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VIRTUAL LABORATORIES: MESOCOSMS AND GAMEWORLDS

Abstract: *This article explores the role of digital games as virtual laboratories for addressing ecological and climate change challenges. It begins by examining the intersection of citizen science and digital gaming, specifically initiatives that have enabled global communities to contribute to ecosystem preservation efforts through collaborative data collection, analysis, and problem-solving that have been vital for monitoring marine habitats. Building upon these developments, we will explore how digital games share parallels with mesocosms, attempting to render ecological and Earth systems phenomena legible while simultaneously contributing to contemporary debates surrounding biodiversity, species loss, and climate change. Notably, digital gameworlds have expanded their scope beyond simple ecological simulations, incorporating intricate climate models alongside social, political, and historical elements to craft nuanced, evolving virtual environments that attempt to reflect the fragile interconnection of systems on a planetary scale.*

Keywords: *climate change; digital games; ecology; laboratories; planetary infrastructure*

Virtuální laboratoře: Mezokosmy a herní světy

Abstrakt: *Tento článek zkoumá roli digitálních her jako virtuálních laboratoří pro řešení ekologických problémů a problémů souvisejících se změnou klimatu. Článek začíná zkoumáním průniku občanské vědy a digitálního hraní, konkrétně iniciativ, které umožnily globálním komunitám přispět k úsilí o zachování ekosystémů prostřednictvím společného sběru dat, analýzy a řešení problémů, které byly zásadní pro monitorování mořských biotopů. V návaznosti na tento vývoj prozkoumáme, jak digitální hry sdílejí paralely s mezokosmy, pokusíme se lépe vysvětlit jevy ekologických systémů a zároveň přispějeme k současným debatám o biodiverzitě, ztrátě druhů a změně klimatu. Jedním z hlavních bodů je, že digitální herní světy rozšířily svůj záběr nad rámec jednoduchých ekologických simulací a zahrnují složité klimatické modely spolu se sociálními, politickými a historickými prvky, aby vytvořily detailní vyvíjející se virtuální prostředí, která se pokoušejí odrážet křehké propojení systémů v planetárním měřítku.*

Klíčová slova: *změna klimatu; digitální hry; ekologie; laboratoře; planetární infrastruktura*

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1. Introduction: Laboratories on a Disk

With an estimated three billion users worldwide and a valuation exceeding $30 billion, digital games have become the defining mass medium of the 21st century.[1] A growing interest in the recognition of digital games as valuable avenues for research and serving as pedagogical tools has led to characterising their role as cognitive artifacts that are capable of fostering "systems thinking" or "systems competence."[2] From this viewpoint, digital games are embraced as immersive and interactive virtual environments that can facilitate the development of cognitive skills essential for grasping the structural characteristics and dynamics of complex systems. Digital games provide a unique platform for individuals to actively explore simulated representations of real-world systems, uncovering patterns, relationships, and interconnections that might otherwise remain obscure or difficult to discern in daily circumstances.

Under this light, digital games have been characterised as affordances that provide players with "rewards, options that allow the user to navigate obstacles in a personalised way, opportunities to try out hypotheses and to fail in a safe space, iterative advance based on prior decisions and consecutive challenges that unfold logically. These rules echo many characteristics of scientific inquiry."[3] It is through this prism of scientific inquiry that we explore how planets or environments even when digitally rendered, can have real world effects on our physical infrastructures and habitats. Additionally, what we refer to as virtual environments within digital games serve as sandboxes that foster interest in questioning our understanding of the seemingly intractable complexity of phenomena related to biodiversity loss, ecosystem management, and climate change.

Expanding on our exploration of virtual environments in digital games, we focus on how complex planetary systems are distilled into manageable discrete components that are facilitated by actionable in-game inputs and displays. Pursuing this thread further, "digitization" does not necessarily imply simplification, instead digital games allow us to explore forms and performances of agency. These performances can also be conceived along the

[1] Josh Howarth, "How Many Gamers Are There? (New 2024 Statistics)," *Exploding Topics* (blog), June 11, 2024.
[2] Joelle-Denise Lux and Alexandra Budke, "Playing with Complex Systems? The Potential to Gain Geographical System Competence through Digital Gaming," *Education Sciences* 10, no. 5 (2020): 130.
[3] Aleks Krotoski, "Serious Fun with Computer Games," *Nature* 466, no. 7307 (2010): 695.

lines of producing a spectrum of roles for us to play including but not limited to, environmental managers, citizen scientists that regenerate worsening habitats or guiding automated and robotic technologies in reengineering ecosystems. Roles such as these also emerge from what is argued here at the intersection of citizen science, digital gameworlds as mesocosms, and forms of speculative fiction that are grounded in climate science research. We contend this intersection bridges gaps between researchers and a broader public involvement via digital games that also extends into the realm of imagining alternative futures from our present configuration.

We will articulate this by first examining how digital gaming has come to shape current citizen science initiatives, which focus on gathering data to monitor climate, marine, and land ecosystems. These initiatives coincide with the rise of gamification and its underlying mechanics, which have ballooned in interest among users and citizens worldwide. Public engagement in climate science has expanded through the ubiquitous availability of devices such as laptops, phones, sensors, drones, and citizen science kits that have been instrumental in opening channels for public participation, enabling users to contribute to climate knowledge and ecological infrastructures.

To provide a more concrete link between gamification and its application, typically this involves awarding points, progressing through levels, and earning achievement badges to mould individual behavior and results within a specified environment.[4] NASA's *NeMO-Net* game, which involves users from around the globe in an effort to train machine learning algorithms that classify and evaluate the health of coral reefs, is an example of the marriage between citizen science and gamification. This marriage can also be characterised as a way in which citizen science initiatives have devised approaches to involve individuals not exclusively in a care-free ludic mode, but rather in implicating their role as ecosystem stewards within a planetary web of satellite technology and supercomputers.

Building on *NeMO-Net*, we will explore how climate change models and scientific forecasts are increasingly integrated into digital game environments. Complementing this angle, we will draw upon Alenda Chang and her insightful exploration of the parallels between mesocosms and gameworlds. Chang examines how digital games can be thought of as scale-built systems.

[4] Christo Dichev and Darina Dicheva, "Gamifying Education: What Is Known, What Is Believed and What Remains Uncertain: A Critical Review," *International Journal of Educational Technology in Higher Education* 14, no. 1 (2017): 9.

Mesocosms and digital games she argues, allow for the study of complex phenomena in a controlled environment and at legible scales.

Considerations of scale are relevant given that dimensional relationships have become central to our ability to analyze, comprehend, and forecast the temporal and spatial impacts of phenomena such as climate change. As Anne Pasek has posited: "The mediation of climate change is therefore always the mediation of its scalar dynamics and so also an invitation to imagine unconventional forms of causality and collectivity."[5] Scaling issues also encourage us to consider or take seriously the characterisation of digital game environments, particularly those found in simulation-based games like *SimEarth*, which have been compared to "laboratories on a disk."[6] The convergence of rendering Earth systems into digital games not only demonstrates or gives capacity to simulate vast eons of deep time. It also underscores the potential for open-ended play and experimentation, driving scientific pursuits and cultivating novel perspectives of our Earth systems that in turn evolve into planetary networked laboratories.

The final layer of this article aims to explore the complex interplay between modeling Earth systems and the representation of social, cultural, economic, and historical factors that are depicted in digital gameworlds. The fading distinction between digital and real-world spaces reveals a unique perspective, emphasizing the interlinked and transformative nature of the environments we construct, sustain, or dissolve. When we engage with virtual environments that simulate catastrophes and dwindling resources, we are starkly reminded that these experiences are not entirely divorced from our real-world concerns. Rather, they serve as powerful reflections of our immediate climatic and ecological challenges. Thus, the virtual environments we interact with and manipulate do not merely reside in an abstract or ethereal realm. Instead, the sustenance of these virtual environments are profoundly entwined with the material realities of extraction of resources, metals, and minerals that form the foundation of both in-game as well as our real-world planetary infrastructure.

As we will see, a way to further spell out these realities ties into the inherent role of narrative framing, which has players in these digital games regenerate virtual worlds, where they are immersed in environments grappling with the corrosive effects of biodiversity loss, species extinction, and habitat loss. Ultimately, we maintain this warrants an examination of how

[5] Anne Pasek, "Mediating Climate, Mediating Scale," *Humanities* 8, no. 4 (2019): 159.
[6] Johnny L. Wilson, *The SimEarth Bible* (Berkeley: Osborne McGraw-Hill, 1991).

climate models integrated into digital games prompt us to actively play out alternative realities, thereby providing us with the cognitive resources to compose narratives for emerging and vanishing worlds that extrapolate from current climate and Earth science research.

2. The Emergence of the Network Laboratory & Role of Citizen Science in NeMO-Net

The perception and representation of the scientific laboratory have undergone a significant transformation. What was once a place evocative of a "house of experiment," reminiscent of medieval alchemical practices, has evolved into specialised facilities housing state-of-the art technical resources. The contemporary articulation of the laboratory exists at the nexus of extensive networks of expertise and knowledge sharing that transcend institutional and national boundaries. The conventional conception of the scientific laboratory has been perceived as a controlled setting that allows for meticulous manipulation and regulation of variables in order to isolate and examine specific factors under investigation. Here, the scientific laboratory is barred or exposed to minimal external disturbance effects, yet this narrative has come under scrutiny due to the profound impacts of industrialisation, urbanisation, and networked infrastructure sweeping the planet.[7] Such progressive developments have illuminated the interdependence of scientific laboratories in wider techno-social contexts and environments. When we examine how laboratories actively participate in, replicate, and even transform realities beyond their physical boundaries, we begin to challenge the perceived insulation of laboratories from so-called external disturbances. The idea that the laboratory cannot be defined or understood in a singular, timeless, or universally applicable way becomes apparent when we observe its manifestations throughout different historical and cultural contexts.[8] Through this lens, laboratories function as social and cultural infrastructure corresponding to specific periods, reflecting the dominant social institutions and practices of the era. Moreover, critical perspectives have extensively written about how laboratories have undergone a process of evolution and transformation due to the exogenous influx of a variety of

[7] Henning Schmidgen, *"Laboratory," Encyclopedia of the History of Science,* accessed October 21, 2024; Robert E. Kohler, "Lab History: Reflections," *Isis* 99, no. 4 (2008): 761–68.
[8] Peter Galison and Emily Thompson, *The Architecture of Science* (Cambridge, MA: MIT Press, 1999).

imported organisms, working personnel, instruments, sampled data, as well as conflicting epistemological and ontological frameworks.[9]

As we have moved into the 21st century, the concept of scientific laboratories has expanded beyond traditional settings. Now a growing network of environmental sensors, geospatial devices, and crowdsourced data collection is playing a formative role in gathering data among diffused locations, practices, and enactments. The setup of makeshift laboratories across multitudinous locations marks a significant shift in data collection practices. Makeshift or improvised field stations aggregate raw data from various sources, including oceans, forests, and jungles, through both in-situ and remote sensing methods. The intermingling of digital, remote, and in-situ technologies assume automated or non-human positions of "sensing by other means," moving us beyond a rooted anthropomorphic framework of the classical five senses.[10]

Citizen science, a multifaceted practice engaging non-experts in scientific activities, has gained interest as a valuable approach to research. The proliferation of geo-information technologies, particularly location-aware devices, has been instrumental in enabling users globally to acquire, use, and share geographical information.[11] A major component of citizen science revolves around citizen sensing, a practice that integrates communities with sensors or digital tools to consolidate environmental data. This burgeoning practice has come to encompass a shift in the roles, arrangements, and methods of data collection and analysis. The narratives that are offered related to citizen science center upon empowering individuals to become active participants and collaborators in environmental monitoring and research, thus redefining traditional boundaries between expert and amateur contributions to scientific knowledge.[12] Related narratives also push forward the framework of environmental data justice as a practice synergising with citizen science where "data can be a part of envisioning and enacting al-

9 Bruno Latour, *Laboratory Life: The Construction of Scientific Facts* (Princeton, NJ: Princeton University Press, 1986); Karen Barad, *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning* (Durham: Duke University Press, 2007).

10 Jennifer Gabrys, "Sensors and Sensing Practices: Reworking Experience across Entities, Environments, and Technologies," *Science, Technology, & Human Values* 44, no. 5 (2019): 723–36; Cymene Howe, "Sensing Asymmetries in Other-than-human Forms," *Science, Technology, & Human Values* 44, no. 4 (2019): 900–10.

11 E. C. McClure et al., "Artificial Intelligence Meets Citizen Science to Supercharge Ecological Monitoring," *Patterns* 1 (2020): 100109.

12 Nicola da Schio, "The Empowering Virtues of Citizen Science: Claiming Clean Air in Brussels," *Engaging Science, Technology, and Society* 8, no. 1 (2022): 29–52.

ternative futures, not just perpetuating harms and injustice."[13] A number of citizen-led or collaborative initiatives can be displayed along the lines of monitoring or measuring, for example, air quality or water-related issues that aid in emergency water management, as well as conducting biodiversity observations within local environments.[14]

Initiatives may include more extensive geographical territories, wherein contributors may originate from various regions or even traverse continents. Here, projects rooted in scientific research often drive the development of large-scale spatio-temporal datasets playing a crucial role in tracking and implementing UN Sustainable Development Goals.[15] User engagement has also extended critically to monitoring ecosystems, as exemplified by NASA's Citizen Science for Earth Systems Program. Utilizing the help of Landsat satellite imagery and a smartphone app, it has enlisted over 1,000 unique users to assist in mapping global kelp forests. Through leveraging the widespread availability of user devices and the connectivity provided by global infrastructures, citizen science then becomes a vital pillar in collecting and annotating data from heterogeneous locations. It is with the hope that by gathering data from a number of locations, through devices or sensors and the unique relationships between users and environments, a more granular and ground-truth picture of specific impacts of climate change or biodiversity loss can be illustrated.

In recent years, increasing emphasis has also been spotlighted on critical conservation endeavors, with particular attention given to the degraded state of coral reefs. Initiatives that have materialised foster and animate efforts to engage with citizen science to heighten awareness and devise strategies to involve more users in campaigns to address the afflictions of coral reefs. Coral reefs are known to play an invaluable role in marine biodiversity but have faced substantial challenges due to climate change, pollution, unsustainable fishing practices, and the adverse effects of land-based activities.

Responding to these challenges we can turn to NASA's *NeMO-Net* (see Fig. 1), launched in 2020, which has merged citizen science, artificial intelligence, and gamification in the bid to build a dataset designed for assessing

[13] Dawn Walker et al., "Practicing Environmental Data Justice: From DataRescue to Data Together," *Geo: Geography and Environment* 5, no. 2 (2018): e00061.
[14] Jonathan D. Paul et al., "Citizen Science for Hydrological Risk Reduction and Resilience Building," *WIREs Water* 5, no. 1 (2018): e1262.
[15] United Nations Development Programme, "Sustainable Development Goals," accessed October 22, 2024; Dilek Fraisl et al. "Mapping Citizen Science Contributions to the UN Sustainable Development Goals," *Sustainability Science* 15 (2020): 1735–51.

the health of global coral reefs that are essential for maintaining marine biodiversity. *NeMO-Net* has been developing an extensive image library of coral reefs distributed across the globe, combining 3D imagery sourced from divers and snorkelers, as well as 2D images collected from satellites. Using state-of-the art fluid lensing technology, shallow marine habitats can be captured at millimeter-scale resolution from satellite imagery. This technology allows for the transformation of 2D satellite images into high-resolution 3D reconstructions of coral reefs in many cases, significantly enhancing our ability to study these ecosystems remotely.[16]

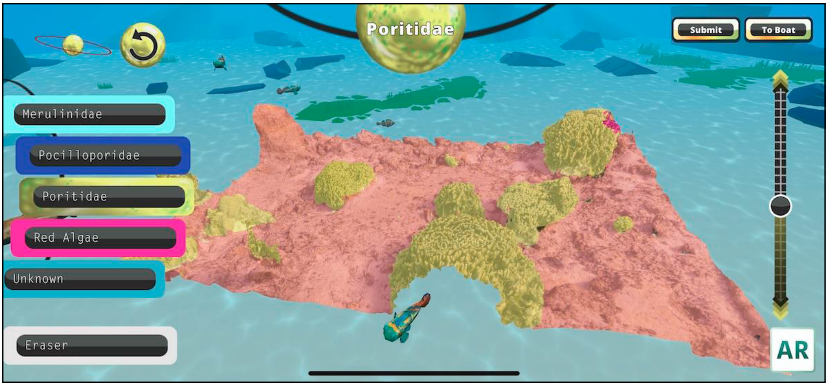

Figure 1: *NeMO-Net*, NASA, 2020. Source: Image courtesy of Ved Chirayath (NASA NeMO-Net Team).

Presented as a game that entails users progressing through levels by their classification, they can explore corals worldwide where they engage in the practice of painting or rather classifying coral reefs by painting 3D and 2D images that are sourced from NASA's state-of-the-art FluidCam instruments. The game also provides users with detailed field guides, featuring images and descriptions of coral species. These guides assist users as they analyze 3D model renderings of coral, using digital brushes to paint and classify different coral types based on color. Players advance through levels

[16] Ved Chirayath and Alan Li, "Next-Generation Optical Sensing Technologies for Exploring Ocean Worlds – NASA FluidCam, MiDAR, and NeMO-Net," *Frontiers in Marine Science* 6 (2019): 645408.

by submitting their classifications earning badges according to their accuracy and the volume of submissions.

Data collected through the *NeMO-Net* game is then fed into NASA's open-source NeMO-Net neural network, powered by NASA's Pleiades supercomputer. Respectively, the crowdsourced annotations obtained from the gameplay are used as training data for the NeMO-Net machine learning algorithms, enabling the algorithms to learn patterns and features associated with different coral reef health conditions. Once trained, these machine learning algorithms automate the classification and evaluation of coral reef health using multi-resolution Earth observation datasets.[17] The resulting automation enables the algorithms to identify and evaluate the condition of coral reefs around the globe by analyzing satellite imagery and other remotely sensed data through a range of spatial resolutions.

Even with the promises of democratizing data collection and citizen empowerment, citizen science projects do confront issues with maintaining consistent levels of engagement from users, restricting access to users based on access or possession of appropriate devices, and ensuring that there is continuous data collection that can then lead to fluctuations in data quantity and quality. The varying levels of public engagement and commitment in citizen science have also been linked to whether participants perceive their contributions as having a direct impact on their daily lives.[18] We nonetheless can spotlight *NeMO-Net* as a project exploring the convergence of scientific research, public participation, and interactive media in relation to marine ecosystem monitoring. The collaboration between NASA and citizen scientists not only exemplifies but also invites further scrutiny of participatory methodologies aimed at democratizing data collection, annotation, and analysis.

The evolving landscape of citizen science platforms illuminates how habitats are sustained through collaborative and participatory planetary-scale networks. Distributed monitoring networks recursively modify the very environments and infrastructures they monitor through the circulation of automated data between interoperating devices and sensors. Thus, networked sensors do not just measure and map realities, they reform territories and relations through encoded actuations. *NeMO-Net* demonstrates

[17] Jarrett van den Bergh et al., "NeMO-Net: Gamifying 3D Labeling of Multi-Modal Reference Datasets to Support Automated Marine Habitat Mapping," *Frontiers in Marine Science* 8 (2021): 645408.
[18] Erika N. Speelman et al., "Serious Games and Citizen Science: From Parallel Pathways to Greater Synergies," *Current Opinion in Environmental Sustainability* 64 (2023): 101320.

that digitally linked observation platforms exercise important influence matched to their observational powers, making and remaking territories just as much as detecting existing ones.

3. Scaling The Mesocosm: Eco-Visualising Planets

With citizen science foregrounding our attention upon the intersection of planetary infrastructures, devices, and the mechanisms of gamification, we can shift to exploring the relationship between mapping and representing the realities of climate systems and habitat destruction in digital games. Drawing inspiration from theorist Alenda Chang and her work, an intriguing link can be established between mesocosms which are experimental ecosystems commonly utilised in biological research and digital games. Mesocosms are utilised to tailor the degree of manipulative control over an enclosed ecosystem to a specific scale. This poses the question of how far we can infer that our observations identified at this level are representative of a larger counterpart ecosystem.[19] We can imagine that we set up a mesocosm to study the relationship and effects of temperature changes on the growth and reproduction of a freshwater aquatic plant species and its associated microorganisms. The mesocosm can consist of a series of interconnected tanks or chambers, each containing the desired water chemistry, nutrients, and initial species composition. We can then manipulate the temperature within specific tanks while maintaining consistent conditions in others, permitting them to monitor the response of the aquatic plant species and its microbial community to temperature fluctuations. A mesocosm scaled down to a manageable resolution ideally has us discerning the effects of our inputs and the degree of modulation we exercised in testing our experiment, which would be otherwise difficult or impossible on a large scale.

Chang draws parallels to the manner in which gameworlds serve as mesocosms or controlled virtual environments, with such environments encouraging us to probe, manipulate, and test hypotheses of in-game systems on smaller or relatively legible scales. In this fashion, players can manipulate variables related to resource management, ecosystem dynamics, or the behavior of non-player characters (NPCs) in response to their decisions and observe the resulting effects. Echoing Ian Bogost's concept of the "simulation gap," which acknowledges the inherent limitations and

[19] Alenda Y. Chang, *Playing Nature: Ecology in Video Games* (Minneapolis: University of Minnesota Press, 2019).

oversimplifications in real-world models, such an approach opens up opportunities for players to engage with and critically examine the simulation. Nonetheless, these gaps are not merely limitations, but also create for players a rich space for creativity and interpretation. It is by exploring these gaps, players can gain insights into the rules and problem space that the game presents, while also applying their own understanding of how the game system fosters a dialogue about its connection to the complex target systems its aims to represent.[20] The interplay of mechanics and user engagement also ties digital games into their role as cognitive artifacts that nourish feedback systems conducted through a type of "thinking-through-doing." Thinking-through-doing involves players adopting what Lorenzo Magnani refers to as "manipulative abduction," which highlights the central role of scientific cognition in formulating and evaluating explanatory hypotheses.[21] To further illustrate manipulative abduction, we emphasise the integral role of actively manipulating and interacting with external objects or representations in generating and testing hypotheses. Digital gameworlds often incorporate various cognitive tools and representations to enhance player experience and understanding. Players are typically furnished with an array of cognitive aids, such as mini-maps and world maps, heat maps, terrain analysis overlays and resource flow diagrams.

Visual aids also come into play when specifically scoping in on how digital gameworlds attempt to emulate climate or Earth science models, challenges inevitably surface with respect to accurately representing the complexities and intricacies of real-world systems. This is also brought to relief with climate or Earth science models attempting to simulate, or in a sense, simplify, complex processes for the purpose of shrinking the resolution and manipulability of the model. Such models of course cannot fully capture the multitude of interlocking systems and the vast temporal and spatial scales involved. As Paul N. Edwards points out,[22] Earth Science deals with a wide range of interdependent systems, including the atmosphere, oceans, cryosphere, land surfaces, and biosphere. Each of these systems is incredibly complex, with countless variables and interactions that operate on different scales and timeframes. The field also encounters constraints

[20] Ian Bogost, *Persuasive Games: The Expressive Power of Videogames* (Cambridge, MA: MIT Press, 2007).
[21] Lorenzo Magnani, "Model-Based and Manipulative Abduction in Science," *Foundations of Science* 9, no. 3 (2004): 219–47.
[22] Paul N. Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (Cambridge, MA: MIT Press, 2010).

in terms of the materials that can be manipulated and experimented with in both laboratory and real-world environments.[23] Unlike experimental sciences such as physics and chemistry, where phenomena can be tested in controlled environments, Earth system phenomena are often too complex and difficult to manipulate directly. Therefore, modeling becomes essential in bridging the gap between our limited observations and the long-term processes we seek to understand.

While striving for a form of realism and educational value, digital game designers have also derived inspiration from scientific climate models and integrated them, notably featured in titles such as *Fate of the World* (2011). Players in this global strategy game, which predates the major Paris Climate Conference in 2015, assume the role of an international organisation responsible for addressing and managing the complex challenges of climate change through policy decisions. *Fate of the World* would integrate the climate prediction model developed by the Climate Dynamics Group at the University of Oxford.[24] The model utilised within the game encompassed a wide array of factors, including global temperature, greenhouse gas emissions, gross domestic product (GDP), economic parameters, energy output from various sources, and precise demographic data for each geographical region.

Over time simulations and game developers have also incorporated what are known as open source reduced-complexity climate models such as Hector. Reduced-complexity climate (RCM) models, are recognised for their computational efficiency and adaptability across a wide range of applications.[25] Among many other reduced complexity models, Hector stands out for its capabilities in quickly generating future climate projections, such as scenarios estimating the impact of carbon dioxide removal technologies on energy-water-land systems. In other words, these models excel at producing extensive ensembles of results while requiring only a fraction of the computational resources needed for a single run of an Earth System Model (ESM).[26]

[23] Nicholas A. Soltis et al., "The Relationship between Active Learning, Course Innovation, and Teaching Earth Systems Thinking: A Structural Equation Modeling Approach," *Geosphere* 15, no. 5 (2019): 1703–21; Alisa Bokulich and Naomi Oreskes, "Models in the Geosciences," in *Springer Handbook of Model-Based Science*, eds. Lorenzo Magnani and Tommaso Bertolotti (Dordrecht: Springer, 2017), 891–911; Phil Oh Seok, "Abduction in Earth Science Education," in *Handbook of Abductive Cognition*, ed. Lorenzo Magnani (Cham: Springer, 2022), 1–31.
[24] Myles Allen et al., "The Exit Strategy," *Nature Climate Change* 1, no. 5 (2009): 56–58.
[25] Kalyn Dorheim et al., "Hector V3.1.1: Functionality and Performance of a Reduced-Complexity Climate Model," preprint, submitted September 7, 2023.
[26] Michio Kawamiya et al., "Two Decades of Earth System Modeling with an Emphasis on Model for Interdisciplinary Research on Climate (MIROC)," *Progress in Earth and Planetary*

We can trace a legacy of planetary models that influenced games such as *SimEarth* (1990) which borrowed influence from James Lovelock and Andrew Wilson's Daisyworld. Designed to test the plausibility of the Gaia hypothesis, Daisyworld was conceived as a cybernetic system that models how a planet might continuously stabilise itself through interwoven organic processes. James Lovelock gained prominence by working at the Jet Propulsion Laboratory, conducting research and comparing the lifeless atmosphere of Mars to a life-enabling Earth, which eventually laid the foundations to develop his Gaia theory. As described in the *SimEarth* manual, the simulation functionality resembled a "laboratory on a disk," furnishing an experimental computational mesocosm for investigating planetary evolution. In his reflection on *SimEarth*, James Lovelock described it in the preface to the accompanying gamebook:

> *SimEarth* itself is neither a game nor a science based model. […] [I]t represents an original form; a convenient dynamic map […] of a planet, displayed in time as well as space – something on which speculative games or models can be played, a test bed for all those "what-ifs." It is a wonderful and timely integration of our newly developed capacity to make personal computer models with our need to use them to understand the earth and ourselves. […] *SimEarth* gives you the chance to enter the Gaia argument as a player.[27]

Inspired by the Gaia theory and behaving as a systems simulation, *SimEarth* contains multiple in-game scenarios that enable the simulation of the non-linear behavior of Earth systems. Players have at their disposal an array of scenarios they can explore, ranging from the Cambrian Earth to Lovelock's Daisyworld, and even terraforming Mars into a planet conducive to Earth-like lifeforms. By manipulating the initial conditions of a planet's composition and triggering interventions, players can witness their planet develop or decline over vast temporal horizons, allowing them to take a seat before the stage and act of planetary evolution.

SimEarth and other similar games typify a broader concept that has evolved into eco-visualisation through their approach to portray complex ecological processes and their resultant impacts. Eco-visualisation is understood as a method that aims to illustrate the interconnections between ecological environmental patterns and their associated impacts. Offering the potential to foster a more nuanced understanding of the feedback processes

Science 7, no. 1 (2020): 1–17.

[27] Johnny L. Wilson, *The SimEarth Bible* (Berkeley: Osborne McGraw-Hill, 1991).

that exist between societal activities and ecological systems, it has come to be regarded as a critical eco-pedagogical tool.[28] The flourishing interest in eco-visualisation has sparked curiosity and discussion regarding its potential applications and the mediums through which it can be effectively employed. Videos, climate graphs, interactive visuals, and, increasingly, digital games have emerged as tools to explore the influence of human behaviors on the environment and the complex relationships within ecosystems.

Digital games offer a unique approach to eco-visualisation by transforming complex ecological dynamics into tangible, abductive and manipulable experiences. As previously mentioned, many digital games incorporate in-game interfaces, visual displays, maps, and charts as cognitive tools. Dynamic in game displays visually represent crucial environmental data, including resource constraints, emissions, pollution levels, and energy flows.

A notable and interesting example of eco-visualisation we can draw attention to is the world-building game *Eco* (2018) (see Fig. 2).[29] More than just a game, *Eco* serves as a social experiment, challenging players to collaboratively build a civilisation while managing the game's internal complex ecosystems. One of the many narratives central to the game thrusts players into building alliances, moderating consumption, and engaging in governance and diplomacy to avert an impending catastrophe from a meteor impact. With this looming threat, players must manage resource collection and pollution levels driven by activities like farming, hunting, crafting, and power plant construction. Throughout the game, the visualisation of ecological data plays an indispensable role in players' decision-making processes. Players then have access to a rich array of simulated data representations that measure, model, and analyse the health of multiple ecosystems.

[28] Erica Löfström, Christian A. Klöckner, and Ine H. Nesvold, "Nature in Your Face – Disruptive Climate Change Communication and Eco-Visualization as Part of a Garden-Based Learning Approach Involving Primary School Children and Teachers in Co-Creating the Future," *Frontiers in Psychology* 11 (2020): 568068.

[29] Kristoffer S. Fjællingsdal and Christian A. Klöckner, "Gaming Green: The Educational Potential of *ECO* – A Digital Simulated Ecosystem," *Frontiers in Psychology* 10 (2019): 2846.

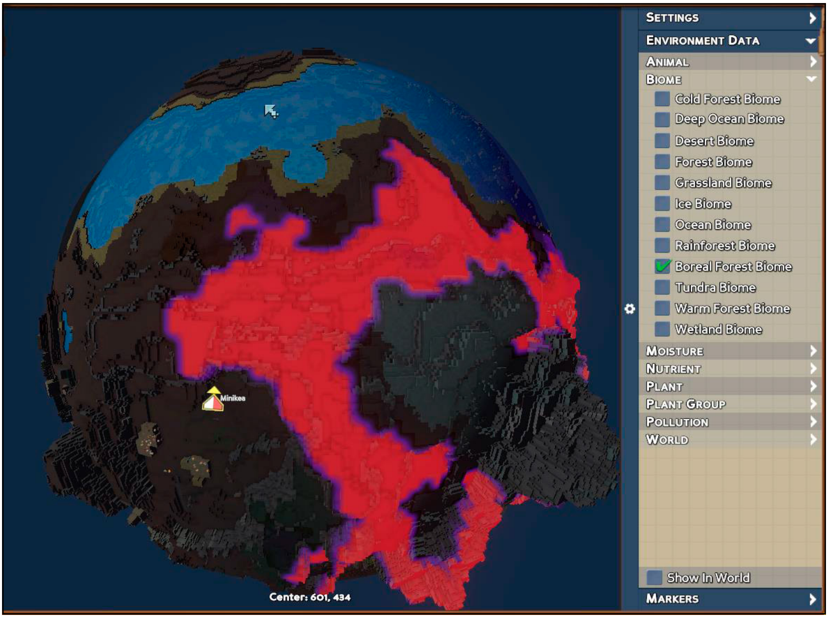

Figure 2: *Eco*, Strange Loop Games, 2022. Source: Image courtesy of Strange Loop Games.

The game features multispectral overlay visualisations that display various ecological data layers, such as soil quality, pollution dispersion, and wildlife population densities. Through accessing these interfaces, maps, and data displays players assess the health of their ecosystem at a glance, much like how scientists use satellite imagery to monitor Earth's environments. The in-game data can be harnessed as evidence or documentation to provide grounds for proposing laws and systems of governance to your fellow peers in the bid to try and maintain a balance of ecosystem and economy based on data. Occupying dual roles players actively understand they are the source of the challenges presented within the game and the architects for potential solutions.

The access to multispectral overlay visualisations and data simulation within virtual worlds like *Eco* exhibits a notable similarity to the complex planetary system that integrates and processes satellite imagery. Satellite imagery has been instrumental in furthering our understanding of Earth's climate and the ongoing changes it undergoes. Scholars Paul N. Edwards and Benjamin Bratton, in their major works *A Vast System* (2010) and *The Stack* (2016) respectively, have explored how our understanding of climate change is inextricably linked to the vast array of instruments, computers, data collection practices, and scientific collaborations that form the foundational backbone of our knowledge about the Earth's climate system. Advanced satellite systems like Landsat and the Sentinel play crucial roles in environmental monitoring, carrying out essential tasks such as land cover classification, phenology tracking, hydrological assessment, and climate impact analysis. By design, *Eco* incentivises players to take on the responsibility of also critically analyzing the relevance of this simulated environmental data. Such data also translates decisions concerning the natural resource use, conservation, and development within these virtual worlds that also bear the costs of resource depletion. Ultimately, players assume equally a critical role not only as surveyors of this planet but importantly their ecological stewards.

Wrestling with energy allocation and resource management in these virtual ecoworlds requires us to draw attention to the underlying physical infrastructure that powers them. Including not only the personal devices and screens we engage with but also the required data centers, cloud computing servers, hardware, and network connections that alert us to the energy-intensive realities at the bedrock of our physical planetary infrastructure. Namely, environmental realities encompass the extraction of rare-earth minerals and the vast amount of energy consumed to maintain our cloud infrastructure. It comes to inflect what Alenda Chang emphasises, "the edge effects" that blur a distinction between the virtual and real, or what is defined as the boundary between two different habitats or ecosystems. Edge effects in relation to digital gaming, can be understood as the real-world environmental impacts that arise from the infrastructure and resources required to support these digital games and environments.

As Chang incisively questions, "How virtual is the virtual when the ubiquity of digital technology is premised on globe-spanning resource extraction and waste?"[30] This bridges a conception of our media as profoundly elemental echoing Marshall McLuhan's perceptive remark at the dawn of the information age: "New media are not bridges between man and nature,

[30] Alenda Y. Chang, *Playing Nature: Ecology in Video Games* (Minneapolis: University of Minnesota Press, 2019).

they are nature."[31] To put it bluntly, there is no abstraction or procedural generation of virtual worlds that can exist in isolation from the material-intensive extractive processes of minerals and metals that form the very basis of our global infrastructure, interfaces, and screens. The environmental footprint of video gaming becomes increasingly pronounced whether from data-intensive online gaming to GPU-powered virtual worlds.[32] We are deeply enmeshed in larger environmental or rather planetary narratives and contribute to digital footprints that connect us to expansive biogeochemical cycles and geological timescales that dwarf our everyday perceptions.

4. Imaginaries of Future Earth(s): Earth to Be Rescued?

The suitability of digital games and their environments as tools for researchers, policymakers, and other stakeholders remains an evolving topic of discussion. However, their potential as risk-free ventures or low-risk alternatives offers distinct advantages in certain scenarios. Writing about the nature of laboratories and digital games through his study of the game *Dwarf Fortress*, Robbie Fordyce posits how gameworlds can act "as an unwitting laboratory for political and economic experimentation."[33] By conjuring speculative scenarios and immersing players within them, gameworlds provide a space for testing ideas and technologies without the inherent risks and costs associated with real-world experimentation.

We can steer our focus to the usage and experimentation of untested technologies that are featured in digital games such as *Fate of the World* and *Half-Earth: Socialism*. One technology that has gained traction and notoriety particularly at a wide-scale level is geoengineering. Defined as the "intentional modification of the Earth's climate and it has been proposed in order to mitigate the climate response to elevated greenhouse gas (GHG) emissions."[34] Technologies linked to geoengineering have been widely debated and polarizing on several grounds, with concerns underscoring the possible unintended effects of large-scale manipulation and modification of

[31] Eric McLuhan and Frank Zingrone, eds., *Essential McLuhan* (New York: Routledge, 1997), 272.
[32] Charlie Fletcher, "Game Changers: Achieving Sustainability in the Video Game Industry," *Earth.Org*, January 9, 2024.
[33] Robbie Fordyce, "Dwarf Fortress: Laboratory and Homestead," *Games and Culture* 13, no. 1 (2015): 2.
[34] Kieran Ohara, "Climate Engineering," in *Climate Change in the Anthropocene*, ed. Kieran Ohara (Amsterdam: Elsevier, 2022), 167–86.

the Earth's climate to decelerate or even reverse global warming. The term is primarily used to refer to technologies like solar radiation management and carbon dioxide removal, which have not been tested on a large scale. There exists a crucial differentiation between the concepts of carbon geoengineering and solar geoengineering.[35] The former aims to mitigate climate change by eliminating carbon dioxide from the atmosphere, thus addressing the underlying causes of this phenomenon – the buildup of carbon dioxide in the atmosphere. Conversely, solar geoengineering involves efforts to either redirect sunlight back into space or enhance the quantity of solar radiation that is sent back into space, with the aim of cooling the Earth.

A myriad of games have cropped up that engage players in tackling climate change having them evaluate the choices or imperatives of resorting to geoengineering or terraforming. Conventionally, geoengineering technologies are associated with solar radiation management or natural as well as ecosystem-based approaches, given that geoengineering can include natural processes linked to reforestation and wetlands restoration. *Terra Nil* (2023) (see Fig. 3) is a recent game that embodies the potential of games to engage players in the complex process of ecosystem reconstruction and rewilding, with players transforming a range of desolate wastelands into flourishing ecosystems. *Terra Nil* challenges players to breathe life into barren terrains, as they guide them through the intricate process of ecosystem restoration in 16 distinct biomes. Restoring the respective ecosystems of each biome entails the strategic placement of diverse structures, including biodomes, algae greenhouses, purifiers, and salinators, with the objectives of producing electricity, remediating polluted soil or water, and reestablishing vegetation. As players work to regenerate these landscapes, they must carefully consider the placement of each building engineered to clean up its toxic effects.

35 Ibid.

Figure 3: *Terra Nil*, Free Lives, 2023. Source: Image courtesy of Devolver Digital.

Interestingly, *Terra Nil* omits any presence of humans and any assumption that these habitats will be restored for human habitation or utility. The design choice subtly introduces a non-anthropocentric perspective by focusing solely on ecosystem restoration without human infrastructure as the end goal. Perhaps this design choice aligns with emerging real-world practices in ecological restoration, where robotics and automated systems are now increasingly deployed in a range of environments from deep ocean depths to forest canopies. The game's vision of environmental recovery mirrors current robotic applications, eliminating predators of coral reefs to drones seeding forests, suggesting a future where ecological rehabilitation may be largely guided by non-human automated agents. As climate breakdown overlaps with the rise of AI and robotics, *Terra Nil* might be played as presaging an already present future where select terrains transform into living laboratories that could involve the expanded role of automated technologies maintaining lifeforms and ecosystems.[36] Despite *Terra Nil* offering us a thought experiment in ecosystem restoration, it may not fully explore the complex web of effects that shape our real-world landscapes and importantly their histories. In reality, the landscapes we inhabit are the byproducts of

[36] Andrew Lockhart, Simon Marvin, and Aidan While, "Towards New Ecologies of Automation: Robotics and the Re-Engineering of Nature," *Geoforum* 145 (2023): 103825.

human activities such as agriculture, urbanisation, and industrial development that are critically inseparable from social and economic concerns.

Titles that weave together a focus upon the social, economic, and historical dimensions that shape or transform landscapes and planets can be identified such as *Imagine Earth* (2021). Set in the year 2048, wherein the Earth has been decimated by large corporations, the premise of the game centers on colonists who are forced to depart from Earth and are entrusted with the responsibility of devising a sustainable form of colonisation on another planet in their capacity as colony administrators. Here the salient focus upon preserving resources, building infrastructure, and the effective management of the colony's population, all while mitigating its environmental footprint becomes a fascinating experiment.

Players are inevitably locked into tradeoffs if they desire to become active in generating revenue for their colonies through a dynamic trade system that allows them to engage in interplanetary commerce with other colonies and factions, exporting surplus resources or goods. And yet, the harsh frictions of resource depletion, environmental degradation, and social inequality become starkly apparent when making economic decisions, especially in the pursuit of resource extraction. When embarking on these pursuits the visible impacts of atmospheric emissions and ground pollution that inevitably affect your colonies become more urgent. Increasing temperatures can lead to the melting of polar caps, with colonies struggling to remain afloat due to rising sea levels. The construction of oil power plants, while generating immense power, can also result in oil slicks that damage local waters and reduce fishing yields if left unmaintained.

Decisions hold significant consequences, as the choices players make bear profound implications not only for the virtual worlds they inhabit but also for the real-world environments they seek to understand and influence. An underlying tension emerges in our quest to save ourselves and find a new home and colony in outer space, whereby we inevitably fall back into what appears to be a vicious loop of extraction-and-bust practices. *Imagine Earth* shoehorns in through the course of playing, critical questions and reflections upon whether we can we ever break free from the cycle and underlying logic of exploration that necessarily entails extraction or colonisation? Are we as a species destined to contribute to the downfall of any planet we inhabit, perpetually moving from one world to the next in an endless cycle of depletion and abandonment? Perhaps we need to also sketch other imaginaries that strive to transform our conception of planet Earth, linking alternative pathways for conceiving and test-bedding novel social, political, and ecological arrangements. Radical proposals could be the "Half-Earth" concept.

4.1 Half-Earth: Reimagining Zones of Habitation & What Can We Speculate?

Returning our focus to Earth, E. O. Wilson's bold "Half-Earth" concept epitomises an imaginative vision that pushes the boundaries of plausibility in envisioning our planet's transformation and restoration. Wilson's concept, presented in *Half-Earth: Our Planet's Fight for Life,* argues for creating a network of protected areas, such as national parks, wildlife reserves, and marine protected areas, that would cover roughly half of the Earth's surface.[37] The Half-Earth thought experiment has nonetheless been subject to criticisms concerning the lack of feasibility in convincing governments, landowners, and communities to allocate such a significant portion of land for conservation purposes. Criticism has also been leveled with respect to the potential negative consequences that can ensue, such as the potentially massive displacement of Indigenous and local communities and the lack of attention to environmental justice.[38] Some have also written that it is critical to consider if or whether alternative approaches can be adopted to address biodiversity loss while integrating human needs and activities.[39] Others have put forth criticism that Wilson's vision reinforces the belief that humans can be segregated from nature, these alternative approaches emphasise the need for intensive and active management involving humans as an integral part of ecosystems.[40]

[37] Edward Osborne Wilson, *Half-Earth: Our Planet's Fight for Life* (New York: Liveright Publishing Corporation, 2016).
[38] Bram Büscher et al., "Half-Earth or Whole Earth? Radical Ideas for Conservation, and Their Implications," *Oryx* 51, no. 3 (2017): 407–10.
[39] Erle C. Ellis and Zia Mehrabi, "Half Earth: Promises, Pitfalls, and Prospects of Dedicating Half of Earth's Land to Conservation," *Current Opinion in Environmental Sustainability* 38 (2019): 22–30.
[40] Helen Kopnina, "Half the Earth for People (or More)? Addressing Ethical Questions in Conservation," *Biological Conservation* 203 (2016): 176–85.

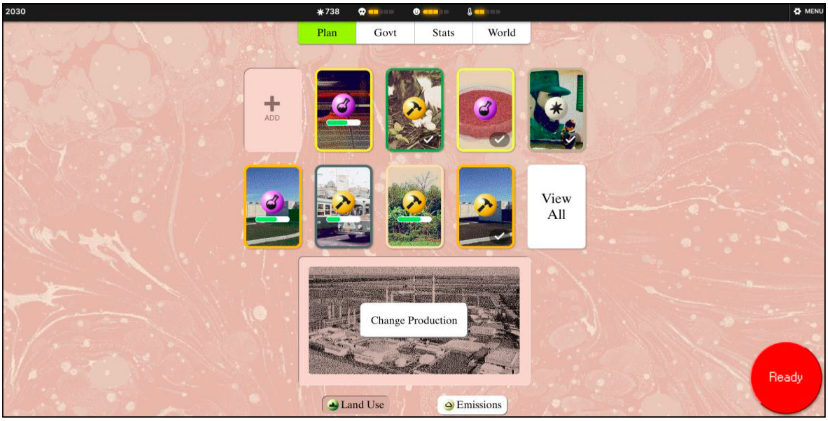

Figure 4: *Half-Earth: Socialism*, Trust, 2020. Source: Image courtesy of Trust.

The game *Half-Earth: Socialism* (2022) (see Fig. 4), created by developers and designers Francis Tseng and Son La Pham in collaboration with Berlin-based Trust, imports E. O. Wilson's idea and translates it into an online, browser-friendly experience, while also drawing inspiration from the eponymous book by Drew Pendergrass and Troy Vettese. As the authors describe, *Half-Earth Socialism* derives influence from what the Viennese philosopher and social scientist, Otto Neurath would have characterised as a "scientific utopia." The practice of scientific utopianism spurs the development of counterfactual scenarios that are not intended to faithfully represent or perpetuate existing aspects of society but rather to gestate alternative social systems that would demo the feasibility of alternative futures or specific policies. A principal ingredient of this practice nurtures the exploration and discovery of new potential premises, arguments, and descriptions of counterfactual scenarios.[41] In *Half-Earth: Socialism* players are transported to an alternative timeline starting from the year 2022, where regional powers have come together under the governance of a global planning authority known as Gosplant. As planners, players are to adhere to the principal objectives of limiting global warming below 1°C, ultimately pushing towards negative emissions, reducing extinction rates to under 20%, and achieving net zero

[41] Alexander Linsbichler and Ivan Ferreira da Cunha, "Otto Neurath's Scientific Utopianism Revisited – A Refined Model for Utopias in Thought Experiments," *Journal for General Philosophy of Science* 54, no. 2 (2023): 233–58.

emissions. During our gameplay as a planetary manager, we must navigate a complex web of coalitions, whereby we are lobbied by competing ideological factions that represent the global population.

As gameplay progresses we must skillfully maneuver through the challenges of pandemics, making strategic decisions that may include: endorsing population-control measures, implementing consumption limits, protecting and restoring ecosystems, expanding marine protected areas, imposing restrictions on air travel, exploring geoengineering techniques like marine cloud brightening, or transitioning to veganism. Nevertheless, choices reverberate across the globe, potentially leading to complex challenges that unravel through creeping global food shortages, fuel scarcity, electricity blackouts, or even widespread nutritional deficiencies. As these issues compound, they feed into global discontent and unrest that jeopardises your given objective and leads to your eventual toppling.

To strike a balance between depth and accessibility, the developers of *Half-Earth: Socialism* made the game accessible by allowing players to engage through a web-based browser. Upon launching the game, users are greeted by an interface presented in a dialogue box, known as the Gosplan planning application. The interface provides annual reports that track the user's progress based on the decisions they have made throughout the game. Players are guided and accompanied by a deck of cards that describe the time range and potential effects that span research technologies, infrastructure projects, and policies. Selecting any of these choices can take multiple years to decades to have their full impact observed as players are operating under shrinking time horizons to meet their policy milestones. A notable component that the designers were particularly curious to incorporate into the game was the previously mentioned Hector climate model. The model not only serves to calculate and project climate effects but also simulates the cascading impacts on crucial systems such as food production and biodiversity, among other environmental factors.[42]

Notwithstanding reservations that digital games may be too speculative and can slide into forms of escapism, the interactive exploration of potential futures through climate models in these games enables us to participate in constructing imaginative narratives that we have associated with nourishing an abductive approach in gameplay. Incorporating an interest in "specula-

[42] Francis Tseng and Son La Pham, "Half-Earth Socialism: A Plan to Save the Future from Extinction, Climate Change and Pandemics," *Half-Earth Socialism*, accessed October 18, 2024.

tive fiction" can be useful here, whereby what we mean by "speculative" is not entirely divorced from possibility, but rather empowered by statistical analysis, research, and traditional knowledge that is used to bend our imagination.[43] Moreover, speculative fiction counters what Laura op de Beke writes[44] concerning the tendency of such games mentioned above, like *Fate of The World* to premediate or pre-envision possible futures that may emerge.

Op de Beke keys into how gameworlds can reinforce outcomes or expectations that condition and shrink our imaginative apertures, effectively eliminating other worlds or imaginaries that may arise. Instead, op de Beke advocates for maintaining a critical eye on how in-game technologies are deployed, policies are adopted, and scientific and political possibilities are framed or procedurally mechanised that also arrest us to certain outcomes or decision trajectories. Digital games can further tether us to what appear to be the inevitabilities of a planet marked by a militarised techno-scientific paradigm, rapacious economic forces, displacement of populations, massive species and biodiversity loss. This also extends further to the mediation or more specifically the scales or optics we take in immersing ourselves in virtual worlds reflecting problems of our own. A dominant isometric god-eye view of reducing planets to clickable representations that can be easily managed and manipulated overlooks the intricate and often messy realities of localised or embodied perspectives. Specifically, we neglect the on-ground realities and relationships between Indigenous inhabitants, lifeforms, knowledge systems, and their ecosystems.[45]

Recognizing that a more pronounced socio-political dimension may not serve as a fulcrum in a few of the titles addressed in this paper, this should not detract from the way narratives can be composed out of the ingredients of alternative visions, actions, and interfaces that can assist in incubating or dissolving worlds. Virtual worlds and environments serve as powerful conceptual blueprints, offering unique perspectives that also draw on playing through complex systems composed of a complex web of causes, forces, and histories that shape our real-world habitats. If the digital games inves-

[43] Liam Young, "Planet City," accessed October 18, 2024, https://liamyoung.org/projects/planet-city; David Rousell, Amy Cutter-Mackenzie, and Jasmyne Foster, "Children of an Earth to Come: Speculative Fiction, Geophilosophy and Climate Change Education Research," *Educational Studies* 53, no. 6 (2017): 654–69.
[44] Laura op de Beke, "Procedural Futurism in Climate Change Videogames," *Alluvium: 21st-Century Writing, 21st-Century Approaches* 9, no. 3 (2021): 1–10.
[45] Souvik Mukherjee, *Videogames and Postcolonialism: Empire Plays Back* (Cham: Springer, 2017).

tigated here indeed compel us to question or problem-solve in a meaningful manner, then pursuing inquiries into the conditions for the emergence and sustenance of life forms serves as a foundation. This foundation enables us to create spaces for expanding and experimenting with horizons that include non-human entities, allowing us to explore our capacity for different compositions and relations among our common planetary ground.

5. Conclusion

As digital games and virtual worlds exert a widening influence on our imagination, we have aspired to investigate their roles as potential mesocosms or controlled environments for testing future scenarios. Digital spaces or worlds also serve as windows that expand our perspective to a planetary scale, where our interactions within these simulated environments also have real-world effects in averting the destruction of habitats. At a fundamental level, we have observed the numerous ways in which digital games mediate and eco-visualise our entanglements, calling us to attend to the manner in which we interface with and abstract both the infrastructural and natural ecosystems that constitute our planet. By examining digital games through this lens, we have aimed to investigate their potential to contribute to a deeper understanding and literacy concerning the complex relationships between planetary infrastructure, technology, and the environment.

A crucial development as we have analysed has hinged upon the continuing and increasing accessibility of various devices, measuring instruments and sensors, game engines, web browser-hosted games, and virtual worlds that span the globe. This accessibility has facilitated and enriched lanes for the fusion of scientific and gameworld collaboration, in now expanding user involvement from phone devices to sensors. One possible pathway we can see blossoming could be centered upon the intersection of climate-based research, modeling, and citizen science that can be reimagined in light of the proliferating affordances of immersive virtual environments (IVEs): Virtual Reality, Augmented Reality, and Mixed Reality technologies.[46] Recent advancements in real-time simulations of dynamical chemistry have been among examples that have been integrated into citizen science through the use of virtual reality (VR). Participants wear VR headsets to immerse them-

[46] Anna C. Queiroz et al., "Immersive Virtual Environments and Climate Change Engagement," in *Proceedings of the 2018 International Scientific Conference on Virtual Learning* (Graz: Verlag der Technischen Universität Graz, 2018), 153–64.

selves in real-time molecular dynamics simulations. Using hand-held controllers, they can interact with the virtual environment, including the ability to "pull" atoms and perturb or direct the dynamics of the molecular system. Harnessing this approach contributes to crowd-sourced data gathering, as users actively shape and influence the behavior of the simulated molecular system.[47] The budding interest in virtual reality and its palpable adoption are observed in varying degrees with projects that have simulated the future effects of climate change on forests,[48] disaster preparation and management,[49] and tree species distribution.[50] These developments could equip us with the opportunity to experience and perceive changes in temperature and climate not just quantitatively. We could inhabit and encompass new ways of experiencing and interpreting the nuanced scales and time dependent changes in global environmental systems.

Moreover, with explosive advances in artificial intelligence, digital game environments are bound to transform even more dynamically, allowing us to "play real-time data" by porting real-time data into immersive environments gleaned from an array of datasets, climate models, and sensors diffused throughout the planet. Augmented immersive virtual environments would be continuously modulated to reflect the updated real-time fluctuations of regional or local temperatures, global emission levels, regional water levels, and crop yields. Real-world information could be replicated and perpetually updated in virtual game environments modeled after our own, which we have seen realised in the form of *Microsoft Flight Simulator* (2020) in collaboration with Meteoblue, a provider of daily weather data updates. In their bid to maximise the realism of flight conditions for virtual pilots, the game features a gargantuan digital twin that is considered the largest open-world to date. The simulator ferries in actual real world weather conditions from weather stations dispersed around the world to be rendered in the simulator having us contend with visibility issues and navigational challenges.

[47] Robin J. Shannon et al., "Exploring Human-Guided Strategies for Reaction Network Exploration: Interactive Molecular Dynamics in Virtual Reality as a Tool for Citizen Scientists," *Journal of Chemical Physics* 155, no. 15 (2021): 154106.
[48] Jiawei Huang et al. "Walking through the Forests of the Future: Using Data-Driven Virtual Reality to Visualize Forests under Climate Change," *International Journal of Geographical Information Science* 35, no. 6 (2020): 1155–78.
[49] CORDIS, "Extended Reality for DisasteR Management And Media plAnning: xR4DRAMA," *European Commission*, last modified December 27, 2023.
[50] Hanqing Qiu et al., "Forest Digital Twin: A New Tool for Forest Management Practices Based on Spatio-Temporal Data, 3D Simulation Engine, and Intelligent Interactive Environment," *Computers and Electronics in Agriculture* 215 (2023): 108416.

Despite connecting us to real-time data in novel ways, we cannot escape the sobering realities of climate change, resource depletion, and biodiversity loss that our planet faces. The intensive energy requirements and mineral extraction that play a major part of the story, as well as key elements in the supply chain for creating immersive virtual environments, often remain hidden from view on our screens. Yet, they form an essential substrate upon which our planetary digital infrastructure depends. As we embrace digital game worlds that are increasingly transformed into networked laboratories or rather planetary networks, we must also acknowledge the thermodynamic realities underpinning them. It is hoped that this recognition nonetheless opens and strengthens existing avenues for collaboration among scientific research networks, planetary citizens, and non-human entities contributing from multiple scales in shaping future worlds.

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