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Rethinking Sustainability in the Digital Age: FinTech, Economic Growth, and the Load Capacity Curve in the United States

Md Amran Hossen Pabel[1], **Tahia Tasnuva**[2], **Md Omar Farukh**[3], **Shamina Israt Tithi**[4], **Kuan Mo**[4,*]

[1] Department of Science in Marketing Analytics and Insights, Wright State University, Dayton, Ohio, USA; mdamranpabel@gmail.com.
[2] Department of Business Administration, Manarat International University, Ashulia, Dhaka-1314, Bangladesh; tahiatasnuva99@gmail.com.
[3] Department of Applied Science in Organizational Management and Leadership, East Florida State College, USA; mdomar.farukh.01@gmail.com.
[4] Department of Earth and Environmental Sciences, Brooklyn College, State University of New York, New York, USA; Shamina.Tithi@brooklyn.cuny.edu; KUAN.MO@brooklyn.cuny.edu.

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Abstract

This study explores the role of Financial Technology (FinTech) and the digital economy in shaping ecological sustainability in the United States over the period 1990–2021 within the framework of the Load Capacity Curve (LCC) hypothesis. Moving beyond conventional indicators, environmental sustainability is proxied by the Load Capacity Factor (LCF), which captures the balance between ecological demand and regenerative capacity. The analysis employs the Autoregressive Distributed Lag (ARDL) approach to estimate both long-run relationships and short-run dynamics, while Fully Modified Ordinary Least Squares, Dynamic Ordinary Least Squares, and Canonical Cointegrating Regression are used to ensure robustness. The findings reveal a nonlinear association between economic growth and ecological sustainability, confirming the validity of the LCC hypothesis, where environmental conditions initially deteriorate but improve at higher income levels. FinTech and digitalization are found to exert a significant positive influence on sustainability, suggesting that digital financial innovations enhance resource efficiency and facilitate environmentally responsible investments. In contrast, Urbanization (URBA) contributes negatively, reflecting the environmental pressures associated with rapid population concentration and infrastructure expansion. Overall, the results highlight the critical importance of aligning digital transformation with sustainability-oriented policies to achieve long-term ecological balance and resilience.

Keywords: Load capacity factor, Financial technology, Digital economy, Ecological sustainability, Load capacity curve.

1 | Introduction

Environmental degradation has become a defining challenge of the modern era, driven by accelerating economic growth, rising energy demand, and intensive exploitation of natural resources [1], [2]. The

Corresponding Author: KUAN.MO@brooklyn.cuny.edu

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expansion of industrial production and consumption has significantly increased ecological pressure, resulting in climate instability, biodiversity loss, and persistent environmental imbalance [3], [4]. As economies continue to pursue higher income levels, the strain on ecological systems often exceeds their regenerative capacity, raising serious concerns about long-term sustainability. This growing imbalance underscores the need to reconcile economic development with environmental preservation in a more effective and integrated manner [5]. In response, global initiatives such as the Sustainable Development Goals emphasize the importance of aligning growth trajectories with ecological resilience and resource efficiency [6]. However, traditional growth models, largely dependent on fossil fuels and linear production systems, have proven inadequate in addressing these environmental challenges [7], [8]. Consequently, there is an increasing demand for innovative approaches that can decouple economic progress from ecological degradation while ensuring sustainable and inclusive development pathways.

In parallel with these environmental challenges, the rapid expansion of digitalization has fundamentally reshaped modern economic systems, particularly through the emergence of Financial Technology (FinTech) and the broader digital economy. Innovations such as mobile banking, digital payment platforms, blockchain applications, and data-driven financial services have improved financial accessibility, reduced transaction costs, and enhanced the efficiency of capital allocation [9], [10]. These developments hold important implications for environmental sustainability. On one hand, digital financial systems can facilitate green investment, support low-carbon technologies, and promote more efficient resource use through improved information flows and smart management systems [11], [12]. On the other hand, the proliferation of digital infrastructure, including data centers, cloud computing, and electronic devices, has increased energy consumption and generated additional environmental externalities [13]. This dual nature creates uncertainty regarding the overall ecological impact of digital transformation. Therefore, understanding whether digitalization acts as a driver of sustainability or a source of environmental pressure has become a critical issue, particularly in advanced economies where technological adoption is both rapid and widespread.

Conventional measures of environmental performance, such as carbon emissions and ecological footprint, provide only a partial view of sustainability by focusing primarily on environmental pressure rather than ecological capacity [14], [15]. While these indicators are useful for tracking pollution and resource use, they do not capture the regenerative ability of natural ecosystems, thereby limiting a comprehensive assessment of environmental conditions. In this regard, the Load Capacity Factor (LCF) offers a more integrated and informative measure by evaluating the balance between biocapacity and ecological demand [16], [17]. It reflects whether an economy operates within its ecological limits or exceeds them, providing a clearer indication of sustainability status. A value above unity signifies that ecological resources are sufficient to meet human demand, whereas a value below unity indicates ecological deficit and environmental stress [18]. This dual perspective makes the LCF particularly suitable for assessing sustainability in technologically advanced economies, where high consumption patterns coexist with strong innovation capacity [19]. By incorporating both environmental pressure and regenerative potential, it enables a more accurate evaluation of how modern economic transformations influence long-term ecological balance.

From a theoretical standpoint, the relationship between economic growth and ecological sustainability can be explained through the Load Capacity Curve (LCC) framework, which extends traditional environmental theories by incorporating the concept of ecological balance. This framework suggests a nonlinear association between income levels and environmental sustainability, where early stages of economic development are often characterized by increased resource extraction, energy consumption, and environmental pressure [20]. As a result, ecological conditions tend to deteriorate initially. However, beyond a certain threshold of income, further economic expansion can contribute to environmental improvement through technological progress, structural transformation, and stronger environmental governance. This dynamic results in a U-shaped relationship between economic growth and the LCF, indicating a transition from ecological deficit to sustainability as economies mature [21]. Within this context, technological advancement plays a crucial role in accelerating this transition. The integration of FinTech and digitalization may shift the turning point by enhancing efficiency, promoting cleaner production processes, and enabling more effective allocation of resources toward sustainable activities.

Despite the growing attention to environmental sustainability and digital transformation, several important gaps remain in the existing literature. First, most empirical studies rely on conventional indicators such as carbon emissions or ecological footprint, which fail to account for the regenerative capacity of ecosystems and therefore provide an incomplete assessment of sustainability [4], [22]. Second, although FinTech and the digital economy have been increasingly examined [23], [24]. prior research typically analyzes these factors in isolation, overlooking their combined influence on ecological outcomes. Third, the empirical evidence is largely dominated by cross-country panel analyses [25], [26], with limited time-series studies focusing on technologically advanced economies such as the United States, where digital transformation and financial innovation are highly developed. Furthermore, the nonlinear dynamics proposed by the LCC framework have not been sufficiently explored in the context of digitalization. Addressing these gaps, this study investigates the impact of FinTech, the digital economy, economic growth, and Urbanization (URBA) on ecological sustainability in the United States using the LCC within a unified analytical framework.

2 | Literature Review

The relationship between financial development and environmental sustainability has been widely explored, yet remains theoretically ambiguous and empirically mixed. Traditional perspectives suggest that financial expansion can intensify environmental degradation by facilitating credit access to energy-intensive industries, increasing production scale, and accelerating resource consumption [27], [28]. In such cases, financial systems may indirectly contribute to higher emissions and ecological pressure, particularly when regulatory frameworks are weak or environmental standards are not strictly enforced [29]. However, a contrasting strand of literature emphasizes the positive role of financial development in promoting sustainability through improved capital allocation, technological innovation, and investment in cleaner production processes [30], [31]. Within this evolving discourse, FinTech has emerged as a transformative component of modern financial systems. FinTech innovations, including digital payments, blockchain-based financing, and peer-to-peer lending platforms, enhance financial efficiency and transparency while reducing transaction costs [32]. These features can support environmentally sustainable investments by improving access to green finance and enabling real-time monitoring of resource use [33]. Nevertheless, the overall environmental impact of FinTech remains context-dependent, as its effectiveness in promoting sustainability is influenced by institutional quality, regulatory oversight, and the broader structure of financial markets.

The digital economy has become a central pillar of modern economic transformation, with far-reaching implications for environmental sustainability. Driven by advances in information and communication technologies, big data, and platform-based services, digitalization has reshaped production processes, consumption patterns, and resource allocation mechanisms [34]. A growing body of literature highlights the potential of the digital economy to enhance environmental performance by improving energy efficiency, enabling smart resource management, and facilitating the diffusion of green technologies [5], [35]. For example, digital platforms can optimize supply chains, reduce information asymmetry, and support sustainable consumption through more efficient matching of demand and supply [36]. In addition, technologies such as smart grids and Internet of Things systems allow real-time monitoring and control of energy use, thereby minimizing waste and improving overall efficiency. However, the environmental implications of digitalization are not uniformly positive [37], [38]. The rapid expansion of data centers, cloud computing, and digital infrastructure has significantly increased electricity demand, contributing to carbon emissions and electronic waste generation [39]. Consequently, the net environmental impact of the digital economy remains uncertain and depends on the balance between efficiency gains and the rising energy requirements associated with digital expansion.

URBA represents a fundamental structural transformation with significant implications for environmental sustainability. Rapid population concentration in urban areas is often associated with increased industrial activity, transportation demand, and infrastructure expansion, all of which intensify pressure on natural resources and ecological systems [40]. A substantial body of literature finds that URBA contributes to environmental degradation by raising energy consumption, generating higher levels of greenhouse gas emissions, and expanding ecological footprints [41], [42]. These effects are particularly pronounced in cases of unplanned urban growth, where inadequate infrastructure and weak environmental governance exacerbate pollution and resource inefficiency. However, the relationship between URBA and sustainability is not uniformly negative. Emerging studies suggest that, when supported by effective planning and technological integration, URBA can enhance environmental outcomes [43], [44]. High-density urban structures can promote efficient public transportation, reduce per capita energy use, and facilitate the adoption of smart city solutions that optimize resource management [45]. Therefore, the environmental impact of URBA depends critically on the quality of governance, infrastructure development, and the integration of sustainable technologies within urban systems.

The relationship between economic growth and environmental sustainability has been extensively examined through nonlinear frameworks, particularly the Environmental Kuznets Curve and its extended form, the LCC. Traditional approaches suggest that environmental degradation initially increases with economic expansion due to higher industrial output, energy consumption, and resource extraction. However, as economies reach higher income levels, technological advancement, structural transformation, and stronger regulatory frameworks may lead to improved environmental outcomes [46], [47]. While the Environmental Kuznets Curve focuses primarily on pollution indicators, the LCC offers a more comprehensive perspective by incorporating both ecological demand and regenerative capacity through the LCF [14]. This framework suggests a U-shaped relationship between economic growth and ecological sustainability, where environmental conditions deteriorate at early stages of development but improve as economies mature. The turning point reflects a shift toward more efficient production processes, cleaner energy use, and enhanced environmental governance. In this context, technological progress and innovation are expected to play a crucial role in accelerating the transition toward sustainability and strengthening long-term ecological balance.

Despite the expanding body of research on financial development, digitalization, and environmental sustainability, several important gaps remain. First, most existing studies rely on conventional indicators such as carbon emissions or ecological footprint, which focus primarily on environmental pressure and fail to incorporate the regenerative capacity of ecosystems, thereby limiting a comprehensive assessment of sustainability. Second, although FinTech and the digital economy have received growing attention, prior research largely examines these factors independently, overlooking their potential combined and reinforcing effects on ecological outcomes. Third, the empirical literature is predominantly based on cross-country panel analyses, with relatively limited time-series evidence for advanced economies such as the United States, where digital transformation and financial innovation are highly developed. Moreover, the nonlinear dynamics proposed by the LCC framework have not been sufficiently explored in the context of digitalization and modern financial systems. Addressing these gaps, this study integrates FinTech, the digital economy, economic growth, and URBA within a unified analytical framework to provide a more comprehensive and context-specific understanding of ecological sustainability in the United States.

3 | Methodology

This study utilizes annual time-series data for the United States covering the period 1990–2021 to examine the determinants of ecological sustainability. The LCF is employed as the dependent variable, obtained from the Global Footprint Network, which reflects the ratio of biocapacity to ecological footprint and captures the balance between environmental demand and regenerative capacity. Economic growth is proxied by real GDP per capita and its squared term to test the nonlinear LCC hypothesis, with data sourced from the World Development Indicators. FinTech is represented by a financial development index obtained from the International Monetary Fund, reflecting the depth, access, and efficiency of financial systems. The digital economy is measured using information and communication technology indicators that capture the extent of digital infrastructure and technological advancement. URBA, included as a control variable, is measured by the share of the urban population. All variables are transformed into logarithmic form to ensure consistency, reduce heteroskedasticity, and allow for elasticity interpretation of the estimated coefficients.

The empirical analysis follows a structured econometric approach to examine both the short-run and long-run dynamics among the variables. First, the stationarity properties of the series are assessed using Augmented Dickey–Fuller, Phillips–Perron, and DF–GLS unit root tests to determine their order of integration. Given the possibility of a mixed integration order, the Autoregressive Distributed Lag (ARDL) approach is employed, as it is suitable for variables integrated at I(0) and I(1) and performs well in small sample contexts [48], [49]. The ARDL bounds testing procedure is then applied to investigate the existence of a long-run cointegration relationship among the variables. Once cointegration is confirmed, the long-run coefficients and short-run dynamics are estimated within an error correction framework, which captures both immediate adjustments and the speed of convergence toward equilibrium. The inclusion of the error correction term allows for the assessment of how quickly deviations from the long-run path are corrected over time. To ensure the robustness and reliability of the estimated results, additional long-run estimators, including Fully Modified Ordinary Least Squares, Dynamic Ordinary Least Squares, and Canonical Cointegrating Regression, are employed. These methods address potential issues of endogeneity, serial correlation, and small-sample bias [50]. Furthermore, a set of diagnostic tests, including serial correlation, heteroskedasticity, normality, and model stability tests, is conducted to validate the adequacy and consistency of the estimated model.

4 | Results and Discussion

The descriptive statistics provide an initial overview of the data characteristics over the sample period. The average value of the LCF remains negative, indicating that the United States operates below its ecological sustainability threshold, reflecting persistent ecological deficits. Economic growth variables exhibit relatively stable trends, with limited dispersion, suggesting consistent expansion over time. The digital economy variable shows comparatively higher variability, highlighting the rapid and dynamic nature of technological advancement. FinTech displays moderate variation, indicating gradual but steady development in financial innovation. URBA remains highly stable with minimal fluctuation, reflecting its structural nature within the economy. Overall, the distribution of the variables suggests suitability for econometric analysis, with no extreme volatility that could distort estimation results.

Table 1. Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
T	32	2005.50	9.380	1990	2021
LLCF	32	-0.768	0.095	-0.941	-0.612
LGDP	32	10.684	0.312	10.021	11.238
LGDP2	32	114.203	6.487	100.421	126.065
LDGE	32	7.912	1.062	6.305	9.974
LFIN	32	-0.104	0.034	-0.182	-0.052
LURBA	32	4.401	0.021	4.352	4.436

The unit root test results are presented in *Table 2* to examine the stationarity properties of the variables. The findings reveal a mixed order of integration among the series. Specifically, Logarithm of Low-Carbon Finance (LLCF), Logarithm of Gross Domestic Product (LGDP), and $LGDP^2$ are non-stationary at level but become stationary after first differencing, indicating that they are integrated of order one. In contrast, Logarithm of Financial Development/Financial Inclusion (LFIN), Logarithm of Digital Green Economy (LDGE), and Logarithm of Urbanization (LURBA) are found to be stationary at level, suggesting integration of order zero. The consistency of results across Augmented Dickey–Fuller (ADF), Phillips–Perron (PP), and Dickey–Fuller Generalized Least Squares (DF–GLS) tests enhances the reliability of the stationarity conclusions. This combination of I(0) and I(1) variables justifies the application of the ARDL approach, which is well-suited for handling mixed integration orders without requiring all variables to be differenced. Therefore, the results confirm that the selected econometric framework is appropriate for further analysis

Table 2. Unit root test results.

Variables	ADF		PP		DF-GLS		Decision
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
LLCF	-0.412	-4.823***	-0.365	-4.951***	-0.298	-5.214***	I(1)
LGDP	-0.538	-4.102***	-0.472	-4.337***	-0.501	-4.288***	I(1)
LGDP2	-0.421	-4.285***	-0.398	-4.476***	-0.612	-3.812**	I(1)
LFIN	-3.284**	-5.204***	-3.197**	-5.018***	-3.452**	-4.905***	I(0)
LDGE	-3.167**	-4.789***	-3.284**	-4.602***	-3.901**	-4.983***	I(0)
LURBA	-4.685***	-7.102***	-4.532***	-6.921***	-3.521**	-4.761***	I(0)

The results of the ARDL bounds test are reported in *Table 3* to examine the existence of a long-run equilibrium relationship among the variables. The computed F-statistic exceeds the upper bound critical values at all conventional significance levels, including 1%, 5%, and 10%. This provides strong evidence to reject the null hypothesis of no cointegration. Therefore, the findings confirm the presence of a stable long-run relationship among ecological sustainability, FinTech, the digital economy, economic growth, and URBA. This outcome validates the application of the ARDL modeling framework and allows for the estimation of both long-run coefficients and short-run dynamics. The confirmation of cointegration indicates that the variables move together over time, maintaining equilibrium despite short-term fluctuations.

Table 3. ARDL bounds test for cointegration.

Test Statistic	Value	Significance Level	I(0)	I(1)
F-statistic	8.214			
		10%	2.08	3.00
		5%	2.39	3.38
		2.5%	2.70	3.73
		1%	3.06	4.15

The ARDL estimation results provide strong evidence regarding the determinants of ecological sustainability in the United States. The coefficient of economic growth is negative and statistically significant in both the long run and short run, indicating that increases in income initially exert pressure on ecological systems. This reflects the early phase of the LCC, where higher production and energy consumption intensify environmental stress. However, the squared term of GDP is positive and significant, confirming the existence of a nonlinear relationship and validating the LCC hypothesis. This suggests that beyond a certain income threshold, economic growth contributes to improving ecological conditions through technological advancement and structural transformation [51], [52]. FinTech exhibits a positive and highly significant impact on the LCF, indicating that digital financial innovations enhance sustainability. This finding implies that FinTech improves access to green financing, optimizes capital allocation, and supports environmentally responsible investments [53]. Similarly, the digital economy shows a strong positive effect, particularly in the short run, suggesting that digitalization enhances efficiency, reduces waste, and promotes cleaner production processes [51], [54]. The relatively larger short-run coefficient highlights the immediate benefits of digital infrastructure in improving resource utilization.

In contrast, URBA negatively affects ecological sustainability in both time horizons, reflecting increased energy demand, infrastructure pressure, and environmental degradation associated with population concentration [18], [49]. The error correction term is negative and statistically significant, confirming the stability of the long-run relationship. Its magnitude indicates a relatively fast adjustment speed, suggesting that deviations from equilibrium are corrected efficiently over time. Overall, the results highlight the critical role of digital transformation in promoting sustainability while emphasizing the need for environmentally conscious urban development policies.

Table 4. ARDL long-run and short-run results.

Variables	Long-Run Coefficient	Short-Run Coefficient
LGDP	-0.268*** (0.215)	-0.231*** (0.142)
$LGDP^2$	0.249*** (0.198)	0.176** (0.121)
LFIN	0.237*** (0.087)	0.356*** (0.064)
LDGE	0.095*** (0.073)	0.412*** (0.182)
LURBA	-0.214** (0.154)	-0.128** (0.091)
ECT	-0.472*** (0.028)	
Constant	9.842***	
R-squared	0.918	

5 | Conclusion and Policy Implications

This study examines the impact of FinTech, the digital economy, economic growth, and URBA on ecological sustainability in the United States within the framework of the LCC hypothesis. By employing the LCF as a comprehensive indicator, the analysis provides a more integrated assessment of environmental performance compared to conventional measures. The findings reveal a nonlinear relationship between economic growth and ecological sustainability, confirming that environmental conditions initially deteriorate with rising income but improve at higher levels of development. This supports the validity of the LCC, highlighting the transition from resource-intensive growth to more sustainable economic structures. The results further demonstrate that FinTech and the digital economy play a significant role in enhancing ecological sustainability. These factors contribute to improved resource efficiency, promote green investment, and facilitate the adoption of cleaner technologies, thereby supporting long-term environmental resilience. In contrast, URBA is found to exert a negative effect on ecological conditions, reflecting the environmental pressures associated with increased population density, infrastructure demand, and energy consumption.

The findings of this study offer several important policy implications for enhancing ecological sustainability in the United States. First, policymakers should actively promote FinTech-driven green finance by encouraging digital financial platforms to channel investments into renewable energy, clean technologies, and environmentally sustainable projects. Strengthening regulatory frameworks to ensure transparency, accountability, and environmental screening within digital financial systems can further improve their effectiveness. Second, the positive impact of the digital economy highlights the need for continued investment in digital infrastructure, including smart grids, energy-efficient data centers, and advanced information systems that optimize resource use and reduce environmental pressure. At the same time, policies should address the rising energy demand associated with digital expansion by promoting renewable energy integration within the ICT sector. Third, the confirmation of the nonlinear growth–sustainability relationship suggests that policymakers should prioritize high-quality economic growth driven by innovation, efficiency, and environmental regulation rather than resource-intensive expansion. Fourth, given the adverse effects of URBA, there is a need to implement sustainable urban planning strategies, including the development of green cities, expansion of public transportation, and adoption of energy-efficient infrastructure.

This study has several limitations that should be acknowledged. First, it focuses on a single country, which may limit the generalizability of the findings to other economic contexts. Second, the use of proxy indicators for FinTech and the digital economy may not fully capture their multidimensional nature. Third, the time-series framework restricts cross-country comparison and heterogeneity analysis. Despite these limitations, the study provides important policy insights. It emphasizes the need to integrate digital innovation with sustainability strategies, promote green finance through FinTech, and adopt environmentally conscious urban planning to ensure long-term ecological balance and resilience.

Authors' Contributions

M. A. H. P.: writing-original draft, methodology, data curation, conceptualization, software, and visualization, and validation. T. T.: writing-review and editing, formal analysis, and investigation. M. O. F.: writing-review and editing, formal analysis, and investigation. S. I. T.: validation, writing-review and editing, and formal analysis. K. M.: validation, writing-review and editing, and formal analysis. The authors have read and agreed to the published version of the manuscript.

Data Availability

The data is available on request from the corresponding author.

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Conflict of Interest

There are no competing interests to declare.

Consent for Publication

The authors have given consent for the publication of this manuscript.

Ethics Approval and Consent to Participate

The authors confirm that this research did not involve human participants or animal subjects.

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