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INTEGRATING GREEN ECONOMY AND FINANCIAL TECHNOLOGIES TO ADVANCE ENVIRONMENTAL SUSTAINABILITY

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ABSTRACT

This study provides a comprehensive examination of how the green economy, financial technologies (FinTech), and governance collectively influence environmental sustainability in the United States over the period 1990–2024. Using descriptive indicators, cointegration methods, error-correction modeling, and quantile vector autoregression (QVAR), complemented by heatmap-based diagnostic analysis, the research captures both long-run equilibrium relationships and short-run adjustment mechanisms. Environmental sustainability is evaluated through the Environmental Performance Index (EPI) in conjunction with greenhouse gas emissions indicators. The results indicate that the expansion of renewable energy, forest preservation, and green-adjusted GDP significantly reduce emissions levels. At the same time, advances in financial technologies (FinTech)—such as digital payment platforms and peer-to-peer lending—broaden access to green finance and improve the efficiency of capital allocation. In contrast, digital currencies exhibit mixed environmental impacts, primarily due to their high energy consumption. Heatmap-based evidence reveals strong transmission channels, where shocks to green-economy or FinTech variables are rapidly reflected in environmental indicators, highlighting substantial structural interdependence. Moreover, governance quality plays a critical moderating role by enhancing policy alignment and strengthening adaptive resilience. Overall, the findings emphasize the need for strong institutional frameworks, well-designed green-finance incentives, and effective regulatory measures to address the environmental externalities associated with energy-intensive digital technologies.

KEYWORDS: Green Economy; Fintech; Environmental Sustainability, Heatmaps, Renewable Energy.
JEL Classification : Q56 ; Q58 ; G20 ; O44 and C32

1. Introduction

Sustainable development has moved to the forefront of contemporary economic debate, driven by heightened recognition of the mutually reinforcing links between economic performance, environmental stewardship, and social welfare (Desai, 2020). The green economy proposes a paradigm shift in development thinking, aiming to decouple growth from environmental degradation while embedding principles of equity and inclusion (Sun & Chen, 2024). It emphasizes resource efficiency, systematic carbon-reduction strategies, and the incorporation of ecological criteria into all stages of policy design and implementation (Khan et al., 2024). In contrast, conventional growth trajectories—anchored in high-intensity extraction, production, and consumption—have demonstrated clear limits causing environmental damage and deepening socio-economic vulnerabilities (Zuo & Luo, 2024). Addressing these structural deficiencies requires the deployment of innovative financial mechanisms and the strengthening of governance systems capable of scaling green technologies and promoting sustainable practices across economic domains (Agrawal et al., 2024).

The green economy provides a strategic response to mounting ecological and social pressures by advancing technologies and practices that elevate resource productivity and curb environmental degradation (Mukhopadhyay, 2024). Its policy relevance has expanded globally, as both advanced and emerging economies increasingly rely on green-growth frameworks to pursue long-term sustainability objectives (She & Mabrouk, 2023). Parallel to this shift, financial technologies (FinTech) have become pivotal instruments in the sustainability transition, supplying new mechanisms for mobilizing environmentally oriented capital, enhancing transparency in green finance, and broadening access to financial services for eco-focused initiatives (Zhu et al., 2023).

By supporting a low-carbon, resource-efficient, and socially inclusive development trajectory, the green economy stimulates income and employment through coordinated public and private investment in assets and infrastructures that reduce pollution, limit emissions, and improve energy efficiency (Mustafa et al., 2022). Within this ecosystem, FinTech tools—including digital payments, online lending platforms, blockchain applications, and artificial-intelligence-based analytics—substantially improve financial intermediation and service delivery. Their growing deployment in green-finance activities is particularly consequential, as it accelerates capital flows toward environmental projects and reinforces the broader reorientation of economic systems toward sustainability.

At the same time, green technologies across key sectors—energy, manufacturing, transportation, construction, and agriculture—function as core drivers of the transition, enabling renewable-energy expansion, waste reduction, and efficiency gains in line with the UN Sustainable Development Goals (Raman et al., 2025). FinTech also strengthens the inclusiveness and resilience of financial systems by extending green-finance opportunities to populations traditionally excluded from formal banking. Ultimately, its transformative potential lies in the ability to generate data-rich, real-time insights that guide firms, investors, and households toward investment choices consistent with sustainable development pathways.

This study investigates the combined influence of three foundational dimensions of sustainable development—green economic activity, financial technology (FinTech), and governance—on environmental outcomes in the United States from 1990 to 2024. The green economy is operationalized through three indicators: the share of renewable energy in total energy use, an environmentally adjusted measure of GDP, and forest coverage relative to national land area. FinTech development is captured by the diffusion of digital payment systems, the expansion of peer-to-peer lending, and the circulation of digital currencies. Governance quality is proxied by a composite index reflecting institutional performance and perceived corruption. All data are drawn from the World Bank, the International Monetary Fund, and widely recognized global indices.

Environmental sustainability is assessed through two endogenous variables—the Environmental Performance Index (EPI) and total greenhouse gas emissions—allowing for a multidimensional evaluation of ecological conditions. The central objective is to analyze the channels through which green-economy measures and digital financial innovations interact to shape these outcomes. More precisely, the study asks: **to what degree do initiatives promoting greener economic structures, alongside the diffusion of FinTech tools, jointly enhance environmental performance and mitigate emissions?** This guiding question frames the empirical inquiry and underscores the potential complementarities between environmental policy instruments and emerging financial technologies in advancing the United States' sustainable development agenda.

The distinct contribution of this study stems from its comprehensive analytical design, which integrates indicators of green economic activity, FinTech advancement, and governance quality within a unified empirical framework. A further element of novelty lies in the application of Quantile Vector Autoregression (QVAR), enabling the assessment of transmission dynamics and response patterns at the median quantile—an approach particularly well suited to uncovering heterogeneous effects across the distribution. Complementing this methodology, the study employs interconnected network structures to distinguish variables that act as sources of shocks from those that primarily absorb them. Heatmap visualizations play a central role in this analysis, illuminating the pathways through which shocks propagate, the intensity of interdependencies, and the ways in which these three domains collectively underpin the shift toward a sustainable development paradigm.

This study contributes to theory thanks to the direct insights provided by the heatmap analysis and the network-based exploration of interdependencies. Its novelty resides in the integrated treatment of three domains—green economic development, financial technological innovation, and governance quality—within a single conceptual and empirical architecture. This comprehensive perspective addresses a notable gap in the sustainable-development literature, where these dimensions have generally been examined separately rather than as mutually reinforcing components of a broader systemic transition. Through the combined use of QVAR modelling and heatmap visualization, the study reveals differentiated variable responses at the median quantile, uncovers the principal channels through which shocks are transmitted, and maps the intensity of cross-domain linkages. These results elucidate how green economy indicators, FinTech dynamics, and governance structures jointly interact to facilitate progress toward a sustainable development trajectory.

The study is organized into three principal sections. The first section synthesizes the relevant theoretical and empirical literature, focusing on the relationships linking the green economy, FinTech, and governance. The second section presents the empirical investigation, beginning with data diagnostics based on descriptive statistics and followed by an exploration of both linear and nonlinear associations among economic, institutional, financial, and environmental variables. Stationarity tests are employed to avoid estimation bias, and cointegration modelling is used to identify long-run equilibria, complemented by linear adjustment mechanisms to assess the combined influence of green-economy measures and FinTech innovations on U.S. environmental sustainability. The section also incorporates QVAR-based analysis of shock transmission at the median quantile and heatmap examinations of cross-variable interactions. The third and final section discusses the policy implications of the findings, outlining potential reform pathways aimed at strengthening environmental governance, advancing green-economy objectives, and leveraging financial innovation to support sustainable development.

2. Literature Review

This study promotes the growing body of research on the nonlinear and multifaceted interactions between green-economy initiatives, financial technological innovations, and governance systems in the pursuit of sustainable development objectives. Although each of these components has been extensively examined in isolation, their interdependencies—particularly those shaped by institutional frameworks—remain insufficiently theorized and empirically documented (Zhang, 2023). Moreover, despite the substantial commitments made by national governments and international financial institutions to finance environmental interventions and accelerate climate-mitigation efforts, major knowledge gaps persist regarding the ways in which financial markets facilitate, constrain, or modulate the shift toward a low-carbon economic structure (Lichtenberger et al., 2022).

The rise of the green economy is a direct response to mounting ecological pressures, positioning it simultaneously as a corrective framework for mitigating environmental degradation and as a strategic avenue for embedding sustainability within economic activity (Zhang, 2023). This paradigm emphasizes investment decisions that incorporate social and environmental criteria across public and private domains, thereby enabling a structural transition toward development models aligned with long-term ecological viability (Zhang, 2023). It represents a fundamental reorientation of economic practice, foregrounding principles of equity, environmental responsibility, and systemic resilience.

Green-economy strategies encompass a wide spectrum of interventions—including biodiversity protection, carbon-emission reduction, afforestation efforts, and improvements in resource efficiency—all aimed at strengthening ecological systems. A core feature of this approach is the internalization of environmental externalities, ensuring that the true ecological costs of production and consumption are reflected in market signals and decision-making processes. This also entails recognizing and valuing natural resources that conventional economic frameworks frequently overlook, thereby discouraging practices that impose disproportionate environmental burdens. Such a reconceptualization requires a deep restructuring of financial systems, shifting their primary orientation from narrow efficiency metrics toward broader goals of sustainability and environmental stewardship (Omurova et al., 2021).

As global awareness of environmental risks intensifies, scholarly interest has increasingly converged on sustainable development and, in particular, on green finance as an instrument capable of reconciling economic growth with ecological responsibility (Pan et al., 2020; Caliari, 2024).

The incorporation of green-economy principles bespeaks the need to reconcile economic expansion with environmental sustainability, emphasizing more efficient patterns of resource use and the accelerated deployment of renewable-energy technologies (Jangid et al., 2025). Technological progress and the emergence of innovative financial instruments further strengthen this paradigm by supporting economic development in ways that align with long-term ecological objectives (Jangid et al., 2025). Within the ongoing digital transformation of the financial sector—driven largely by FinTech—capital markets are increasingly channelled toward environmentally oriented investments, thereby facilitating the structural transition toward a greener economic model (Manta et al., 2025).

FinTech's adaptability and scalability in delivering green-finance solutions constitute a particularly salient yet still insufficiently examined dimension of this transformation. By broadening access to sustainable financial products, FinTech expands participation among both institutional and retail investors, as well as among environmentally aware consumers (Piotrowska & Piotrowski, 2025). Nonetheless, Green FinTech remains a nascent interdisciplinary domain situated at the intersection of business studies, information systems, and financial economics, and therefore requires deeper theoretical and empirical inquiry (Puschmann & Khmarskyi, 2024).

Green finance encompasses a broad spectrum of instruments and institutions—ranging from green bonds and dedicated investment funds to carbon-market mechanisms and specialized entities such as green banks (Naderi & Tian, 2022). At its core, it denotes financial services and capital flows directed toward improving environmental quality and mitigating climate change (Gandreti et al., 2024). More precisely, green finance comprises investments designed either to limit adverse ecological effects or to generate significant positive environmental outcomes (Cai & Guo, 2021). These investments originate from both private and public sectors, each seeking to support environmentally oriented projects and reduce ecological degradation (Nenavath & Mishra, 2023).

FinTech plays an increasingly pivotal role in advancing this agenda. Through innovations such as digital banking platforms, blockchain-based systems, and data-driven analytical tools, FinTech embeds sustainability considerations directly into financial intermediation. These technologies enhance the precision and efficiency of capital allocation toward projects with verifiable environmental benefits, thereby reinforcing the transition to a more sustainable global economy. The rapid digitalization of financial markets is accelerating the expansion of green finance (Xiao et al., 2024), a transformation underpinned by FinTech's capacity to deliver financial products and services more efficiently than traditional approaches (Piotrowska & Piotrowski, 2025).

Empirical evidence indicates that green finance contributes not only to improved environmental outcomes but also to greater economic efficiency and structural transformation, thereby promoting high-quality, sustainable development (Nenavath & Mishra, 2023). The integration of FinTech into green-finance frameworks amplifies these benefits by enhancing transparency, reducing transaction costs, and boosting the effectiveness of environmentally oriented investment projects. Furthermore, digitalization expands access to financial resources and provides innovative mechanisms for monitoring, evaluating, and reporting investment performance, thereby reinforcing accountability and governance (Manta et al., 2025). Together, these dynamics underscore FinTech's central role as a facilitator of capital allocation toward environmentally responsible initiatives and as a catalyst for advancing the transition to a green economy (Jangid et al., 2025).

Technological advancement has become a critical driver of sustainability within both economic and environmental policy frameworks, providing tools that enable growth while safeguarding ecological systems (Manta et al., 2025). Such innovations broaden participation in green initiatives, democratizing access to sustainable investment opportunities and enabling wider stakeholder engagement (Xiao et al., 2024). Digital finance introduces innovative credit and investment products that transcend the resource-intensive constraints of traditional banking, thereby promoting environmental well-being (Jiang et al., 2024). The convergence of finance and technology, encapsulated in the concept of FinTech, harnesses advanced solutions to enhance operational efficiency, increase accessibility, and substantially reduce the costs of financial services (Huang et al., 2025). Beyond improving financial intermediation, FinTech supports the green transformation of industries by facilitating the dissemination of critical information and fostering sustainable practices aligned with global environmental objectives, including carbon peaking and carbon neutrality (Xue et al., 2022).

Recent studies highlight the growing significance of FinTech as a catalyst for sustainability. For instance, El-Sharkawy et al. (2023) find that both green finance and FinTech substantially support sustainable economic growth in India by enhancing environmental quality and promoting resource-efficient practices. Cross-country evidence further suggests that FinTech exerts a positive, though moderate, influence on social and environmental performance at the global level (Fang et al., 2023). Collectively, these findings position FinTech as a pivotal enabler of sustainable development, facilitating access to capital for environmentally responsible projects while advancing transparency, efficiency, and innovation within financial markets. The integration of FinTech with green-finance mechanisms also allows for the scaling of sustainable investments, more effective resource allocation, and enhanced monitoring of environmental outcomes through advanced digital tools. In this context, FinTech emerges as a versatile instrument supporting the global transition toward low-carbon, resilient, and inclusive economic systems, with applications spanning renewable-energy financing, climate-risk mitigation, and sustainable supply-chain management.

Beyond aggregate impacts, recent research has explored the specific pathways through which FinTech shapes environmental outcomes. Du et al. (2022) demonstrate that FinTech enhances corporate ESG performance by easing financing constraints and leveraging fiscal and regulatory incentives, thereby enabling firms to adopt more sustainable operational practices. Similarly, Zhang et al. (2024) show that FinTech development facilitates environmental investment, supports green bond issuance, and reduces carbon emissions among high-polluting enterprises. These effects are heterogeneous, varying according to firm size, sectoral characteristics, and regional context, underscoring the nuanced and context-dependent role of FinTech in promoting ecological performance. Collectively, the evidence positions FinTech as a strategic instrument for advancing environmental sustainability: it improves access to capital, fosters green innovation, and enables more efficient monitoring of environmental outcomes, aligning economic activity with ecological stewardship. Furthermore, the integration of digital financial technologies with green-finance instruments enhances the scalability and cost-effectiveness of solutions to climate-related challenges, accelerating the transition toward low-carbon and sustainable economic systems.

Institutional and structural conditions are pivotal in shaping the effectiveness of green FinTech initiatives. A bibliometric analysis by Zournatzidou (2025) indicates that while Greentech and green-finance ecosystems are expanding rapidly, their success is highly dependent on robust governance structures, encompassing regulatory oversight, policy incentives, and institutional capacity. In a complementary perspective, Caldarola et al. (2024) highlight that an economy’s transition toward sustainability is strongly conditioned by its economic complexity and institutional readiness, emphasizing the necessity of adaptive and resilient regulatory frameworks. These insights suggest that the environmental impact of FinTech is heterogeneous, contingent upon governance quality, institutional thresholds, and the broader structural context in which digital financial technologies are deployed. Consequently, advancing effective green FinTech requires not only technological innovation but also the establishment of enabling environments that harmonize financial, regulatory, and ecological objectives. This approach underscores the imperative of integrating policy design with financial innovation to optimize FinTech’s contribution to environmental sustainability, ensuring that investments are both efficient and ecologically constructive.

The literature further highlights the resilience of FinTech in the face of economic and environmental shocks. For example, Toumi et al. (2023) demonstrate that FinTech firms outperformed traditional non-FinTech counterparts in environmental performance during the COVID-19 pandemic, particularly when they maintained strong environmental disclosure practices. This evidence indicates that FinTech not only facilitates sustainable investment under normal conditions but also functions as a stabilizing mechanism during crises, mitigating environmental risks and sustaining ecological initiatives. By leveraging digital platforms, advanced data analytics, and automated financial processes, FinTech ensures continuity in financing green projects and enables consistent monitoring of environmental outcomes even under turbulent conditions. These attributes underscore FinTech's dual role as both a driver of sustainable development and a mechanism for enhancing the resilience of environmental initiatives, highlighting its strategic relevance for policymakers and investors committed to long-term ecological and economic sustainability. This study addresses existing gaps by providing a governance-centered examination of the interactions among green-economy initiatives, FinTech adoption, and environmental sustainability outcomes. Employing cointegration analysis to prevent spurious inferences, the research estimates the combined effects of financial technologies and green-economy measures on environmental performance, while also exploring shock transmission dynamics through a QVAR model complemented by heatmap visualizations. These multi-layered analyses yield nuanced insights into how regulatory frameworks and technological innovations jointly influence sustainability outcomes within dynamic economic contexts, with a particular focus on the United States. The study further highlights the heterogeneous sensitivities of environmental sustainability indicators to shifts in green-policy interventions and FinTech integration, offering practical guidance for the formulation of effective public policies (Piotrowska & Piotrowski, 2025). Specifically, the research delineates points of convergence between FinTech and sustainable development initiatives, emphasizing its role in promoting eco-innovation, improving energy efficiency, and facilitating reductions in carbon emissions (Ha & Nguyen, 2025).

3. Empirical Analysis

This study undertakes an empirical investigation to assess the combined influence of the green economy and financial technologies (FinTech) on environmental sustainability, with particular emphasis on their role in curbing greenhouse gas emissions, the principal drivers of climate change. The analysis focuses on the United States, a major global economic actor that faces substantial environmental pressures due to its significant contribution to global CO_2 emissions. Covering the period from the 1990s to 2024, the study captures both structural shifts associated with the implementation of green policies and the emergence of digital financial innovations. Green-economy initiatives, by fostering sustainable investments and promoting efficient resource utilization, directly support environmental preservation. Concurrently, FinTech instruments—such as digital payments, green crowdfunding platforms, and blockchain-based solutions—enable the effective channeling of financial resources toward climate-positive projects. The integration of these two dimensions offers considerable potential to mitigate the negative externalities of economic activity and to accelerate the United States' transition toward a sustainable, low-carbon, and climate-resilient development pathway.

To empirically investigate the United States from 1990 to 2024, this study uses a comprehensive set of indicators capturing environmental outcomes alongside relevant economic and financial dynamics. Environmental sustainability is operationalized through two endogenous variables: overall environmental performance, proxied by the Environmental Performance Index (EPI), and the impact of climate change, approximated by total greenhouse gas emissions (Greenhouse). The explanatory variables are categorized into two principal domains. For FinTech, the analysis includes the expansion of digital payments (DigitalPayment), the diffusion of peer-to-peer lending platforms (PP lending), and the adoption of digital currencies (MonnaieDigitale). For the green economy, indicators comprise the share of renewable energy in total energy consumption (Reniable), green-adjusted GDP accounting for environmental costs (GreenGDP), and forest coverage as a percentage of total land area (Forestarea). Control variables capturing additional influences on these dynamics include high-technology exports (hightech) and a composite governance index reflecting institutional quality and perceptions of corruption (QGCG). All data are drawn from authoritative international sources, including the World Bank and the International Monetary Fund (IMF), ensuring consistency and reliability for the analysis.

Green GDP is conceptualized as the conventional measure of gross domestic product adjusted to reflect the economic costs of environmental degradation and natural-resource depletion. This adjustment incorporates estimates of pollution, carbon emissions, and resource exhaustion, which are subtracted from traditional GDP to provide a more accurate representation of economic output in ecological terms (Pan et al., 2023). Tracking the evolution of FinTech across time and countries poses specific challenges, particularly prior to 2010, when digital currencies and peer-to-peer (P2P) lending were either nascent or nonexistent. To address this, our dataset codes values from 1990 to 2010 as zeros or interpolates them based on adoption patterns observed in subsequent years. Data on digital payments are primarily obtained from the World Bank's Global Findex database, supplemented by S&P Kensho indices. Information on P2P lending is sourced from CCAF reports and relevant sectoral databases, while adoption metrics for digital currencies are reconstructed using cryptocurrency market data (Investing.com) and IMF FinTech notes for the post-2014 period.

For the period 2019–2024, the governance indicator is sourced from the World Bank's WDI and WGI databases, which are updated annually with an inherent time lag. Environmental indicators are drawn from the World Bank, the International Energy Agency (IEA), and the Environmental Performance Index (EPI, 2022 edition), with interpolations applied for 2023 and 2024 to maintain continuity in the time series. FinTech measures—including digital payments, digital currencies, and peer-to-peer (P2P) lending—are obtained from S&P Kensho indices and sector-specific databases, enabling updates through December 2024. For 2024, the analysis relies on the latest official releases, complemented by provisional estimates and real-time database updates. A detailed account of all data sources and adjustments is provided in Table 1 (Appendix), ensuring full transparency regarding the integration of finalized statistics and preliminary figures.

All variables have been logarithmically transformed to normalize their distributions, mitigate skewness, and allow for the interpretation of coefficients in elasticity terms. This transformation facilitates proportional and consistent analysis of the relationships between variables. It also underscores that the selected indicators are theoretically grounded rather than arbitrarily chosen, reflecting the study's three core dimensions: green economy, FinTech, and governance. By adopting this approach, we construct a robust and reliable econometric framework capable of capturing the complex interactions among these factors while ensuring the statistical validity and interpretability of the results.

3-1 Preliminary Analysis

For all variables expressed in logarithmic form, we examine their statistical properties through measures of central tendency, dispersion, and distributional shape. This assessment enables the evaluation of symmetry, kurtosis, normality, heteroskedasticity, and volatility for each variable. The analysis is conducted for the United States using annual data spanning the period 1990–2024. A detailed summary of these descriptive statistics is presented in Table 2, offering a comprehensive overview of the distributions and variability of the variables included in the study.

Table 2. Descriptive Statistical Indicators

	Mean	Variance	Skewness	Kurtosis	JB	Q(20)	$Q^2(20)$
LEPI	4.120***	0.018***	0.382	-0.938	1.950	101.938***	100.911***
LGreenGDP	22.449***	5.345***	-0.124	-0.647	0.639	6.620	6.765
Lhightech	7.298***	18.097***	0.633	1.674**	5.871*	32.235***	10.689
LDigitalPayment	4.947***	0.018***	-0.363	-1.263***	2.829	102.908***	103.105***
LMonnaieDigitale	141.980***	344.387***	-0.246	-1.366***	2.811	103.574***	103.565***
LPPlending	1.946***	0.996***	0.245	0.040	0.322	6.829	9.396
LForestarea	8.827***	0.000***	-0.544	-1.162**	3.381	57.394***	57.439***
LReniable	4.669***	15.040***	0.624	-1.200**	3.995	122.111***	97.747***
LGreenhouse	4.900***	0.006***	-0.317	-0.940	1.713	62.235***	62.014***
LQGCG	19.136***	281.323***	0.037	-1.619***	3.502	136.762***	118.266***

Note: The Q(20) and $Q^2(20)$ statistics are the Ljung-Box test statistics used to test the null hypothesis of no serial correlation up to the 20th order in returns and squared returns, respectively. A 20-lag specification is chosen to capture serial dependence over a full half-year period. The Jarque-Bera statistic tests the null hypothesis that a series is normally distributed by examining its first two moments, with the statistic following a χ^2 distribution with two degrees of freedom under the null hypothesis. The Elliott, Rothenberg, and Stock (ERS: 1992) test is a modified version of the Augmented Dickey-Fuller (ADF: 1981) test. Significance levels are indicated as follows: (***) 1%, (**) 5%, and (*) 10%.

Table 2 presents a comprehensive statistical summary of the primary variables employed to examine the effects of the green economy and financial technologies (FinTech) on environmental sustainability in the United States over the period 1990–2024. Measures of central tendency and dispersion indicate that environmental performance (LEPI) and greenhouse gas emissions (LGreenhouse) maintain relatively stable mean values, reflecting a consistent environmental trajectory, while their low variances suggest limited volatility throughout the study period.

Indicators representing the green economy—specifically green-adjusted GDP (LGreenGDP), forest coverage (LForestarea), and the share of renewable energy consumption (LReniable)—exhibit distributions characterized by some asymmetry and the presence of extreme values, as evidenced by negative kurtosis for LForestarea and LRenivable. These patterns capture episodic fluctuations in the implementation of environmental policies and investments in green initiatives, underscoring the gradual progress of the green economy and its role in mitigating adverse environmental impacts.

Regarding FinTech, indicators capturing digital payments (LDigitalPayment), digital currency adoption (LMonnaieDigitale), and peer-to-peer lending (LPPlending) exhibit moderate to high variances and varying degrees of asymmetry, reflecting the gradual and uneven diffusion of these technologies. Normality assessments (Jarque-Bera test) and autocorrelation diagnostics (Q(20) and $Q^2(20)$) reveal that certain variables, particularly LDigitalPayment and LMonnaieDigitale, display non-normal distributions and significant temporal dependencies, characteristic features of financial innovations undergoing rapid adoption.

Collectively, these descriptive statistics suggest that the green economy and FinTech are developing in a complementary fashion within the United States. Digital financial indicators facilitate the financing and investment of green projects, indirectly contributing to the reduction of greenhouse gas emissions, as evidenced by the relatively stable LGreenhouse values and the observed progress in green-adjusted GDP and renewable energy adoption. The findings underscore the joint contribution of financial innovation and green strategies in advancing a more sustainable and climate-resilient economic model.

Building on these insights, the study further examines dependency relationships among sustainable development indicators, green-economy measures, FinTech variables, and contextual factors such as high-technology exports and the composite governance and corruption index. Focusing on the United States over the period 1990–2024, potential linear associations are assessed using the Pearson correlation matrix, presented in Figure 1, which visualizes both the direction and strength of the relationships among the analyzed variables.

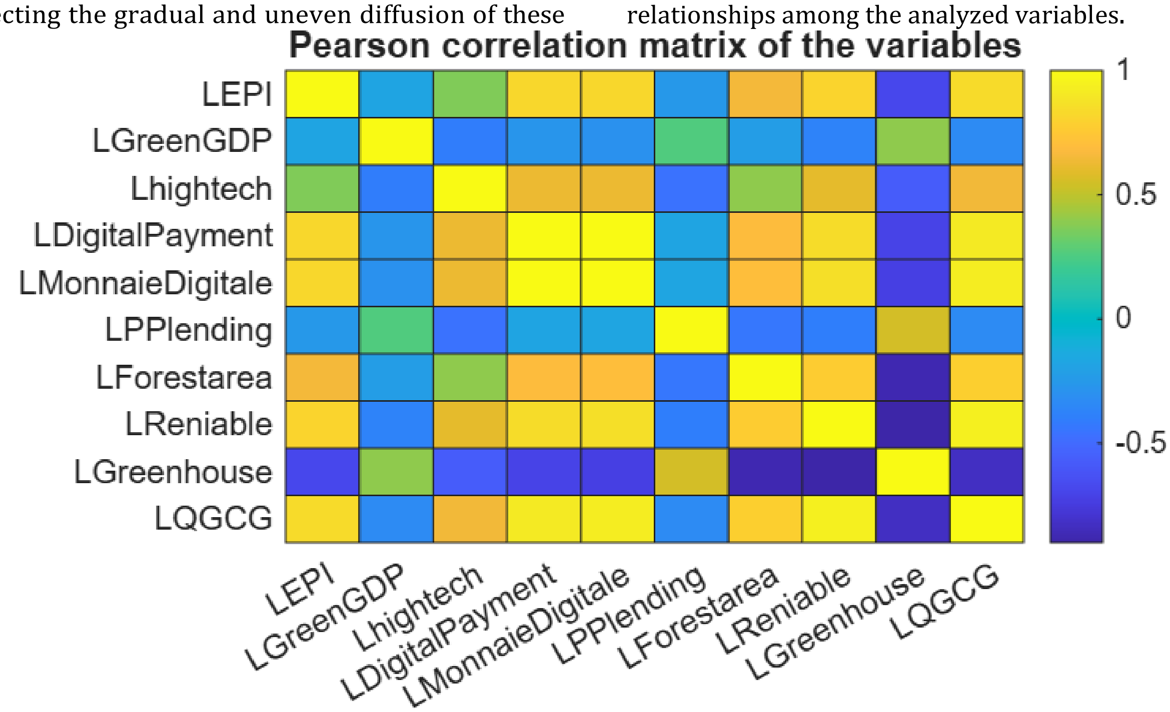


Figure 1: Pearson Correlation Matrix of the variables

Figure 1 presents the Pearson correlation matrix for the variables under study, providing a clear depiction of linear relationships and the strength of associations among indicators of sustainable development, FinTech, the green economy, and governance. The analysis reveals that green-economy variables—green-adjusted GDP (LGreenGDP), forest coverage (LForestarea), and the share of renewable energy (LReniable)—are positively correlated with environmental performance (LEPI) and negatively correlated with greenhouse gas emissions (LGreenhouse). These findings underscore that the expansion of green initiatives directly enhances environmental sustainability and contributes to the reduction of CO_2 emissions, the primary drivers of climate change.

Similarly, FinTech indicators—including digital payments (LDigitalPayment), digital currencies (LMonnaieDigitale), and P2P lending (LPPlending)—exhibit positive correlations with LEPI and LGreenGDP, alongside modest negative correlations with LGreenhouse. This pattern suggests that the adoption of digital financial technologies facilitates the financing and allocation of resources to environmentally oriented projects, thereby reinforcing the effectiveness of green policies. Additionally, governance and high-technology variables (LQGCG and Lhightech) display significant associations with both FinTech and green-economy indicators, indicating that strong institutional frameworks and technological capabilities enhance the synergy between financial innovation and environmental initiatives.

In summary, the correlation analysis reinforces the complementary role of the green economy and financial technologies in advancing the ecological transition of the United States. Green investments, coupled with the adoption of digital financial solutions, contribute to enhanced environmental performance and reduced greenhouse gas emissions, reflecting a dynamic that supports the country's sustainability and climate resilience objectives.

To capture more complex, non-proportional relationships, we further analyze dependencies using the Kendall correlation matrix. Unlike traditional linear measures, this approach uncovers subtler interactions, illustrating how the simultaneous intensification of green initiatives and the expansion of FinTech solutions can amplify reductions in greenhouse gas emissions. In the United States, these nonlinear interactions are particularly salient, highlighting the synergistic effects of green investments and financial innovation in addressing climate change. The results emphasize that environmental sustainability is influenced not only by the scale of ecological policies but also by the capacity of financial technologies to facilitate their effective implementation and tangible impact. Kendall's nonlinear correlation results for all variables are presented in Table 3 (Appendix).

The Kendall nonlinear correlation matrix (Table 3) highlights significant interdependencies among the green economy, financial technologies (FinTech), and environmental sustainability indicators in the United States. FinTech variables, including digital payments (LDigitalPayment) and digital currencies (LMonnaieDigitale), exhibit strong positive correlations with public investments in environmental innovation and renewable energy initiatives, underscoring their catalytic role in financing and implementing green projects. Likewise, public expenditure on environmental innovation is strongly associated with forest coverage and renewable energy adoption, indicating that green-economy efforts directly support the preservation and regeneration of natural resources. Conversely, greenhouse gas emissions (LGreenhouse) are negatively correlated with key FinTech and green-economy indicators—particularly LEPI, LDigitalPayment, and LReniable—suggesting that the combined implementation of green policies and financial innovations effectively mitigates the primary drivers of climate change. These findings reveal a clear synergistic effect: financial technologies facilitate capital allocation and the adoption of sustainable solutions, while green-economy initiatives ensure measurable reductions in emissions, jointly reinforcing environmental sustainability.

The Dickey–Fuller unit root tests (1979–1981) provide a fundamental diagnostic for assessing the stationarity of the time series used in this study. By identifying whether variables—such as those capturing the green economy, FinTech development, and environmental performance—contain unit roots, the tests determine whether these series follow stable patterns or exhibit persistent trends. This distinction is essential, as estimations based on non-stationary data risk producing biased or misleading inferences. Applying the Dickey–Fuller framework clarifies which variables must be differenced to achieve stationarity, thereby reinforcing the econometric validity of the analysis and the robustness of conclusions concerning the joint effects of the green economy and FinTech on environmental sustainability and greenhouse gas reduction. Table 4 reports the Dickey–Fuller results at levels and first differences for all variables examined.

Table 4: Unit Root Dicky-Fuller tests (1979-1981)						
	Lags	Model	En niveau		En différence première	
			T-Statistic	Prob	T-Statistic	Prob
LEPI	1	M1	0.3412	0.7777	-1.7952	0.0694
LGreenGDP	1	M2	0.5621	0.6354	-8.0565	0.0000
Lhightech	2	M1	1.4971	0.9638	-2.2952	0.0482
LDigitalPayment	1	M2	0.9858	0.7463	-6.6720	0.0000
LMonnaieDigitale	1	M2	0.9690	0.7522	-6.8366	0.0000
LPPlending	1	M1	0.9769	0.7327	-7.9581	0.0000
LForestarea	1	M3	-2.5000	0.3260	-5.5651	0.0004
LReniable	2	M3	-2.0870	0.5326	-4.4480	0.0006
LGreenhouse	1	M2	-1.4563	0.5424	-8.4088	0.0000
LQGCG	2	M3	-2.569	0.2958	-8.1590	0.0000

The unit root test results indicate that all variables—whether representing the green economy (Green GDP, renewable energy share, forest area) or FinTech development (digital payments, digital currencies, P2P lending)—are non-stationary in levels but become stationary after first differencing. This confirms that their behavior must be examined through their variations rather than their raw series, consistent with the inherently evolving dynamics of technological innovation and environmental change.

Indicators linked to the green economy—such as Green GDP, renewable energy use, and forest area—emerge as key drivers in reducing greenhouse gas emissions. Their stationarity in first differences indicates that their effects unfold progressively, underscoring the need for stable and long-term environmental policies to generate tangible reductions in emissions. Conversely, financial technology variables, including digital payments, digital currencies, and peer-to-peer lending, play a complementary role in this process. The shift toward a digitalized financial ecosystem indirectly supports emission reduction by limiting reliance on material resources (e.g., paper-based processes and conventional banking infrastructure) and by enhancing transactional efficiency. Moreover, the rise of these digital financial instruments fosters green project financing and broadens financial inclusion, both of which are essential for advancing the energy transition. Finally, the results for greenhouse gas emissions (LGreenhouse) confirm their sensitivity to the joint evolution of green growth and financial innovation. The significance observed in first differences suggests that emission mitigation depends on structural transformations in which the interaction between environmental policies and FinTech adoption amplifies positive outcomes. In this sense, FinTech operates as a catalyst that strengthens the effectiveness and durability of green initiatives, thereby improving the overall impact on climate mitigation in the United States.

3.2. Analysis of the long-term relationships between the green economy and financial technologies in promoting environmental sustainability

The findings indicate that all variables linked to the green economy, institutional quality, financial technologies, and environmental sustainability are integrated of order one. To avoid spurious regressions, we rely on cointegration techniques to model the logarithm of the Environmental Performance Index (LEPI) or greenhouse gas emissions (LGreenhouse) as functions of green, institutional, and technological variables. These long-run relationships are first estimated via ordinary least squares (OLS) and subsequently validated by testing whether each dependent variable is stationary in levels, using the Dickey–Fuller unit root tests (1979–1981). Table 5 summarizes the long-run estimates and the stationarity tests of the associated residuals.

Table 5: Long-term relationship estimation using OLS				
	LEPI		**LGreenhouse**	
	Coefficients	Prob	Coefficients	Prob
Constant	7,7930	0,7411	23,9762	0,0034
LGreenGDP	0,0020	0,7384	0,0005	0,7817
Lhightech	-0,0094	0,0088	-0,0012	0,2700
LDigitalPayment	3,2977	0,3168	2,1442	0,0465
LMonnaieDigitale	-0,0215	0,4022	-0,0165	0,0496
LPPlending	-0,0125	0,5948	0,0165	0,0336
LForestarea	-1,9293	0,3171	-3,0997	0,0000
LReniable	0,0151	0,2731	-0,0103	0,0236
LQGCG	0,0040	0,179	0,0021	0,0335
Residual stationarity tests				
	Lags	Model	T-Statistics	Prob
Residual LEPI	2	M1	-2.4848	0.0147
Residual LGreenhouse	1	M2	-7.6634	0.0000

Table 5 reports the long-run relationships estimated via OLS, using the Environmental Performance Index (LEPI) and greenhouse gas emissions (LGreenhouse) as dependent variables. The results reveal marked contrasts in the determinants of environmental sustainability across the two specifications. When LEPI is the dependent variable, only technological progress (Lhightech) exerts a significant—though negative—effect, suggesting that the diffusion of advanced technologies may initially intensify certain environmental pressures. In contrast, the remaining variables related to the green economy and financial technologies display no statistically significant influence on this aggregate measure of environmental performance.

In contrast, the estimation using greenhouse gas emissions (LGreenhouse) as the dependent variable reveals several significant determinants. Digital payments (LDigitalPayment) exert a mitigating effect on emissions, underscoring the capacity of financial technologies to reduce material resource use and enhance efficiency. Digital currency (LMonnaieDigitale) is likewise significant but contributes negatively, indicating that its expansion may still impose substantial energy demands through its underlying technological infrastructure. Peer-to-peer lending (LPPlending) shows a positive and significant effect, reflecting its potential to channel financing toward green projects that ultimately support emission reductions.

Traditional environmental variables reaffirm their pivotal influence. Forest area (LForestarea) significantly reduces greenhouse gas emissions, consistent with its function as a major carbon sink. Renewable energies (LReniable) also display a significant—though negative—effect, likely capturing short-term adjustment costs that precede the full realization of their environmental gains. Governance quality (LQGCG) emerges as another crucial determinant, underscoring the need for strong institutional frameworks to sustain both green and digital transitions.

Residual stationarity tests further confirm the robustness of the estimated relationships. The residuals from the LEPI and LGreenhouse equations are stationary, validating the presence of cointegration. This indicates that, despite the non-stationarity of individual series, the variables share stable long-term dynamics, demonstrating that the green economy and financial technologies jointly shape the structural trajectory of environmental sustainability in the United States.

We evaluate the linear relationships between environmental sustainability, the green economy, institutional quality, and financial technologies using an error correction model (ECM). This framework captures short-run dynamics—where all variables linked to FinTech, institutions, green development, and environmental performance are stationary in first differences—while preserving the long-run equilibrium implied by the cointegration relationships. The negative and statistically significant error-correction term confirms a stable adjustment mechanism, indicating that deviations from long-term equilibrium are gradually corrected over time.

Table 6 presents the results of the ECM model estimation.

Table 6: ECM estimation using OLS				
	ΔLEPI		**ΔLGreenhouse**	
	Coefficients	Prob	Coefficients	Prob
Constant	0,0294	0,009	-0,0016	0,7797
ΔLGreenGDP	0,0028	0,3436	-0,0003	0,8385
ΔLhightech	-0,0108	0,0029	-0,0037	0,0458
ΔLDigitalPayment	2,2726	0,2439	4,0689	0,0011
ΔLMonnaieDigitale	-0,0186	0,2007	-0,0311	0,0008
ΔLPPlending	0,0111	0,3352	0,0282	0,0002
ΔLForestarea	-1,0777	0,4612	-2,7684	0,0043
ΔLReniable	-0,0169	0,199	0,0041	0,5746
ΔLQGCG	-0,0014	0,7338	0,0023	0,3183
$Residus_{t-1}$	-0,2579	0,0657	-0,3002	0,0000

The error correction model (ECM) in Table 6 reveals the short-run adjustments and the convergence mechanism toward long-term equilibrium among environmental sustainability, the green economy, institutional quality, and financial technologies. The error-correction terms (Residust-1), negative and statistically significant in both specifications (−0.2579; −0.3002), confirm the presence of cointegration and a stable adjustment path.

Short-term effects from financial technologies display heterogeneous patterns. Digital payments exert a positive and significant effect on reducing greenhouse gas emissions, indicating that their diffusion fosters more efficient and environmentally supportive financial activity. Conversely, digital currency shows a negative and significant impact on environmental sustainability, likely reflecting the high energy requirements underlying digital transaction and validation infrastructures. Peer-to-peer lending contributes significantly to sustainability by easing access to financing for green or socially oriented projects. In contrast, high-technology development exerts a negative and significant effect, suggesting that current technological expansion is not yet aligned with ecological objectives and may still produce environmental externalities.

As far as green economy and institutional factors are concerned, the results indicate a nuanced short-term contribution. Green growth indicators (Green GDP) and renewable energy adoption do not exhibit significant immediate effects, likely reflecting the structural and long-term nature of their environmental impacts. In contrast, forest area—a proxy for environmental governance—has a significant negative effect on emissions, emphasizing the role of sustainable resource management in enhancing ecological outcomes. Overall, strong institutions and select FinTech tools, particularly digital payments and peer-to-peer lending, support environmental sustainability. Conversely, innovations such as digital currency and certain high-tech developments may exacerbate ecological pressures, highlighting the necessity of regulatory frameworks to align these technologies with green transition objectives.

3.3. Quantile Vector Auto-Regression (QVAR) Technique

This study applies the quantile connectivity approach of Ando et al. (2022) to examine the interrelations among environmental sustainability, financial technologies, institutional quality, and the green economy in the United States, using annual data from 1990 to 2024. Building on the classical VAR-based framework of Diebold and Yilmaz (2012), and its extensions such as TVP-VAR and LASSO-VAR, the QVAR method offers a distinct advantage: it captures contagion effects under extreme conditions. Unlike standard VAR models, which focus on conditional means and overlook tail dependencies, QVAR assesses dynamic connectivity across quantiles, providing a nuanced perspective on variable interactions during both extreme positive and negative phases (Long et al., 2022; Mensi et al., 2022).

The quantile spillover matrix and the infinite-order vector moving average representation of the QVAR(τ, ρ) model—where τ denotes the quantile and ρ the autoregressive order—are defined as follows:

$$y_t = \mu(\tau) + \sum_{j=1}^{p} \phi(\tau)\, y_{t-j} + \mu_i(\tau)$$

$$= \mu(\tau) + \sum_{i=0}^{\infty} \Omega_i(\tau)\mu_{t-i} \quad (1)$$

Where:

- y_t is an **n×1** vector of endogenous variables.
- $\mu(\tau)$ is an **n×1** vector of intercepts at quantile **τ**.
- **Φ_j(τ)** is an **n×n** matrix of lag coefficients at quantile **τ** for **j = 1, ..., p**.
- $\mu_i(\tau)$ is an **n×1** vector of error terms at quantile **τ**.
- $\Omega_i(\tau)$ is an **n×n** matrix of moving average lag coefficients at quantile **τ**.

The **Generalized Forecast Error Variance Decomposition (GFEVD)**, as in **Koop et al. (1996)** and **Pesaran and Shin (1998)**, defines the forecast horizon **H** as follows:

$$\Theta_{ij}^{z}(H) = \frac{\sum(\tau)_{jj}^{-1} \sum_{h=0}^{H-1}(e_i'\Omega_h(\tau)\sum(\tau)e_j)^2}{\sum_{h=0}^{H-1}(e_i'\Omega_h(\tau)\sum(\tau)\Omega_n(\tau)'e_i)} \quad (2)$$

Here, e_i denotes a zero vector, with unitary value present in the $i-th$ position. In the decomposition matrix, the normalization of elements is represented as:

$$\bar{\Theta}_{(i,j)}^{\varepsilon}(H) = \frac{\Theta_{ij}^{g}(H)}{\sum_{j-1}^{k}\Theta_{ij}^{\gamma}(H)}, \text{with} \sum_{j=1}^{k}\bar{\Theta}_{ij}^{s} \text{ and } \bar{\Theta}_{ij}^{g}(H) = 1 \quad (3)$$

Following Diebold and Yilmaz (2012), the GFEVD-based spillover measures are described below.

$$TO_{j,t} = \sum_{i=1, i\neq j}^{k} \bar{\Theta}_{i,j}^{g}(H) \quad (4)$$

$$FROM_{j,t} = \sum_{i=1, i\neq j}^{k} \bar{\Theta}_{j}^{g}(H) \quad (5)$$

$$NET_{j,t} = TO_{j,1} - FROM_{j,s} \quad (6)$$

$$TCI_t = \frac{\sum_{i,j=1,j\neq i}^{k} \tilde{\Theta}_{i,j}^{\delta}(H)}{k-1} \quad (7)$$

In this framework, $TO_{j,t}$ captures the effect of variable j on variable i, while $FROM_{j,t}$ measures the impact of i on j. $NET_{j,t}$ represents the difference between TO and FROM, with negative (positive) values indicating a net recipient (transmitter) of spillovers. TCI_t denotes the average total connectedness. This extended QVAR approach is particularly useful for examining spillover dynamics under extreme market conditions, providing a refined perspective on the interactions between financial technologies, the green economy, and environmental sustainability in the United States.

The QVAR (Quantile Vector Autoregression) method is particularly suited for examining the influence of financial technologies and the green economy on environmental sustainability. Unlike traditional linear models, it captures nonlinear and asymmetric relationships, making it valuable in contexts characterized by shocks and heightened uncertainty. By analyzing variable responses across different quantiles, QVAR offers a nuanced view of economic dynamics, revealing how external shocks may differently affect environmental outcomes depending on the cycle phase or shock intensity.

A further advantage of QVAR is its robustness to non-normal distributions and fat tails, common in stationary economic series, ensuring more reliable estimates during periods of stress in environmental policies. It also enables the simultaneous analysis of interactions among financial technologies, institutional factors, the green economy, and sustainability indicators, accounting for their interdependencies under external shocks. Overall, QVAR effectively incorporates complexity, heterogeneity, and nonlinearity, making it a particularly apt tool for assessing the impact of shocks and uncertainty on the determinants of environmental sustainability in the United States.

We assess the stability of interconnections and the effects of variables related to the green economy, institutions, financial technologies, and environmental sustainability, all measured in first differences and evaluated at the median quantile. The results at this central distributional point are reported in Table 7 (Appendix).

Table 7 reports the static spillovers among green economy, institutional, financial technology, and environmental sustainability variables, all in first differences and assessed at the median quantile. The total connectedness index (TCI) approaches 90%, indicating a high degree of interdependence. This implies that shocks to any single dimension—be it environmental sustainability, the green economy, or financial and institutional factors—are strongly transmitted across the entire system.

The results identify key variables as net transmitters or receivers of shocks. Institutional quality (QGCG) and environmental indicators (Greenhouse and EPI) function mainly as net receivers, reflecting their sensitivity to external influences. In contrast, green growth (Green GDP) and certain technological factors (high-tech) serve as net transmitters, propagating effects across the system. Notably, Green GDP, with a positive net value of 24.58, plays a central role in shock transmission. Among financial technologies, digital payments and digital currencies display strong interdependencies but are generally neutral or slight net receivers, indicating their influence is contingent on external shocks. Peer-to-peer lending, however, assumes a limited role, acting primarily as a receiver, likely due to its relatively modest impact on overall environmental dynamics. Environmental variables, such as forest area and renewable energy, show significant connectedness yet primarily act as net receivers of shocks, underscoring their sensitivity to economic and technological dynamics and their reliance on robust institutions and green economy initiatives. The greenhouse gas emissions indicator (Greenhouse) receives a notably high share of transmissions (107.10), highlighting its responsiveness to other dimensions and reinforcing its role as a key measure of environmental sustainability.

Overall, the median-quantile results show that short-term dynamics in first differences are marked by strong interdependence: green growth and select technological innovations act as diffusion drivers, while environmental sustainability and institutional variables remain largely exposed to external shocks. This underscores the need to reinforce institutional frameworks and green transition strategies to mitigate the vulnerability of environmental indicators to economic and financial pressures.

Consistent with Mensi et al. (2023), Long et al. (2022), and Yousaf et al. (2022), Figure 2 depicts the directional connectivity network among green economy, financial technology, institutional, and environmental sustainability variables, all in first differences and assessed at the median quantile. Node colors indicate net positions—blue for transmitters, yellow for receivers—while node size reflects the magnitude of connectedness. This network visualization highlights the structure of interconnections and the distribution of roles among variables in the U.S. context.

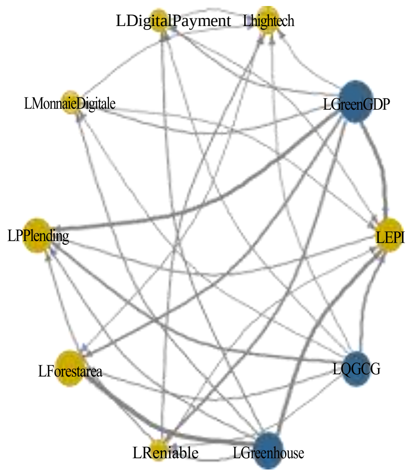


Figure 2. The directional connectivity network

Figure 2 depicts the interconnections among green economy, institutional, financial, and environmental sustainability variables in the United States, all in first differences. Green GDP (LGreenGDP), institutional quality (QGCG), and greenhouse gas emissions (LGreenhouse) emerge as key net transmitters, driving shocks that influence other variables and highlighting the centrality of green growth, institutions, and emissions in environmental dynamics. In contrast, EPI (LEPI), digital payments (LDigitalPayment), digital currency (LMonnaieDigitale), peer-to-peer lending (LPPlending), and forest area (LForestarea) primarily act as net receivers, reflecting their dependence on upstream dynamics. The dense network of links indicates strong interdependence, underscoring that economic, financial, and environmental policies are tightly interconnected and that shocks propagate rapidly across the system.

We analyze the correlation network, a graphical representation that visualizes interdependencies among variables within the system. Each variable is depicted as a node, with connecting lines indicating the presence and strength of correlations. Node color and size, along with link thickness, convey the relative role of each variable—as transmitter or receiver—and the intensity of interactions.

The graphical representation in Figure 3 enhances the interpretation of complex relationships by moving beyond tabular coefficients. It provides an intuitive view of interactions, highlighting central variables, shock transmission pathways, and interdependencies across the green economy, financial technologies, governance, and environmental sustainability. This visual approach is especially useful for understanding systemic structures and informing strategic or policy decisions.

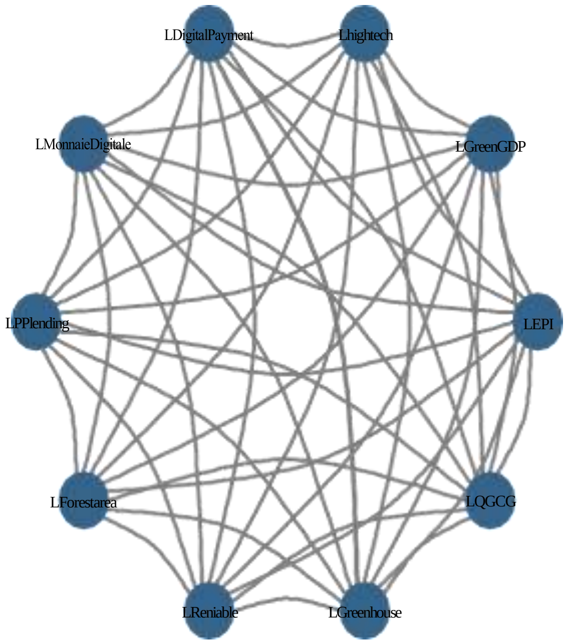


Figure 3: The correlation network between the studied variables

Figure 3 depicts a dense correlation network linking the green economy, financial technologies (FinTech), and environmental and institutional indicators. The circular layout underscores the interconnectedness of all variables, highlighting the complexity and mutual dependence of their relationships. Each node's multiple connections indicate that changes in any dimension—digital finance, technological innovation, governance, or ecological sustainability—propagate throughout the system.

Analytically, this configuration underscores the integrative role of financial technologies (digital payments, digital currencies, and P2P lending) and governance in shaping environmental sustainability. These factors act as catalysts linking the green economy (Green GDP), ecological performance (LEPI), and environmental indicators such as renewable energy, greenhouse gas emissions, and forest cover. The figure confirms that sustainability is inherently systemic, arising from the intertwined dynamics of finance, technology, institutions, and environmental policies. Consequently, public policies and development strategies must adopt a holistic approach, addressing these dimensions simultaneously.

The heatmap visually represents the intensity of relationships among variables using a color gradient, where darker shades indicate stronger effects and lighter shades reflect weaker interactions. In this study, examining environmental sustainability alongside financial technologies, the green economy, and institutions, the heatmap highlights key areas of influence. It reveals, for instance, the strong impact of FinTech adoption, Green GDP evolution, and institutional quality on environmental indicators such as greenhouse gas emissions and resource use. By providing a synthetic and intuitive overview of complex interactions, the heatmap facilitates the identification of dominant dynamics and priority areas for policy intervention. Figure 4 displays the heatmap for all variables in first differences.

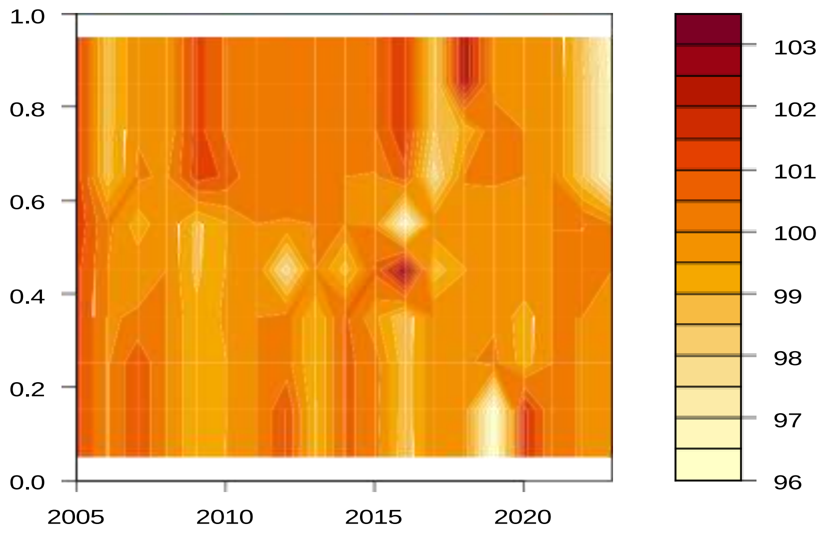
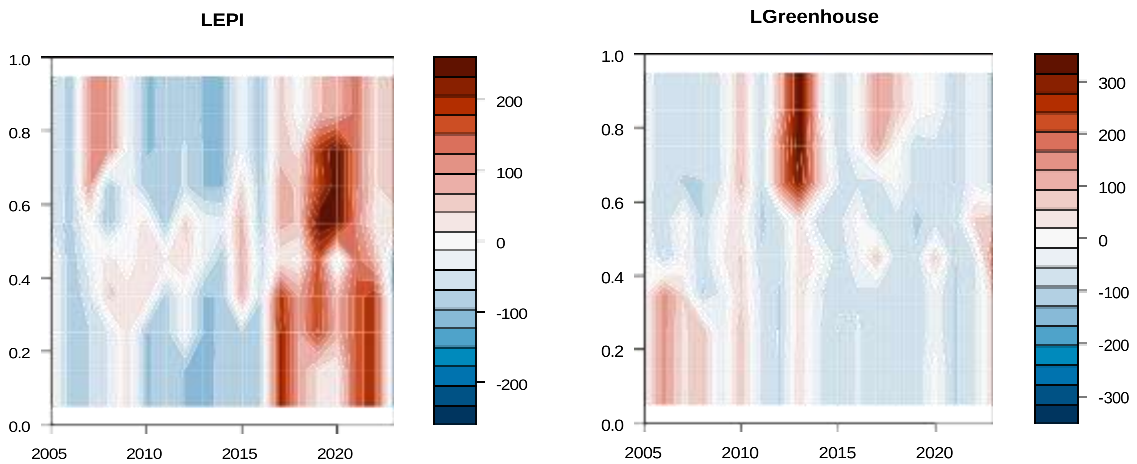
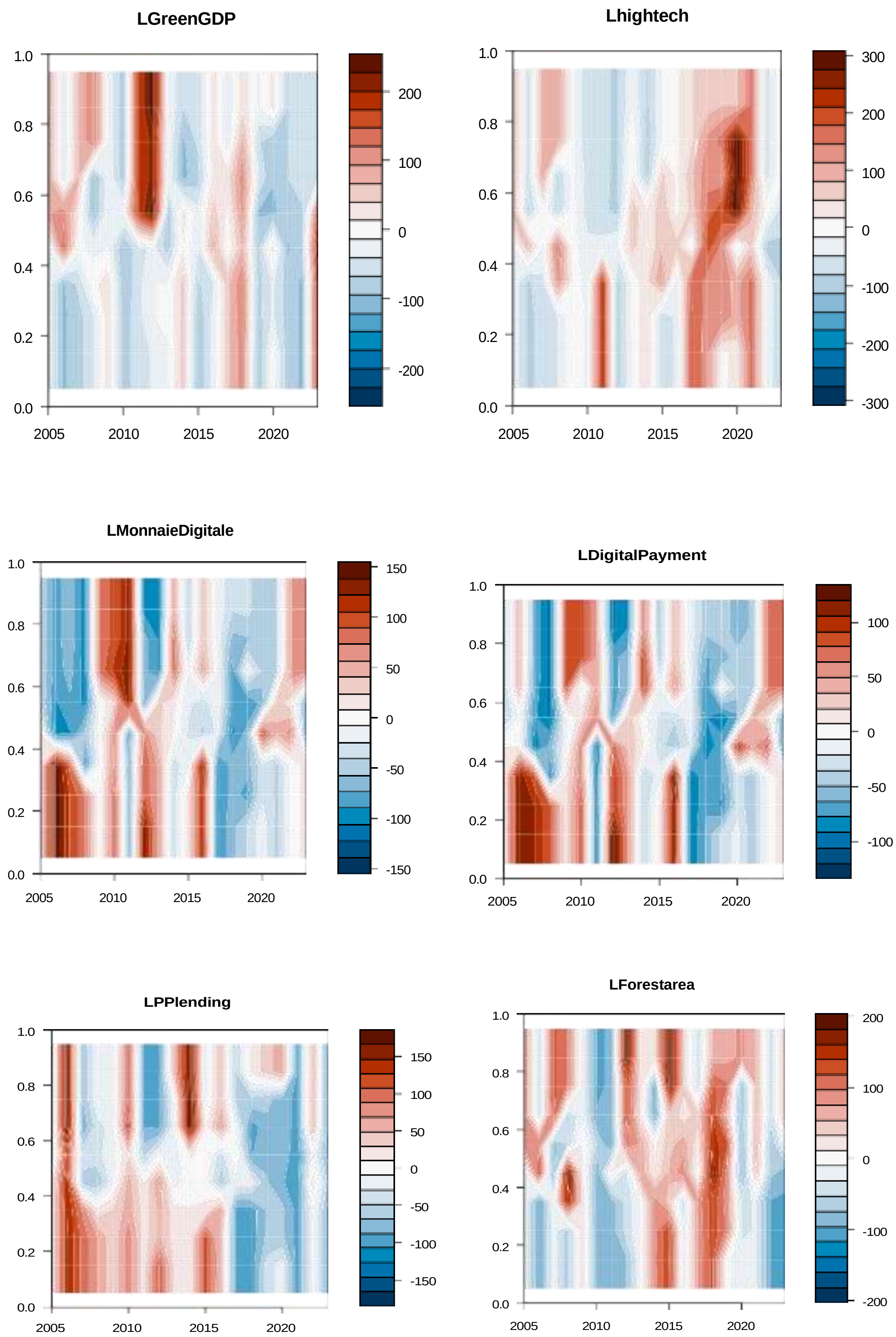


Figure 4: The heatmap of these different variables

Figure 4 presents the heatmap of interconnections among environmental sustainability, financial technologies, the green economy, and institutions in the United States over the study period. Darker areas indicate stronger interactions, reflecting periods of mutual reinforcement, while lighter areas correspond to weaker or more independent relationships. These interdependencies fluctuate over time, peaking during exogenous shocks—such as economic crises, geopolitical events, or technological shifts—and easing during calmer periods. The heatmap underscores that environmental sustainability is closely linked to the intensity of interactions with FinTech, green growth, and governance, with these relationships becoming particularly pronounced during phases of structural transition or heightened economic turbulence.

Figure 5 depicts the dynamic heatmap of first-differenced variables, capturing interactions among environmental sustainability, financial technologies, institutional factors, and green economy components. This visualization highlights the intensity of connectivity and cross-variable relationships, allowing the identification of shock transmission channels, the assessment of interdependency strength, and the understanding of how these dimensions collectively support the transition toward a sustainable development model.




LGreenGDP
Lhightech
LMonnaieDigitale
LDigitalPayment
LPPlending
LForestarea
2005
2010
2015
2020

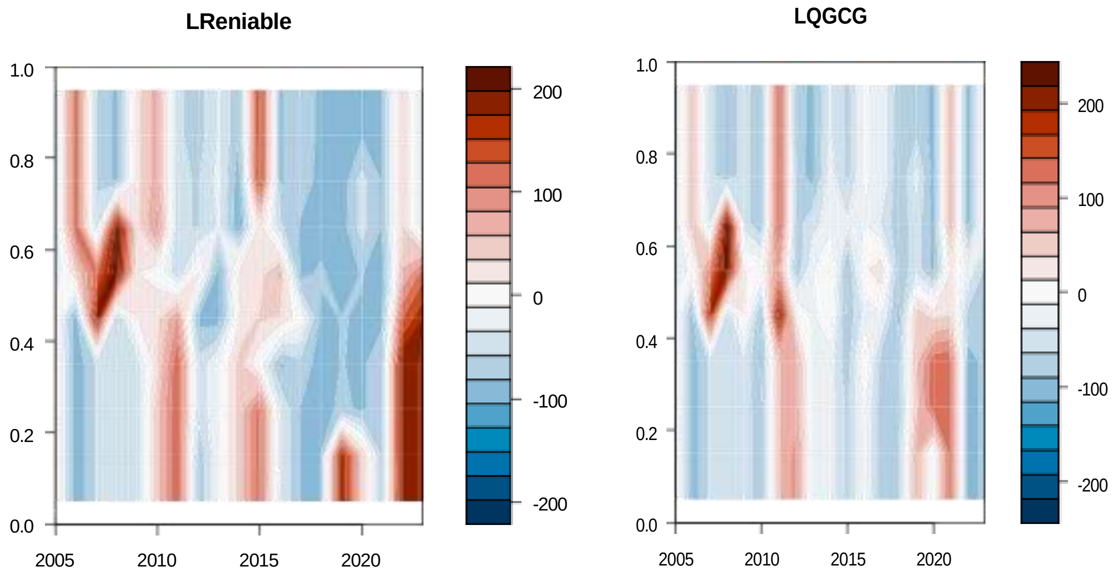


Figure 5: The heatmap of each variable

Heatmaps provide a critical tool for tracing shock transmission within the economic-environmental system, illustrating how disruptions in one domain—such as financial technologies or the green economy—propagate to others and influence overall sustainability. Detailed analysis indicates that FinTech drives innovation by improving access to green financing and enhancing transparency in financial flows. Yet, its impact is heterogeneous: without proper regulation, financial innovations can amplify volatility and transmit shocks across sectors. Accordingly, FinTech emerges as a key channel for the diffusion of financial disturbances, underscoring the vital role of institutions in mitigating risks and directing capital toward sustainable initiatives.

The green economy functions as a key stabilizer. Indicators such as Green GDP and renewable energy show a notable ability to absorb environmental shocks, particularly by mitigating greenhouse gas emissions. The heatmap reveals that while the green economy primarily receives short-term shocks, it enhances systemic resilience over the medium and long term, highlighting strong interdependencies between economic and environmental dimensions. Transmission channels further indicate that green investments directly improve environmental performance and indirectly bolster the effectiveness of financial innovations.

The institutional dimension is central in shaping system interactions. Strong governance and effective controls curb the spread of negative shocks from financial innovations while enhancing the benefits of green investments. High institutional quality stabilizes variable connectivity, underscoring the importance of a solid framework for a sustainable transition. Environmental indicators, including greenhouse gas emissions and forest cover, remain highly sensitive to economic and financial disruptions, emphasizing that sustainability is intertwined with technological and institutional choices. Heatmaps visualize shock propagation and measure interdependency intensity, highlighting that the transition to sustainable development depends on a balance: FinTech and the green economy act as strategic levers, whose effectiveness hinges on robust institutions that direct financial flows toward sustainable projects and maintain system resilience.

3. Conclusion

This study examines the combined effects of the green economy, FinTech, and governance on environmental sustainability in the United States from 1990 to 2024. Using an integrated framework of descriptive statistics, cointegration analysis, error correction models, QVAR, and heatmaps, it provides robust evidence of how these dimensions jointly shape ecological outcomes. The results demonstrate that the ecological transition arises not from isolated factors but from the interplay of technological, financial, and institutional dynamics.

The findings underscore the pivotal role of the green economy in promoting sustainability. Indicators such as green-adjusted GDP, renewable energy use, and forest area act as key levers for reducing greenhouse gas emissions. By internalizing environmental costs, green investments redirect economic growth toward sustainable pathways, while renewable energy and forest cover both lower emissions and enhance ecological resilience. These effects develop gradually, highlighting the need for consistent, long-term environmental policies. Consequently, the green economy functions not only as a corrective mechanism against ecological degradation but also as a central stabilizer supporting system resilience over time.

FinTech emerges as a complementary yet critical driver of sustainability. Digital payments and peer-to-peer lending facilitate funding for environmentally friendly projects, enhance financial inclusion, and improve capital allocation toward green initiatives. By reducing transaction costs, expanding credit access, and fostering innovation in sustainable finance, these technologies contribute directly to lowering greenhouse gas emissions, notably by replacing resource-intensive financial infrastructures and accelerating green investment flows. However, not all innovations are unambiguously beneficial. Digital currencies, for instance, can undermine environmental objectives due to their high energy demands, highlighting the need for regulation and the development of low-impact digital financial infrastructures to ensure that FinTech supports rather than hinders ecological goals.

Governance emerges as a critical cross-cutting factor. Strong, transparent institutions mitigate financial volatility and speculative risks while enhancing the effectiveness of FinTech and green economy initiatives in achieving ecological outcomes. High-quality governance supports emission reductions by ensuring efficient resource allocation, preventing mismanagement, and fostering trust in both green and digital transitions. Conversely, weak governance or corruption can undermine these synergies, increasing environmental vulnerabilities. Thus, institutional strength is a necessary condition for aligning technological and financial innovations with sustainable development goals.

The study further underscores the strong interconnections among the analyzed variables. QVAR and heatmap analyses reveal that shocks in one domain—environmental, financial, or institutional—rapidly propagate to others. Environmental indicators, including greenhouse gas emissions and the Environmental Performance Index, emerge as net receivers, reflecting high sensitivity to external dynamics. Conversely, green GDP and certain technological factors act as transmitters, spreading effects throughout the system. This configuration highlights both the potential and the risks of interdependence: it enables synergy between green policies and financial innovation but also exposes environmental sustainability to economic or technological shocks. These systemic interactions indicate that achieving sustainability requires integrated, rather than fragmented, strategies.

Despite its contributions, this study has several limitations. The use of annual data may obscure short-term fluctuations or intra-year shocks that could provide additional insights. Its empirical focus on the United States limits the generalizability to countries with different institutional frameworks, technological adoption levels, or environmental priorities. Proxy variables for FinTech and governance capture key aspects but inevitably simplify these complex phenomena. Additionally, while QVAR captures nonlinearities and asymmetries, its emphasis on the median quantile leaves room for complementary approaches to assess extreme scenarios, such as financial crises or ecological tipping points.

Future research could proceed along several avenues. Comparative studies across countries would clarify how institutional differences shape the effectiveness of the green economy and FinTech in promoting sustainability. Higher-frequency data—quarterly or monthly—would better capture short-term dynamics and strengthen econometric analyses. Integrating big data and machine learning could enhance understanding of nonlinear dependencies and improve predictive accuracy. Further investigation into the environmental costs and benefits of specific financial technologies, especially cryptocurrencies, is needed to align digital innovation with climate goals. Finally, interdisciplinary approaches combining economics, environmental science, and information systems would offer a more comprehensive perspective on these complex interactions.

From a policy standpoint, the results underscore the need for integrated and proactive strategies. Strengthening institutional quality is essential to stabilize financial flows and channel them toward sustainable projects, with transparency, anti-corruption measures, and regulatory oversight forming the foundation. Public incentives—subsidies, tax benefits, and targeted regulations—should promote green investments while leveraging digital platforms to broaden their impact. Regulators must also mitigate the environmental costs of energy-intensive financial technologies by encouraging low-carbon alternatives, such as greener blockchain protocols. Finally, policy design should be holistic, integrating environmental objectives, financial innovation, and institutional reforms to reinforce resilience and reduce systemic risks highlighted by the interdependence analyses.

In conclusion, this study shows that the ecological transition in the United States relies on the interdependent synergy of green economy strategies, financial technologies, and institutional governance. Each dimension plays a key role, yet their full effectiveness emerges from their interaction: FinTech accelerates the financing and diffusion of green initiatives, the green economy stabilizes environmental progress, and governance ensures coherence, accountability, and resilience. Together, they underpin a sustainable development framework capable of addressing climate challenges. Leveraging this synergy allows policymakers, businesses, and civil society to collectively guide the economy toward a low-carbon, inclusive, and sustainable future.

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Table 3. Kendall's Nonlinear Correlation										
kendall	LEPI	LGreenGDP	Lhightech	LDigitalPayment	LMonnaieDigitale	LPPlending	LForestarea	LReniable	LGreenhouse	LQGCG
LEPI	1.000***	-0.052	0.391***	0.718***	0.718***	-0.214	0.546***	0.814***	-0.577***	0.851***
LGreenGDP	-0.052	1.000***	-0.048	-0.149	-0.149	0.129	-0.039	-0.099	0.177	-0.121
Lhightech	0.391***	-0.048	1.000***	0.335***	0.335***	-0.315**	0.130	0.347***	-0.226	0.435***
LDigitalPayment	0.718***	-0.149	0.335***	1.000***	1.000***	-0.093	0.509***	0.790***	-0.544***	0.786***
LMonnaieDigitale	0.718***	-0.149	0.335***	1.000***	1.000***	-0.093	0.509***	0.790***	-0.544***	0.786***
LPPlending	-0.214	0.129	-0.315**	-0.093	-0.093	1.000***	-0.295**	-0.213	0.379***	-0.266**
LForestarea	0.546***	-0.039	0.130	0.509***	0.509***	-0.295**	1.000***	0.535***	-0.670***	0.608***
LReniable	0.814***	-0.099	0.347***	0.790***	0.790***	-0.213	0.535***	1.000***	-0.611***	0.916***
LGreenhouse	-0.577***	0.177	-0.226	-0.544***	-0.544***	0.379***	-0.670***	-0.611***	1.000***	-0.661***
LQGCG	0.851***	-0.121	0.435***	0.786***	0.786***	-0.266**	0.608***	0.916***	-0.661***	1.000***

(***): Significance at the 1% risk level; (**): Significance at the 5% risk level and (*): Significance at the 10% risk level

Table 7. Static return spillovers at median (Q = 0.50)											
	LEPI	LGreenGDP	Lhightech	LDigitalPayment	LMonnaieDigitale	LPPlending	LForestarea	LReniable	LGreenhouse	LQGCG	FROM
LEPI	6.78	12.73	9.09	10.95	11.11	7.30	8.14	9.30	12.40	12.20	93.22
LGreenGDP	7.84	13.58	10.19	9.53	9.61	7.90	8.53	9.51	12.58	10.74	86.42
Lhightech	8.70	12.14	9.43	10.43	10.50	8.49	7.64	10.32	11.09	11.27	90.57
LDigitalPayment	9.38	12.04	8.84	8.82	8.99	9.19	9.06	9.83	12.38	11.47	91.18
LMonnaieDigitale	9.41	12.01	8.84	8.81	8.96	9.23	9.09	9.84	12.39	11.42	91.04
LPPlending	9.69	12.20	8.75	10.34	10.43	9.15	7.28	10.14	10.43	11.61	90.85
LForestarea	9.03	11.72	9.22	9.82	9.73	7.74	9.33	9.47	12.69	11.27	90.67
LReniable	7.41	13.50	8.03	9.51	9.79	8.06	8.35	11.73	11.86	11.76	88.27
LGreenhouse	7.86	12.82	9.89	10.34	10.22	8.25	7.60	9.43	11.40	12.19	88.60
LQGCG	8.72	11.84	9.79	9.94	9.91	8.30	8.39	10.19	11.28	11.63	88.37
TO	78.04	111.01	82.63	89.66	90.28	74.45	74.08	88.03	107.10	103.92	899.19
Inc.Own	84.82	124.58	92.06	98.48	99.25	83.60	83.41	99.76	118.49	115.54	cTCI/TCI
NET	-15.18	24.58	-7.94	-1.52	-0.75	-16.40	-16.59	-0.24	18.49	15.54	99.91/89.92

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