forest to creating a photorealistic video of that forest's maturation over decades. However, a rigorous scientific distinction is paramount here: visual rendering is not synonymous with biophysical simulation. While AI can generate persuasive imagery, these must be treated as "dynamic visual hypotheses"—visualizations that are grounded in, and constrained by, rigorous biophysical models, rather than independent artistic creations. Used correctly, this transforms generative AI from a design tool into a powerful scientific communication and deliberation interface. It allows diverse stakeholders—from scientists to local communities—to intuitively grasp the implications of a proposed intervention. By visualizing complex data, AI serves to bridge the gap between technical simulations and public understanding.

A Framework for Participatory Stewardship

This powerful new capability necessitates a robust framework for human oversight. The promise of generative AI is accompanied by significant risks, framing it as a "double-edged sword" (Dong and Rudin 2020). The propensity for "hallucination," algorithmic bias, and a lack of true causal understanding are critical flaws (Dong and Rudin 2020, Saw et al. 2025). Furthermore, we must critically address the environmental footprint of

these technologies; the massive computational energy required for training and running video-generative models presents a paradox for environmental science (Strubell et al. 2019, Kaack et al. 2022). The deployment of these tools must be weighed against their carbon costs, necessitating a push towards "Green AI" and efficient inference strategies (Schwartz et al. 2020).

Therefore, this paradigm is not about autonomous AI but a symbiotic "human-in-the-loop" relationship to prevent any form of "AI dictatorship" over social values. The human expert's role expands to become a director, curator, and critic of these generated futures. Scientists must rigorously define the underlying ecological and physical rules that constrain these simulations. They must validate the outputs against established knowledge and interpret the ethical and social implications of the visualized scenarios. The AI generates possibilities; the human provides the scientific grounding, ethical compass, and real-world context.

Realizing this generative and experiential vision requires a new operational framework for environmental science. This framework is built upon three integral components that together create a holistic ecosystem for innovation. The foundation is a new class of "Environmental Stewardship Foundation Models." These models must be trained on multimodal data—spanning ecological, climatic, social, and economic domains—and designed for controllable, verifiable generative tasks. This framework is then operationalized through open source "Generative Digital Twins." These are not merely numerical simulators but interactive platforms where AI-generated strategies can be visualized, tested, and debated by scientists and stakeholders, fostering a transparent design process. Supporting this entire structure is a renewed commitment to interdisciplinary education. We must train the next generation of scientists in the nuanced arts of systems thinking, ethical AI application, and the critical interpretation of AI-generated futures, guided by specialized assessment frameworks (Ning et al. 2024). This integrated framework represents a fundamental commitment to building the tools and human capacity necessary for a truly participatory future. The task ahead is not merely to predict our trajectory, but to collectively deliberate upon and build our destination. By harnessing generative AI as a visual interface to simulate living futures, we can unlock an unprecedented capacity to imagine, communicate, and shape a more resilient world.

Ethics and security

The initial draft of this manuscript was written by HD. English language editing and refinement were assisted by Google Gemini. Furthermore, the figures included in this paper were generated by Gemini based on original concepts and preliminary drafts provided by HD.

Author contributions

H.D. conceived the idea and wrote the manuscript.

Conflicts of interest

The authors have declared that no competing interests exist.

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