LEVERAGING DIGITAL TWINS FOR ECOSYSTEM RESTORATION AND BIODIVERSITY CONSERVATION IN THE GREEN ECONOMY FRAMEWORK

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Abstract: Digital twin (DT) technology is emerging as a pivotal tool for addressing critical environmental challenges, especially in the fields of ecosystem restoration and biodiversity conservation, within the broader framework of the green economy. Digital twins - sophisticated, data-driven virtual replicas of physical systems - offer a transformative approach by enabling real-time monitoring, predictive modelling, and scenario-based planning. These capabilities allow for a nuanced understanding of complex ecological processes and the impacts of human activities on natural systems. The integration of DTs into ecological management introduces advanced tools for enhancing decision-making processes, improving predictive accuracy, and supporting sustainable practices that align with green economy objectives, such as carbon reduction, biodiversity protection, and efficient natural resource use.

This paper employs qualitative methodologies to explore how DT technology can model species-specific behaviors and environmental conditions. This thesis focuses on integrating digital twin technology into environmental management practices, specifically for ecosystem restoration and biodiversity conservation. It explores how digital twins can model ecological changes, simulate the impact of various conservation strategies, and improve decision-making processes. Eventually, the paper examines how digital twin technology can be leveraged to support ecosystem restoration and biodiversity conservation while advancing a green economy. It also aims to demonstrate how this technology can help mitigate environmental costs associated with economic growth, in line with the principles of the Environmental Kuznets Curve (EKC), by enabling more informed and effective conservation strategies.

Keywords: Digital Twins, Ecosystem Restoration, Biodiversity Conservation, Green Economy, Sustainability.

JEL: Z18, D69, F69, **Q56, O44, C63**

Introduction

The global urgency to address environmental degradation, biodiversity loss, and ecosystem fragmentation has intensified, urging the adoption of innovative conservation strategies. The green economy framework, which emphasizes aligning economic growth with environmental sustainability and social well-being, has emerged as a key solution. In this context, digital twin technology - virtual replicas of physical ecosystems - presents transformative potential for ecosystem restoration and biodiversity conservation. By integrating real-time data, digital twins allow stakeholders to simulate, monitor, and analyze ecological scenarios, offering data-driven insights that are both environmentally and economically beneficial. The application of digital twin technology within the framework of the Environmental Kuznets Curve (EKC) offers significant potential, presenting a unique opportunity to predict and mitigate the environmental degradation typically associated with economic development.

Digital twin technology, when applied to ecosystems, may create intricate models of forests, wetlands, coral reefs, and other habitats by integrating real-time data from satellite pictures, sensors, and climate models to replicate both immediate and prolonged environmental changes. This skill allows scientists, conservationists, and policymakers to assess delicate ecological interconnections, examine diverse restoration scenarios, and make educated decisions for sustainable ecosystem management. Digital twins can model the effects of reforestation on biodiversity and carbon sequestration, enabling policymakers to choose effective conservation initiatives. They can also forecast ecosystem resilience to climate-induced stresses, helping in the identification of conservation zones with the most adaptive capabilities.

The ability of digital twins to represent ecosystem services closely aligns with the principles of a sustainable economy, highlighting the importance of ecosystem services - like water purification, carbon sequestration, and soil fertility - in supporting climate resilience and economic stability. Through the quantification of these services, digital twins facilitate the valuation of natural capital, which is a core principle of the green economy, enabling the assessment and management of the economic advantages associated with biodiversity and natural ecosystems.

Digital twins facilitate enhanced ecosystem management by providing stakeholders the opportunity to test and refine conservation strategies prior to their real-world implementation. The ability to predict outcomes is essential as it reduces the risks and expenses associated with interventions, bolsters evidence-based policy-making, and enhances the transparency of restoration initiatives. Furthermore, integrating machine learning and predictive modelling allows digital twins to consistently learn from ecosystem data, enhancing their accuracy over time and addressing new conservation challenges.

The incorporation of digital twins into the green economy framework exemplifies a significant collaboration between technological advancements and ecological principles. Digital twins offer a scalable and dynamic solution for monitoring and restoring ecosystems, playing a crucial role in global initiatives aimed at stopping biodiversity loss, improving ecosystem resilience, and encouraging a sustainable, regenerative future.

The **object** of this study is the integration of digital twin technology into environmental management practices, specifically in the restoration of ecosystems and the conservation of biodiversity. It explores the potential of digital twins to model ecological changes, simulate the impact of various conservation strategies, and enhance decision-making processes.

The **subject** of this paper is to explore how digital twin technology can be leveraged to support ecosystem restoration and biodiversity conservation while promoting a green economy. It aims to demonstrate how this technology can help mitigate environmental costs associated with economic growth, in line with the principles of the EKC, by enabling more informed and effective conservation strategies.

The article **aims** to employ a **qualitative methodology** to examine the application of digital twin technology within the domains of ecosystem restoration and biodiversity conservation, particularly in the context of the green economy framework. Through the exploration of case studies and the analysis of emerging trends, the research highlights the role of advanced simulations and Data-driven solutions in enhancing the utility of digital twins in environmental management. The findings emphasize the necessity of interdisciplinary collaboration, robust data infrastructure, and ongoing technological innovation to fully exploit the potential of digital twins for sustainable ecosystem management. Ultimately, this study contributes to the expanding body of literature on digital twins in environmental science, illustrating their transformative potential for revolutionizing conservation practices within the green economy framework.

To achieve this purpose, the paper will address the following **tasks**:

1. To analyze how digital twin technology can be utilized to simulate ecological changes and predict the effects of various conservation strategies, with a focus on its integration within the framework of the Environmental Kuznets Curve (EKC).

2. To examine the role of digital twins in supporting data-driven decision-making in ecosystem management and biodiversity conservation.

3. To explore simulation modeling of digital twins, including methods for biodiversity modeling.

4. To assess the potential of digital twins in addressing the challenges of environmental degradation and biodiversity loss, particularly in the context of sustainable development within the green economy framework.

5. To explore practical applications and case studies of digital twins in diverse environmental contexts, such as coastal ecosystems and urban areas, highlighting their impact on ecosystem restoration and conservation efforts.

The **thesis** of this paper argues that digital twin technology offers an innovative solution for balancing economic development with environmental sustainability. By providing accurate, real-time simulations of ecosystems, digital twins facilitate the modeling of complex environmental processes, enhance conservation strategies, and support data-driven decisions that align with the goals of the green economy. Despite challenges such as data quality, computational costs, and the need for interdisciplinary collaboration, ongoing technological advancements promise to overcome these barriers, making digital twins a crucial tool for sustainable development and ecosystem preservation.

1. Digital Twin Technology

Michael Grieves[1], formerly a faculty member at the University of Michigan, was recognized for first using the concept of digital twins in manufacturing in 2002 and for publicly introducing the digital twin software concept. In 2010, John Vickers[2] Coined the phrase „Digital Twin".

Figure 1. can illustrate the concept of Digital Twins.

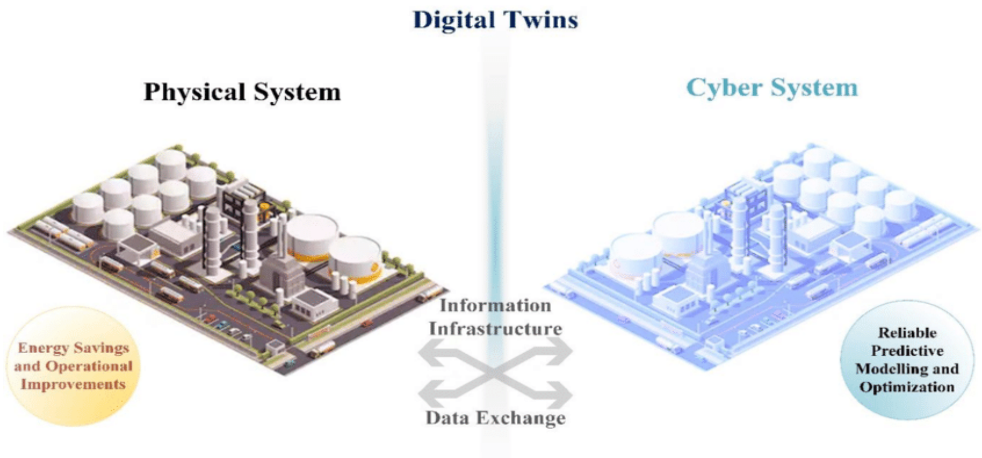

Figure 1. Illustration of a digital twin

Source: Teng, 2021

According to IBM **(IBM, 2021)**, a digital twin is a virtual model that mirrors a physical object or system with high fidelity. It encompasses the entire lifecycle of the object, continuously updated through real-time data integration, and employs simulation, machine learning, and analytical reasoning to support decision-making processes.

According to Amazon Web Services (AWS) **(Amazon, 2024)**, A digital twin is an advanced virtual model that accurately represents a physical object across its entire lifecycle, continuously updated with real-time data from integrated sensors to simulate performance and monitor operational status. This technology can replicate a broad range of real-world assets, from individual equipment in manufacturing to complex systems such as wind turbines and urban infrastructures. By leveraging digital twins, organizations can effectively oversee asset performance, proactively identify potential issues, and make data-driven decisions to enhance maintenance strategies and lifecycle management.

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[1] Michael Grieves is an internationally renowned expert in Product Lifecycle Management (PLM) and originated the concept of the Digital Twin

[2] Mr. Vickers serves as the principal technologist for advanced manufacturing in the Space Technology Mission Directorate at NASA Headquarters and as the senior leader for advanced manufacturing at the NASA Marshall Space Flight Center.

The concept of digital twins has evolved significantly over the years, with key contributions from Michael Grieves and John Vickers **(George, 2023)**.

Early Development: The idea of digital twins began to take shape in the early 2000s. Michael Grieves, while working at the University of Michigan, introduced the concept during a presentation on Product Lifecycle Management (PLM) in 2002 (Carlos, 2019). He envisioned a virtual representation of physical objects and processes, which could be used for simulation, monitoring, and maintenance.

NASA's Involvement: John Vickers, a principal technologist at NASA, collaborated with Grieves on projects that required advanced simulation and modeling techniques (George, 2023). Their work at NASA involved creating virtual models of spacecraft to predict and solve potential issues, such as those encountered during the Apollo 13 mission (Carlos, 2019).

Formalization of the Concept: The term „digital twin" was formally introduced by Grieves and Vickers to describe the integration of physical and virtual systems. This concept was further elaborated in Grieves's book (Grieves, 2011).

Widespread Adoption: Since its formal introduction, the digital twin concept has gained widespread adoption across various industries, including manufacturing, healthcare, and supply chain management. The ability to create virtual replicas of physical assets has revolutionized how companies design, test, and maintain their products and processes (George, 2023)

A digital twin is an advanced, data-rich virtual model that accurately reflects real-world assets, systems, or processes through synchronized interactions at specified frequencies and precision levels. Developed to achieve defined objectives, digital twins are oriented toward specific use cases and supported by comprehensive data integration. Their foundation is built on reliable data, principles of physics, and domain-specific expertise, and it operates within robust frameworks of IT (Information Technology), OT (Operational Technology), and ET (Engineering Technology) systems. Digital twin systems are transforming business operations by enabling rapid, automated insights, supporting continuous optimization, and facilitating data-informed decision-making. Through the integration and synchronization of IT, OT, and ET infrastructures, these systems use both real-time and historical data to create accurate representations of past and current states while enabling projections of potential future scenarios.

Digital twin prototypes employ data to construct predictive models, allowing simulations of anticipated future conditions before full integration into IT, OT, and ET systems. This iterative modeling approach ensures precise alignment with the actual physical entities and processes they represent, enhancing predictive capabilities and strategic management across a wide range of industries.

2. Leveraging Digital Twins in the Context of the Environmental Kuznets Curve (EKC)

The Environmental Kuznets Curve (EKC) suggests an inverted U-shaped relationship between environmental degradation and economic development, as illustrated in Figure 2. The Environmental Kuznets Curve posits that as economies develop, environmental degradation initially intensifies, peaks, and then subsequently diminishes as nations attain elevated income levels and invest in sustainable practices. Utilizing the EKC idea in conjunction with digital twins for ecosystem restoration and biodiversity conservation can provide significant insights into the potential impact of technology on this trajectory within a green economy framework.

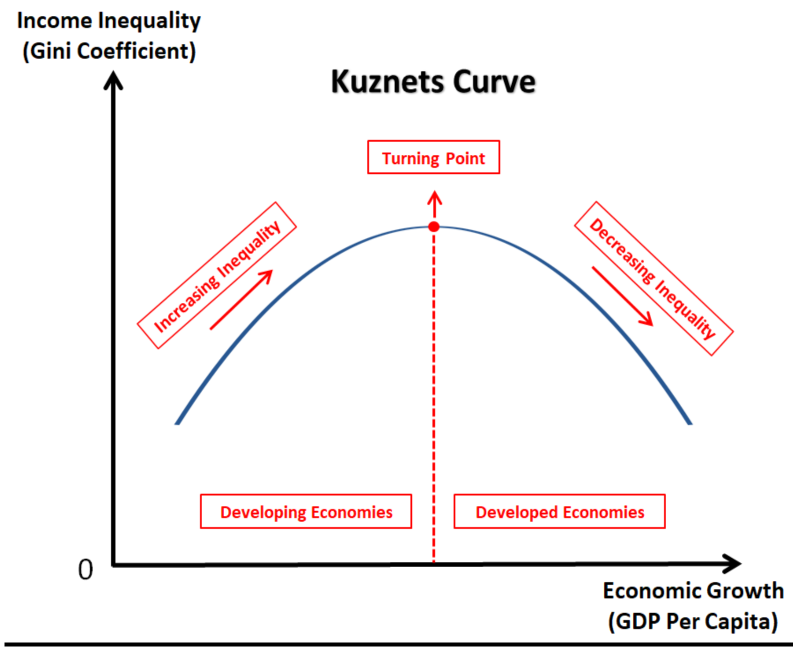

Figure 2. The Environmental Kuznets Curve (EKC)

Source: Ansari, 2023

Digital twins - virtual representations of physical entities and ecosystems - facilitate real-time monitoring, modelling, and decision-making. DTs have demonstrated significant potential in ecosystem restoration and biodiversity conservation by delivering precise data, predictive modelling, and scenario analysis that guide resource-efficient and environmentally friendly solutions. Digital twins may influence the Environmental Kuznets Curve (EKC) and the green economy framework, and can be explained as follows:

a. Early Development Stage: During the early phases of economic development, environmental degradation frequently escalates due to significant dependence on resource extraction and inadequate environmental safeguards. Digital twins may initially appear as a costly technology predominantly available to affluent nations. However, targeted investment in digital twins at this stage could help developing economies skip certain phases of environmental degradation by allowing them to make informed, data-driven decisions. This could result in a „flattening" of the EKC, minimizing the peak level of degradation before transitioning to more sustainable practices.

b. Industrial Growth Stage: During rapid industrialization, the traditional EKC suggests an increase in pollution and habitat loss. Here, digital twins can help monitor and manage resource use more effectively, leading to reduced waste and improved ecosystem management. For example, digital twins could simulate the impact of industrial activities on local biodiversity, allowing governments and industries to adjust before actual damage occurs. This could help reduce the severity of environmental degradation at this stage, potentially shifting the EKC curve downward.

c. Transition to Sustainability Stage: As an economy prospers, there is an increased capacity and inclination to invest in environmental conservation. Currently, digital twins can play a crucial role in ecosystem restoration initiatives, including reforestation, soil health rehabilitation, and Water Quality assessment. Digital twins enable more precise, efficient restoration methods by modeling the complex interactions within ecosystems and predicting the long-term effects of different conservation strategies. With better management tools, the shift to sustainable practices becomes more effective, further reducing the environmental impact at higher income levels and possibly steepening the downward slope of the EKC.

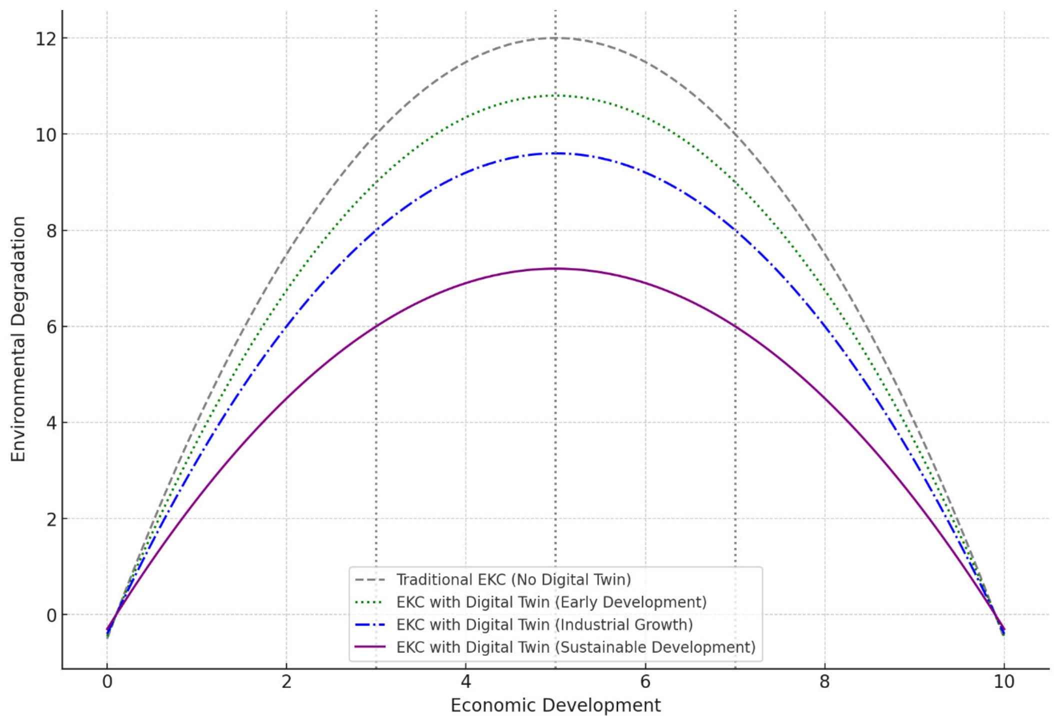

Figure 3. Environmental Kuznets Curve (EKC) and digital twin impact on ecosystem Restoration

Source: Author's illustration

Here is a graph illustrating in Figure 3, the Environmental Kuznets Curve (EKC) with the impact of digital twins across different stages of economic development:

- **Traditional EKC**: Depicted by the grey dashed line, it shows the typical rise and fall in environmental degradation as economies develop.
- **EKC with Digital Twin Integration**:

o **Early Development** (green dotted line): Digital twins have a slight impact, lowering environmental degradation.

o **Industrial Growth** (blue dash-dot line): There is a Moderate impact as digital twins help reduce resource use and pollution.

o **Sustainable Development** (purple solid line): Significant impact as digital twins enable advanced conservation and restoration efforts, resulting in reduced environmental degradation.

The above illustration shows how digital twins could potentially „flatten“ the EKC by lowering the peak of environmental degradation earlier in the development process.

The green economy framework emphasizes sustainability, biodiversity preservation, and climate resilience. The incorporation of digital twins into this framework possesses several benefits:

- **Accelerated Biodiversity Conservation:** Digital twins enhance biodiversity by providing comprehensive ecological simulations that forecast species interactions with one another and their surroundings. Digital twins foster a restoration of habitat and biodiversity evaluations, integrating economic growth with biodiversity objectives and preserving ecological equilibrium throughout economic development.
- **Resource Efficiency and Circular Economy:** Digital twins enhance resource efficiency in agriculture, forestry, and fisheries by providing real-time feedback and predictive insights, thereby minimizing waste and alleviating pressure on natural ecosystems. This supports the transition of economies towards a circular economy model, wherein resources are recycled and prevents ecosystems from over-extraction.
- **Carbon Reduction and Climate Goals:** In a green economy, carbon reduction is a primary objective. Digital twins can simulate carbon sequestration methods, optimize reforestation projects, and track carbon emissions across sectors, therefore adjusting economic growth with climate targets. This could reduce the environmental degradation related to the early stages of economic growth, potentially modifying the Environmental Kuznets Curve (EKC) shape by keeping emissions lower throughout the development stage.

3. Simulation Modelling of Digital Twins for Ecosystem Restoration and Biodiversity Conservation within the Green Economy Framework

An ecosystem's digital twin mirrors its physical traits and functions by utilizing real-time data and sophisticated modelling methods. Digital twins combine sensor data, satellite imagery, and environmental metrics like temperature, humidity, and soil conditions, along with wildlife tracking information. The virtual ecosystem reflects alterations in the physical ecosystem, providing valuable insights into species interactions, habitat modifications, and the effects of pollution.

- ***Components of Digital Twins for Ecosystems:***

o Data acquisition through sensors, IoT devices, and remote sensing (satellite and drone data).

o Modeling software such as GIS platforms and ecological simulation tools.

o Data processing and machine learning algorithms to process and predict changes in the ecosystem.

- ***Simulation Modeling Techniques for Ecosystem Restoration:***

Simulation modelling offers a valuable platform to evaluate various restoration strategies in a controlled environment, allowing for the assessment of potential outcomes ahead of actual implementation. Common approaches for simulation involve the following:

- Agent-based modeling (ABM) (Schmitz, Merijn, Buarque, & Sousa, 2023): ABM replicates the behaviors and interactions of distinct agents, including animal species, plants, or human participants, within an ecosystem. This serves as a valuable tool for analyzing challenging interactions, including predator-prey relationships or the movement of species in response to shifts in their environment.

- System Dynamics (SD) (BenDor, 2021). System dynamics modeling effectively illustrates the feedback loops and time delays present in ecosystems, including nutrient cycles, water flows, and population growth. This aids in illustrating the interactions among various components within an ecosystem as they change over time.

- Cellular Automata (CA) (Yang, et al., 2023)**:** CA models employ grid-based representations to effectively simulate the spatial and temporal dynamics within ecosystems. This method proves to be efficient in illustrating the dynamics of vegetation growth, the progression of fire, or changes in land use throughout various scales.

- Machine Learning and Predictive Modeling: Machine learning has the capability to identify patterns and forecast ecosystem reactions to specific restoration efforts by utilizing both historical and real-time data. Methods like deep learning and reinforcement learning are frequently employed to enhance restoration strategies.

- ***Biodiversity Conservation through Digital Twins:***

Digital twins have the capability to monitor biodiversity through the assessment of species distribution, habitat quality, and population health. Conservation initiatives for biodiversity gain significant insights from predictive models and simulations, which identify key areas for intervention and evaluate the risk factors endangering vulnerable species.

- ***Methods for Biodiversity Modelling***:

- Species Distribution Modeling (SDM) (Elith & Leathwick, 2009). SDM establishes the possible habitat of a species across various environmental scenarios, frequently employing machine learning models that are informed by geographic and climate data.

- Ecosystem Service Modeling **(Erik Jeremy Nelson, 2009)**. This involves determining the advantages that ecosystems offer, including carbon capture, water filtration, and pollination services. Digital twins imitate these services to guide policies and investments in the green economy.

- Climate Resilience Simulation (CReDo, 2024). Digital twins enable the simulation of climate change scenarios, enabling the assessment of impacts on biodiversity and the evaluation of resilience to extreme events, including droughts and wildfires.

4. The Application of Digital Twins within the Green Economy Framework

In the context of the green economy, digital twins play an essential part in enhancing sustainable resource management, developing climate adaptation strategies, and informing policymaking. Noteworthy applications include the following:

Resource Optimization: Simulation models can enhance the efficiency of water usage, land management, and energy resources, thereby supporting sustainability objectives.

Impact Assessment of Restoration Efforts: Through the process of the simulation of restoration activities, digital twins enable the estimation of both ecological and economic impacts resulting from interventions like reforestation, habitat restoration, or pollution control.

Carbon Sequestration Simulation: Digital twins may simulate carbon capture in forests, wetlands, or marine ecosystems, aiding in the achievement of greenhouse gas reduction objectives within a sustainable economic framework.

Recent developments in artificial intelligence, remote sensing technologies, and the Internet of Things will enhance the capabilities of digital twins, facilitating the creation of more precise and adaptable models of complex ecosystems.

Additionally, developments in distributed computing and cloud-based platforms will enhance the accessibility of high-performance simulation modelling for ecosystem restoration and biodiversity conservation.

5. Case Studies

a. Destination Earth Initiative (EU)

Destination Earth (DestinE) is a significant initiative supported by the European Commission (EU, 2024), focused on creating a highly accurate digital twin of our planet. This project synthesizes information regarding climate, land use, and biodiversity to enhance forecasts related to environmental and ecological transformations, such as extreme weather occurrences, habitat deterioration, and the decline of biodiversity.

- **Implementation**. Implementing DestinE, conservationists can model different ecosystem interventions and evaluate their possible effects on biodiversity and the stability of ecosystems. This platform has the potential to enhance ecosystem restoration initiatives, enabling policymakers to assess and refine conservation strategies while reducing ecological trade-offs.
- **Significance**. As one of the largest digital twin projects globally, DestinE acts as a foundational model for utilizing interconnected digital twin infrastructures to strengthen the green economy, especially in shaping sustainable policies and pinpointing areas that need focused conservation initiatives. Project ARISE (Netherlands) (Arise, Arise-biodiversity, 2024)

The ARISE project, located in the Netherlands (Arise, 2024), aims to establish an infrastructure that can identify and monitor all multicellular species present in the country. This approach utilizes sensors, DNA barcoding, and machine learning to streamline the process of species identification.

This digital twin model offers an extensive framework for monitoring the health of species, biodiversity, and ecological stability throughout time. Conservationists might leverage ARISE's data to evaluate the progress of ecosystem recovery, pinpoint emerging threats, or monitor invasive species as they arise.

The establishment of a comprehensive biodiversity data network by ARISE illustrates the potential of national-level digital twin initiatives to strengthen ecosystem resilience and improve conservation decision-making. The scalable model has the potential to motivate other nations to develop their own digital twins focused on biodiversity.

b. Urban Coastal Ecosystem Digital Twin for Singapore

A digital twin of Singapore's coastal ecosystem (Jianxin Yang, 2023) would integrate data from marine sensors, weather models, and tidal records to effectively manage and restore coastal biodiversity while addressing the challenges posed by urban development.

- **Implementation.** By adopting this digital twin, city planners and conservationists can model the consequences of rising sea levels, assess programs to restore marine habitats, and monitor the health of coastal biodiversity in real time. For instance, simulations could be used to determine the best geographic sites for the rehabilitation of coral reefs or the planting of mangrove trees.
- **Significance**. The significance of this project depends on the fact that it is in line with Singapore's objective of establishing a smart city and a green economy. It demonstrates how digital twins can be used to include biodiversity data in urban planning processes to improve climate resilience and to encourage biodiversity conservation in coastal regions.

c. NVIDIA Omniverse and Planetary Computer for Conservation (Microsoft)

Microsoft's Planetary Computer and NVIDIA's Omniverse (NVIDIA, 2023) are advanced digital twin platforms aimed at enabling extensive environmental monitoring and ecological simulations. While these platforms are in the early stages of development, they provide essential infrastructure for extensive environmental datasets, especially concerning biodiversity.

- **Implementation.** These platforms could potentially be applied to develop digital twins of endangered habitats, including coral reefs or arctic ecosystems. The data capacity of the Planetary Computer enables the simulation of climate adaptation strategies, which can assist in safeguarding vulnerable species and habitats from shifting environmental conditions.
- **Significance**. Through the inclusion of sophisticated data processing and storage capabilities, these digital twin platforms enhance research and conservation efforts on a global level, acting as a fundamental support for eco-friendly initiatives in conservation by enabling data-informed, sustainable development projects.

d. GEO BON's Global Biodiversity Observation System (GBiOS)

The GEO BON initiative (BON, 2022) is a global monitoring system that includes a digital twin approach to observing changes in biodiversity across various continents. The integration of diverse global datasets encompasses satellite data, field observations, and contributions from citizen science.

- **Implementation.** GBiOS enables the tracking of species populations, monitoring of threatened ecosystems, and implementation of restoration actions on a global scale. The system has the capability to identify patterns of deforestation and provide direction for reforestation initiatives aimed at habitat restoration.
- **Significance.** Through a globally interconnected digital twin network, GBiOS offers a collaborative platform for biodiversity conservation, effectively supporting the objectives of the green economy by facilitating comprehensive, data-informed decisions on an international level.

The selected case studies, though limited in number, illustrate the promising capabilities of digital twin technology in improving ecosystem restoration, conserving biodiversity, and managing resources sustainably, all of which are vital for a green economy framework.

Conclusion

The theoretical contribution of this study underscores the potential of digital twin technology to align economic development with environmental sustainability. By incorporating digital twins into the green economy framework, the paper demonstrates how technology can simulate and predict ecological changes, helping to mitigate the environmental degradation often linked to economic growth.

This study provides a theoretical foundation for integrating digital twins into ecosystem management, emphasizing their role in informing policies and strategies for biodiversity conservation. The connection between digital twins and the Environmental Kuznets Curve (EKC) further reinforces the possibility of reducing environmental costs as economies grow, enabling societies to achieve more sustainable development early in their economic trajectories.

The theoretical exploration highlights how digital twins can enhance the understanding of ecological dynamics and ecosystem services, offering a more robust approach to managing natural resources. The ability of digital twins to predict environmental changes and test various conservation strategies before implementation offers a promising avenue for advancing the theoretical framework of sustainable development, ecological economics, and environmental policy-making.

From a practical standpoint, the application of digital twin technology has already yielded promising results. The paper discusses successful case studies where digital twins have been used to restore ecosystems and conserve biodiversity. For example, in coastal and urban ecosystems, digital twins have enabled scientists and policymakers to simulate the impacts of conservation strategies, such as marine protection or green infrastructure planning. These practical applications underscore the power of digital twins in improving resilience to climate change and enhancing biodiversity conservation efforts.

Furthermore, the use of digital twins to model ecosystem services -such as carbon sequestration, water purification, and soil fertility - has practical implications for valuing natural capital, a core principle of the green economy. By quantifying the economic benefits associated with biodiversity and ecosystem services, digital twins help integrate environmental considerations into economic decision-making processes. The practical benefits of digital twins are also evident in their ability to reduce costs and risks associated with conservation interventions by providing accurate predictions and simulations.

Both the theoretical and practical results achieved in this study demonstrate that digital twin technology offers a significant advancement in ecosystem restoration and biodiversity conservation. Theoretically, digital twins provide a robust framework for understanding and addressing the ecological challenges tied to economic growth, while practically, they enable more informed decision-making and cost-effective conservation strategies. As the technology continues to evolve, overcoming existing challenges such as data quality and computational requirements, digital twins will likely become an even more essential tool in fostering a sustainable, green economy.

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