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Article

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International Journal of Energy Economics and Policy

Provided in Cooperation with:
International Journal of Energy Economics and Policy (IJEEP)

Reference: Hong-Nham Nguyen Thi/Le Thanh Ha (2024). An integration of environmental innovation and digitalization in promoting TFP of the agriculture sector in Vietnam. In: International Journal of Energy Economics and Policy 14 (6), S. 457 - 469.
https://www.econjournals.com/index.php/ijeep/article/download/17063/8334/40043.
doi:10.32479/ijeep.17063.

This Version is available at:
http://hdl.handle.net/11159/703045

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2024, 14(6), 457-469.

An Integration of Environmental Innovation and Digitalization in Promoting TFP of the Agriculture Sector in Vietnam

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Received: 26 June 2024 **Accepted:** 02 October 2024 **DOI:** https://doi.org/10.32479/ijeep.17063

ABSTRACT

The growing interplay between environmental innovation, digitalization, and total factor productivity (TFP) in agriculture highlights an urgent need to understand their complex relationships. This study utilizes the R^2 decomposed linkage method to examine contemporaneous and lagged linkages among environmental innovation, digitalization, and TFP in Vietnam's agricultural sector from 1994 to 2022. Our findings indicate that digitalization had a weak control on environmental innovation from 2010 to 2015 and in 2022, with a reversal observed during the 2008-2010 period and, more notably, from 2018 onward. Digitalization also dominated agriculture before 2008 and from 2019 to 2020, with significant effects from 2010 to 2016. Environmental innovation primarily influenced TFP from 2014 to the end of the period, with both contemporaneous and lagged effects. Since 2017, digitalization has increasingly driven environmental innovation, exemplified by advancements in precision agriculture and environmental monitoring technologies. These innovations have notably enhanced agricultural TFP, improving efficiency and productivity through digital tools and data analytics. Overall, these results highlight the critical role of digital technologies in advancing agricultural productivity and environmental sustainability, suggesting that continued investment in digitalization is essential for fostering growth and innovation in the sector.

Keywords: Sustainable Agriculture, The R^2 Decomposed Linkage Method, Agriculture Sector, European Countries, Digitalization
JEL Classifications: G21, F21

1. INTRODUCTION

Weather patterns and growing conditions vary significantly in agricultural areas over time. However, the way critical inputs like nitrogen and irrigation water are currently applied frequently needs to pay more attention to this geographical heterogeneity, which results in both over- and under-application of these inputs in different fields. The environment is harmed, and crop productivity is jeopardized. For cost-effectiveness, fertilizer is sprayed in the fall after harvest, causing nitrogen run-off before crops might use it in the spring. Similarly, herbicides are frequently sprayed before plant emergence or canopy closure, with no attention to the precise timing and place of weed emergence. As a result, there are now more weeds resistant to glyphosate and less diverse weeds overall. Site-specific crop management has been impeded by inadequate technology, labor availability, and little comprehension of spatial input heterogeneity.

The idea of digitalization is expressed in the agricultural industry by what is frequently referred to as "smart farming" or "digital agriculture." (Finger, 2023). Using different digital technologies across the farming and agri-food industries is known as "digital agriculture." These technologies are diverse and include things like sensors, robots, blockchain technology, digital communication tools, analytical decision-making tools, and cloud-based services. Digital technology such as sensors, robots, and digital communication tools are increasingly used in agricultural methods like hydroponic, indoor, vertical, and greenhouse farming(Khanna et al., 2022). More sophisticated methods blend digital, mobile, IoT, and cognitive technology. Precision agriculture, for example, uses various equipment, including robotics, drones, autonomous vehicles, sensors, control systems, guidance systems with GPS capability, and variable rate technology. With the aid of these instruments, farmers can accurately control the planting, fertilization, irrigation, and pesticide application processes, among other aspects of crop production. Precision agricultural livestock farming techniques include robotic or automated systems for milking and feeding, RFID technology, and sensors. In addition, accessible data is analyzed using artificial intelligence (AI) and predictive analytics software to advise farmers on soil management techniques, crop rotation, and the best times to sow and harvest (Finger, 2023; Khanna et al., 2022).

In the horticulture value chain, lowering food loss and raising energy efficiency are critical areas where technological innovations are vital. Stakeholders may tackle difficulties related to climate adaptation and mitigation by minimizing waste at different stages of the supply chain through the integration of software-driven approaches. In the postharvest supply chain, for example, wireless sensors and Internet of Things (IoT) devices can allow for real-time monitoring of crops throughout storage and transportation, enabling prompt interventions to prevent spoilage or loss. Furthermore, food producers can optimize the efficiency of processes in postharvest activities such as fermentation, drying, cooling, extraction, packing, and smart materials and mobile apps powered by artificial intelligence (AI) to cut down on waste and energy consumption. Basically, software and digital solutions are the engines that drive sustainable practices. They minimize environmental harm, increase energy efficiency, and cut down on food loss across the agricultural value chain.

The primary topic of this study is the role that digitalization plays in advancing the sustainability of the agriculture industry. Digitalization, in our opinion, is essential to raising the efficiency, employment, export potential, and environmental sustainability of the farm industry. A number of earlier studies have demonstrated the significance of digitalization in increasing productivity (Gal et al., 2019; OECD, 2022). In terms of employment, several recent studies have shown that new technologies typically result in the creation of new jobs. In particular, the impacts of job creation outweigh the consequences of displacement, leading to an increase in net employment (Degryse, 2016; Cirillo et al., 2021). Significantly, although robots have taken the place of workers and some employment, they have also lowered production costs and raised productivity (Abiri et al., 2023; Batisheva et al., 2018; Bocean, 2024). Digital technologies are playing an increasingly important role in the adoption of cutting-edge agricultural practices (Batisheva et al., 2018). The use of digital technologies includes efforts aimed at improving resource allocation efficiency, promoting innovations in agricultural production, and enhancing agricultural productivity (Benyam et al., 2021; Zou et al., 2024). There has been a dramatic change in the global landscape of agricultural practices and management as a result of digital technologies (Bocean, 2024). With the integration of sensors, Big Data, and artificial intelligence in agriculture, farmers have been able to optimize production, reduce expenses, and increase yields (Bolfe et al., 2020; Meinke, 2019). In addition, digital technology has opened up new possibilities for precision agriculture, where every aspect of the production process is finely calibrated to enhance efficiency and reduce environmental impact (Bolfe et al., 2020; Finger, 2023). Using satellite photos and mobile sensing platforms, the agriculture sector identifies problems and enhances agricultural productivity by maximizing the use of available resources. By developing smart and digital agriculture, soil, water supplies, and weather fluctuations on croplands can be detected, assessed, and controlled simultaneously by utilizing robotics, wireless systems, mobile applications, and Internet of Things-based automation to increase field efficiency and minimize expenses (Finger, 2023). Wireless sensors and Internet of Things devices have been used in the field of automation to deploy smart irrigation systems, to control water loss, and to continuously identify soil nutrient levels in remote areas (Sparrow and Howard, 2021).

There are gaps in the literature since not many academics have looked into various aspects of sustainability. First, rather than offering a thorough examination of the consequences of digitalization on all facets, earlier studies only addressed one component of sustainability. Secondly, there hasn't been much research done in the literature on the connection between digitization and agriculture's sustainability. Innovation is stimulated by investments in information and communication technologies (ICTs), especially cloud computing, as stated by the OECD Digital Economy Outlook 2020. Additionally, there have been conflicting results regarding how digitization has affected environmental problems (Ezrachi and Stucke, 2020). Digitalization can facilitate the introduction of both incremental and radical items and procedures, as well as the formation of new and developing ecosystems, according to Ezrachi and Stucke (2020). It can also increase dynamic efficiency.

Our paper adds to the current literature. First, we examine the link between environmental innovation, digitalization, and TFP in Vietnam using the R^2 decomposed linkage method. Second, we provide portfolio techniques that integrate dynamic elements, as well as a portfolio with distinctive minimal connectivity. These strategies show how the green cryptocurrency market's volatility is impacted by energy uncertainty. Finally, we look at how energy uncertainty in the green cryptocurrency market.

Below is a synopsis of the remaining portion of the article. Section 2 contains our evaluation of pertinent literature, and Section 3 explains the model, data, and estimation procedure. In Section 4, we present our empirical findings, and in Section 5, we wrap up the article.

2. LITERATURE REVIEW: DIGITALIZATION OF THE AGRICULTURAL INDUSTRY

The rapidly expanding quantity and scope of digital technology usage propelled the agri-food industry's and agricultural production's digital transition (Amiri-Zarandi et al., 2022; Iaksch et al., 2021; MacPherson et al., 2022; Wolfert et al., 2017). According to Wolfert et al. (2017), these technologies can be widely used in various farming production domains, from animal farming and arable systems to horticulture and greenhouse management. 'Smart farming' is the term used to describe this integration of digital technology, intelligent sensors, and apps that often operate in real-time (Dhanaraju et al., 2022; Javaid et al., 2019; Walter et al., 2017). We try to provide a broad overview of upcoming and currently utilized digital technology. In order to accomplish this, we recommend a structure that combines five essential aspects of digital technologies: (i) technologies related to georeferencing and location; (ii) diagnostic and application tools; (iv) automated and autonomous procedures in farming systems and machinery; and (v) networks, data, and interaction.

International navigation satellite networks and spatial data networks are two examples of georeferencing and location-based technology widely used in the agricultural industry and play critical roles in many digital breakthroughs and applications (Gopal and Chintala, 2020; Weersink et al., 2018). These technologies enable highly localized operations like input application and harvesting, making using direction systems and controlled traffic farming easier. As a result, they prevent unnecessary input applications and save gasoline, which permits decreases in both private expenses and environmental externalities (Etana et al., 2020; Gasso et al., 2013; Macák et al., 2023). They also make it possible to carry out pre-planned strategies precisely, like seeding maps, and to thoroughly record every stage of the manufacturing process, including what was done, exactly how, where, and when (Ehlers et al., 2021, 2022; Kukk et al., 2022). Animal production systems are also increasingly using georeferencing technologies to help track the location and movement of animals inside and outside (Chapa et al., 2021; Dayoub et al., 2024; D'Urso et al., 2023; Džermeikaitė et al., 2023; Hindermann et al., 2020; Mishra, 2023; Zhang et al., 2021).

The increasing growth and advancement of digital diagnostic technologies have made it easier to collect data and build monitoring systems at different spatial and temporal scales. These sensors include drones, satellite imaging, handheld gadgets, and tractor-mounted sensors. As such, data collected using these instruments can encompass anything from single leaves, plants, and field segments to whole landscapes (Messina and Modica, 2022; Mulla, 2013). Numerous production-relevant data points, such as crop biomass, soil moisture, nitrogen levels, vegetation state, and weed presence, are available through diagnostic tools (Anderegg et al., 2023). As they allow for the real-time tracking of animal health, welfare, and production indicators via sensors and devices, they are equally crucial in animal production systems (Lovarelli et al., 2020; Dos Reis et al., 2021). Digital technology is revolutionizing agriculture performance evaluation. Harvesters with sensors are one type of yield monitor that allows for highly localized performance assessment regarding harvest amount and quality (Li and Zhang, 2023; Redhu et al., 2022). Moreover, real-time and high-resolution yield estimation is becoming increasingly possible with remote sensing techniques, even in historically proven complex systems, such as regularly grazed or mowed grasslands (Eltazarov et al., 2023; Hou and Pu, 2024; Vroege et al., 2021). Robots that milk cattle make it possible to record animal-specific performance data in livestock production (Martin et al., 2022). In general, farms are building up large and varied datasets that can be connected to other data sources, including weather, insect activity, and environmental factors, internally and externally (Dubuis et al., 2019; Zachmann et al., 2023).

Applicative technologies are essential to this integration because they allow for increasingly automatic and real-time modifications to decisions based on gathered data (Wolfert et al., 2017). For instance, in precision agriculture, the time and allocation of fertilizer or pesticide application in an area are directed by information from several sources, such as sensors tracking the health of the vegetation and yield monitors estimating possible yields. Similarly, precision livestock farming makes individual-level feeding and veterinary measure adjustments possible, making it easier to take preventative measures against new problems (Berckmans, 2017; Papakonstantinou et al., 2024). Precision farming frequently depends on new technology for input implementation, which means expensive expenditures in equipment such as variable-rate pesticide sprayers, seeders, and fertilizer spreaders. However, conventional equipment can also be modified to convert digital data into modified management choices. For example, they design more expansive "management zones" inside a field where irrigation, fertilizer, pesticide, and seed intensities can be tailored (Finger, 2023). The efficiency of data-intensive applications is improved by the development of Big Data technologies and cloud-based, high-performance computing (Lokers et al., 2016). Moreover, integrating diverse sensors and data sources for efficient decision-making increasingly depends on artificial intelligence (Galaz et al., 2021).

Accordingly, digital technology helps make the shift to machinery, farming methods, and automated and autonomous operations easier (FAO, 2022). This includes using robots and more self-governing gadgets, weed detection and control in fields and feeding systems, and fully automated input applications (Mogili and Deepak, 2018; Wadod and Mohammed, 2023). The adoption of completely autonomous operations and robots remains restricted by regulatory barriers despite their technical and financial feasibility for specific production systems (Lowenberg-DeBoer et al., 2022). However, it is expected that autonomous systems, equipment, and robots will be crucial in the future, carrying out various tasks in areas such as barns, greenhouses, and vertical agriculture without direct human decision-making. An example of an automated machine that can grow, manage, and harvest crops autonomously is the "Hands-Free Hectare" project in the UK (Lowenberg-DeBoer et al., 2022; Maritan et al., 2023; Rose and Bhattacharya, 2023). Technologies that operate independently are becoming more and more critical in livestock production, especially in dairy and indoor systems for pigs and poultry, where human decision-making and manual labor are replaced wholly or partially, turning farms into "cyber-physical administration systems" (Liu et al., 2023; Majumdar et al., 2023; Tang et al., 2021; van Hilten and Wolfert, 2022). According to Asseng and Asche (2019), there are even instances of whole "farms without farmers."

In the agricultural industry, digital tools can transform networks, knowledge, and communication altogether (van Hilten and Wolfert, 2022). In addition to improving and automating processes, the combination of intelligent sensors creates new linkages between machines, operations, and people, which improves information sharing. There is currently a rising focus on highly interconnected intelligent agricultural systems, whereas previous digital advances mainly concentrated on separate applications at the farm level (Wolfert et al., 2017). Machines, sensors, and monitoring devices are becoming more networked through data exchange, computing, and Internet of Things technologies (Galaz et al., 2021). Additionally, a prominent trend that is becoming more and more prevalent is the usage of digital twins to represent machinery, procedures, fields, animals, entire farms, and manufacturing chains(Alves et al., 2019; Peladarinos et al., 2023; Purcell and Neubauer, 2023; Verdouw et al., 2021). Agronomic knowledge structures, guidance, extension services, food value chain choices, governance structures, and even global trade are all impacted by the fast-changing nature of digitalization in the agricultural industry(Klerkx and Rose, 2020; Rose and Bhattacharya, 2023). Digital networks connecting farmers, processors, users, legislators, and upstream sectors are still in their infancy. It is anticipated that the growing use and interconnectivity of sensors would improve agricultural production methods' transparency by enabling real-time tracking of every stage of the process, from seeding to the finished product on the shelf. In order to integrate diagnostic and application tools in real-time at a low cost and with automation and autonomy, many digital breakthroughs are based on novel network technologies like blockchain and next-generation communications technologies like 5G or 6G (van Hilten and Wolfert, 2022). Furthermore, by doing away with the requirement for on-site processing capacity, these advancements allow remote data analysis and server processing by utilizing cloud storage and analytics, which may lower costs and improve the resilience of digital devices and technologies (van Hilten and Wolfert, 2022).

Farming systems could become much more efficient due to digital developments. To minimize gasoline and material costs without compromising production levels, direction systems and controlled traffic farms, for example, make it easier to avoid redundant activities (e.g., Gasso et al., 2013). Furthermore, a more focused application of inputs like pesticides and fertilizers is made possible by variable rate technology, including applicative precision farming instruments, which lowers both external environmental costs and private variable costs (Finger et al., 2019). Similarly, precision livestock farming can maintain output while improving environmental and animal welfare results through modified feeding and veterinary procedures (Berckmans, 2014). Additionally, digitalization allows farmers to replace ecologically damaging activities with less destructive ones. For example, instead of employing herbicides, they can use mechanical weeding robots or eliminate dangerous fields or stable employment. Digital innovations can positively impact the environment, animal welfare, economy, and society by promoting efficiency and substitution and reducing hazardous working conditions.

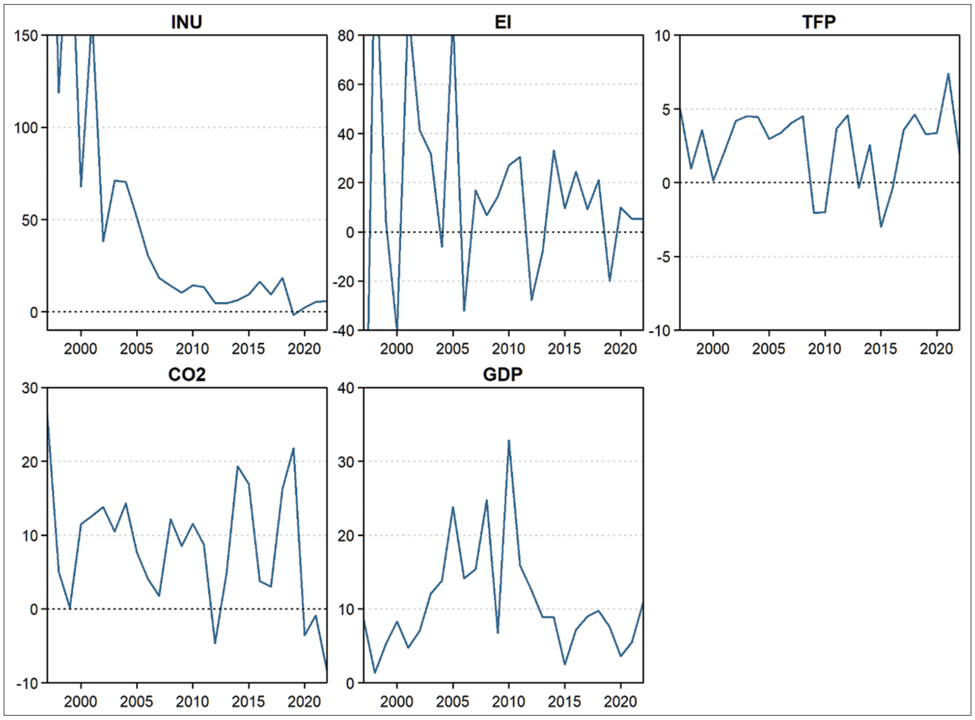
3. STATISTICAL ANALYSIS AND METHODOLOGY

3.1. Statistical Analysis

Our paper uses yearly time series data to explore environmental innovation in Vietnam, covering technological advancements. It delves into innovation in environment-related technology (EI), Individuals using the Internet (% of the population) (INU), Index of Agricultural Total Factor Productivity (TFP in agriculture), CO_2 emissions (CO_2), gross domestic product (GDP), and from 1994 to 2022.

Figure 1 illustrates the returns of our indicators. Notably, the growth rate of digitalization declined significantly from the beginning of the period until 2022, with a slight increase towards the end of the period. Before 2000, Vietnam witnessed the initial stages of digital transformation, primarily through the establishment of basic telecommunications infrastructure and the introduction of internet services (ITU, 2002). The government's recognition of the importance of information technology (IT) was reflected in policies promoting IT development (Chu, 2000). By 2002, Vietnam's digital landscape had evolved with the expansion of internet access and the proliferation of mobile phone usage, marking a significant peak in digital growth (WB, 2003). By 2010, Vietnam had further advanced its digital capabilities, driven by significant investments in IT infrastructure and the rise of the digital economy, resulting in yet another peak in the growth rates of digitalization (Vietnam Ministry of Information and Communications, 2011). Between 2016 and 2018, Vietnam experienced another surge in digitalization, propelled by the widespread adoption of smartphones, the growth of e-commerce, and the implementation of the National Program for IT Application in State Agencies. This period marked substantial progress in integrating digital technologies into everyday life and governance (ASEAN Main Portal, 2019). Following 2020, the COVID-19 pandemic accelerated digital transformation across all sectors, as remote work, online education, and digital services became more prevalent. This period saw Vietnam achieving new heights in digital growth rates, reflecting a resilient and adaptive digital economy (OECD, 2021). This trend highlights the robust penetration of digitalization within the country. Environmental innovation surged in the early years but experienced a sharp decline around 1995, followed by rapid growth. This trend persisted until 2005, when the fluctuations diminished, leading to a slight positive trend towards the end of the period. It can be attributed to attributed to the economic restructuring and challenges Vietnam faced during the early stages of its "Doi Moi" economic reforms. The subsequent rapid growth might be linked to increased governmental and international support for sustainable development initiatives (Baum, 2020). Conversely, TFP in Vietnam's agricultural sector experienced consistent positive growth rates throughout the examined period, with the exceptions of 2010 and 2015. During these years, the sector encountered significant challenges, such as unfavorable weather conditions, pest infestations, and disease outbreaks, which adversely affected productivity (Ho, 2012). These adversities led to a stagnation in productivity improvements, as evidenced by the TFP growth rate falling to zero. The year 2010 was marked by severe weather events, including prolonged droughts and unexpected floods, which disrupted farming activities and damaged crops extensively. The pest outbreaks during this period further exacerbated the situation, leading to significant yield losses. Similarly, in 2015, Vietnam's agricultural sector was hit hard by a combination of adverse climatic conditions and pest infestations. These included the most severe El Niño event recorded in decades, which brought about prolonged drought

Figure 1: Growth rates



and water shortages, further straining agricultural productivity (FAO, 2016). Such challenges underscore the vulnerability of the agricultural sector to environmental and biological threats. Addressing these vulnerabilities requires a multifaceted approach, including investments in resilient agricultural practices, improved pest and disease management systems, and robust disaster preparedness and response strategies. These measures are essential for sustaining productivity growth and ensuring food security in the face of climatic and biological uncertainties (Giang, 2024). Notably, TFP growth rates reached zero in the years 2000 and 2013. In 2000, the country was undergoing structural adjustments and reforms, which temporarily disrupted agricultural productivity (Vu and Nguyen, 2021). Similarly, in 2013, extreme weather events, including severe droughts and floods, significantly impacted agricultural output, leading to zero TFP growth (Loayza and Otker-Robe, 2013). GDP generally showed growth rates throughout the period, with a few near-zero slowdowns around 1995, 2015, and 2020. This can be linked to specific economic and external shocks, such as the lingering effects of the “Doi moi” reforms, the global financial crisis, and the COVID-19 pandemic, respectively. The peak in GDP growth between 2005 and 2010 aligns with Vietnam’s economic boom due to robust domestic and foreign investment (The World Bank In Viet Nam, 2024). CO_2 emissions recorded zero growth around 2000 and negative growth in 2013 and from 2020 to 2022. It might be due to the implementation of early environmental protection policies and environmental regulations and the impact of the COVID-19 pandemic, which reduced industrial activity and emissions (Climate Transparency, 2020).

Table 1 provides a comprehensive overview, revealing positive mean returns across all series. All series are non-normal distribution patterns (Jarque and Bera, 1980) except TFP in agriculture and CO2 emissions. No variables are stationary, as indicated by the ERS unit root test (Elliott et al., 1996). Additionally, complications arise because the weighted portmanteau test (Fisher and Gallagher, 2012) reveals autocorrelation affecting the sole returns in only digitalization and economic growth. These findings validate our methodology and provide compelling evidence supporting the adoption of a novel R^2 decomposed connectedness approach to investigate the nexus among environmental innovation, digitalization, and total factor productivity (TFP) in agriculture.

4. RESULTS

4.1. Averaged Joint Connectedness

Table 2 shows the average outcomes for the interlinkages of various indicators inside the network. The diagonal part of this table describes the change of a single indicator driven by its shocks. In contrast, the off-diagonal components describe how the instability of this indicator influences other indicators (FROM) and how other indicators impact the instability of this indicator (TO). The columns display the independent effects of each type of indicator on one another, whereas the rows explicitly display the influence of each indicator on the forecast error variance of an indicator.

In Panel A of Table 2, the total TCI average value for the entire data set is 86.76%. It is proven that changes to this network might be responsible for 86.76% of the volatility in the network of indicators under investigation. The contribution of each indicator is displayed in the last row of Table 2. This analysis explores the notion that each indicator has a varied role throughout various relationships by dividing the observational portions into contemporaneous and lagged linkages in Panel B and Panel C. The system of all indicators (TCI is 40.35%) can partially explain the contemporaneous dynamic. Nevertheless, this number has increased to 46.42% in the lagged

Table 1: Summary statistics

Statistics	INU	EI	TFP	CO_2	GDP
Mean	51.061*** (0.003)	11.763 (0.241)	2.580*** (0.000)	8.353*** (0.000)	10.801*** (0.000)
Variance	6428.001	2491.113	6.317	70.39	52.169
Skewness	2.359*** (0.000)	−0.767* (0.074)	−0.670 (0.114)	0.052 (0.898)	1.438*** (0.003)
Ex.Kurtosis	5.104*** (0.001)	3.518*** (0.004)	−0.171 (0.757)	−0.437 (0.909)	1.924** (0.031)
JB	52.330*** (0.000)	15.957*** (0.000)	1.975 (0.373)	0.218 (0.897)	12.972*** (0.002)
ERS	−0.370 (0.716)	−1.148 (0.268)	−1.681 (0.112)	−0.447 (0.661)	−1.634 (0.122)
Q (20)	25.030*** (0.002)	12.684 (0.255)	7.119 (0.813)	10.083 (0.496)	25.120*** (0.002)
Q2 (20)	8.044 (0.720)	8.882 (0.629)	4.842 (0.962)	9.451 (0.566)	15.420 (0.105)

GDP: Gross domestic product, TFP: Total factor productivity

Table 2: Averaged joint connectedness

Variables	INU	EI	TFP	CO_2	GDP	FROM
Panel A: Overall						
INU	19.76	25.98	20.91	15.99	17.36	80.24
EI	20.53	16.92	21.46	30.12	10.96	83.08
TFP	34.82	16.29	9.97	19.53	19.39	90.03
CO_2	26.34	34.55	17.46	7.16	14.48	92.84
GDP	24.94	17.96	25.81	18.92	12.37	87.63
TO	106.63	94.78	85.65	84.56	62.19	TCI
NET	26.40	11.70	−4.39	−8.28	−25.44	86.76
Panel B: Contemporaneous						
INU	0.00	19.93	6.73	7.62	7.77	42.04
EI	12.99	0.00	2.21	12.18	6.81	34.20
TFP	13.42	7.15	0.00	6.48	9.71	36.77
CO_2	15.14	26.60	6.55	0.00	5.17	53.46
GDP	12.33	11.56	6.96	4.42	0.00	35.27
TO	53.88	65.24	22.44	30.70	29.47	TCI
NET	11.83	31.05	−14.32	−22.76	−5.80	40.35
Panel C: Lagged						
INU	19.76	6.04	14.18	8.37	9.60	38.19
EI	7.54	16.92	19.26	17.93	4.15	48.88
TFP	21.40	9.14	9.97	13.05	9.67	53.26
CO_2	11.20	7.96	10.91	7.16	9.31	39.38
GDP	12.61	6.40	18.85	14.50	12.37	52.36
TO	52.76	29.54	63.20	53.86	32.72	TCI
NET	14.56	−19.34	9.94	14.48	−19.64	46.42

GDP: Gross domestic product, TFP: Total factor productivity

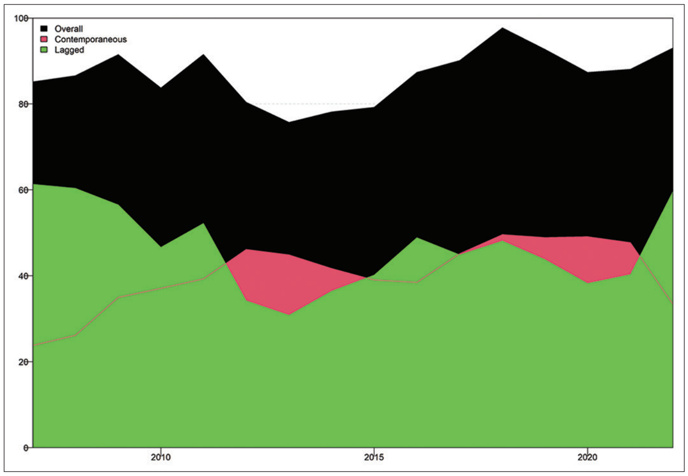
linkage. Digitalization was a net shock transmitter, and economic growth was a net shock receiver through all the dynamics, observing the impact of lagged linkage slightly greater than contemporaneous dynamics. Within the prevailing impact of the lagged linkage over contemporaneous dynamics, environmental innovation was a net shock transmitter, while TFP in agriculture and CO_2 emissions were net shock receivers. In the contemporaneous dynamics, all FROM measures, except for environmental innovation and CO_2 emissions, are generally lower than their lagged counterparts. For example, the FROM measure for environmental innovation in the contemporaneous panel is 34.20%, while it is 48.88% in the lagged panel. Similarly, the FROM measure for CO_2 emissions in the contemporaneous panel is 53.46%, compared to 39.38% in the lagged panel. Regarding the TO measures, most contemporaneous dynamics measures are higher compared to the lagged dynamics. Digitalization has a TO measure of 53.88% in the contemporaneous panel, slightly higher than its lagged TO measure of 52.76%. Environmental innovation also exhibits a significantly higher contemporaneous TO measure (65.24%) compared to its lagged TO measure (29.54%). These differences highlight the varying impacts of contemporaneous and lagged dynamics on the interconnectedness within the system, suggesting that immediate effects often have more substantial influence than delayed effects, except for specific cases like environmental innovation and CO_2 emissions.

4.2. Total Dynamic Connectedness

Moreover, our attention encompasses dynamic linkage diagrams, acknowledging that averaged indicators of connectedness may obscure their temporally fluctuating characteristics. Figure 2 dynamically visualizes the temporal evolution of the overarching connectedness pattern, offering a detailed depiction of its fluctuations over the survey period. Lagged linkage surpassed contemporaneous dynamics before 2011. Furthermore, the picture of the two connections was opposite. The lagged TCI saw a sudden decline in 2013, then increased again, followed by another drop in 2020, and eventually rose at the end of the period. On the other hand, contemporaneous TCI increased rapidly until 2012, surpassing lagged TCI, then gradually decreased until 2016, followed by a period of increase and stability until 2021. However, after 2021, contemporaneous TCI experienced a sharp decline.

The findings indicate that the lagged connections often had a more substantial impact on the dynamics of environmental innovation, digitalization, and TFP in Vietnam's agricultural sector. For

Figure 2: Time-variant of total connectedness



instance, during the period from 2013 to 2015, contemporaneous TCI increased rapidly, peaking in 2012 and then gradually decreasing until 2016. The global financial crisis of 2008-2009 had profound and lasting negative impacts on these variables, causing significant economic shocks that hindered environmental innovation, digitalization, and agricultural TFP (APRACA, 2017). This suggests that immediate interactions among environmental innovation, digitalization, and TFP were more prominent during this time frame. The sharp increase in contemporaneous TCI during this period could be attributed to the implementation of the National Broadband Plan, which significantly improved internet accessibility and digital infrastructure, fostering immediate advancements in agricultural practices (ITU, 2012).

In contrast, the sudden decline in lagged TCI until 2014, followed by a resurgence, indicates a delayed but significant influence of past interactions on current productivity. This could be linked to the impacts of earlier policy implementations, such as the 2005 Law on Information Technology, which laid the groundwork for later technological integration but took time to manifest in tangible productivity gains (Vietnam Ministry of Information and Communications, 2006). The resurgence of lagged TCI post-2014 can be attributed to the cumulative effects of continuous investments in digital literacy and infrastructure development from previous years. Additionally, the period from 2017 to 2021 saw a resurgence of contemporaneous TCI, suggesting renewed immediate interactions between these variables. However, this was followed by a sharp decline in contemporaneous TCI after 2021, indicating a shift back to the dominance of lagged connections. This shift can be attributed to long-term investments and policies, such as the Vietnam National Digital Transformation Program 2025, which emphasizes sustained development over immediate gains (Vietnam Ministry of Information and Communications, 2020). Additionally, the COVID-19 pandemic accelerated the adoption of digital technologies in agriculture, with modern innovations such as precision farming, drone technology, and IoT applications playing a crucial role in enhancing productivity and sustainability (Vietnam Investment Review, 2021). For instance, the deployment of drones for crop monitoring and the use of IoT devices for real-time soil and weather condition tracking improve crop yields and resource efficiency significantly. Additionally, precision farming techniques, facilitated by enhanced digital infrastructure, allowed for more accurate and sustainable farming practices, ultimately boosting agricultural productivity (Thi, 2024).

4.3. Net Total Directional Connectedness

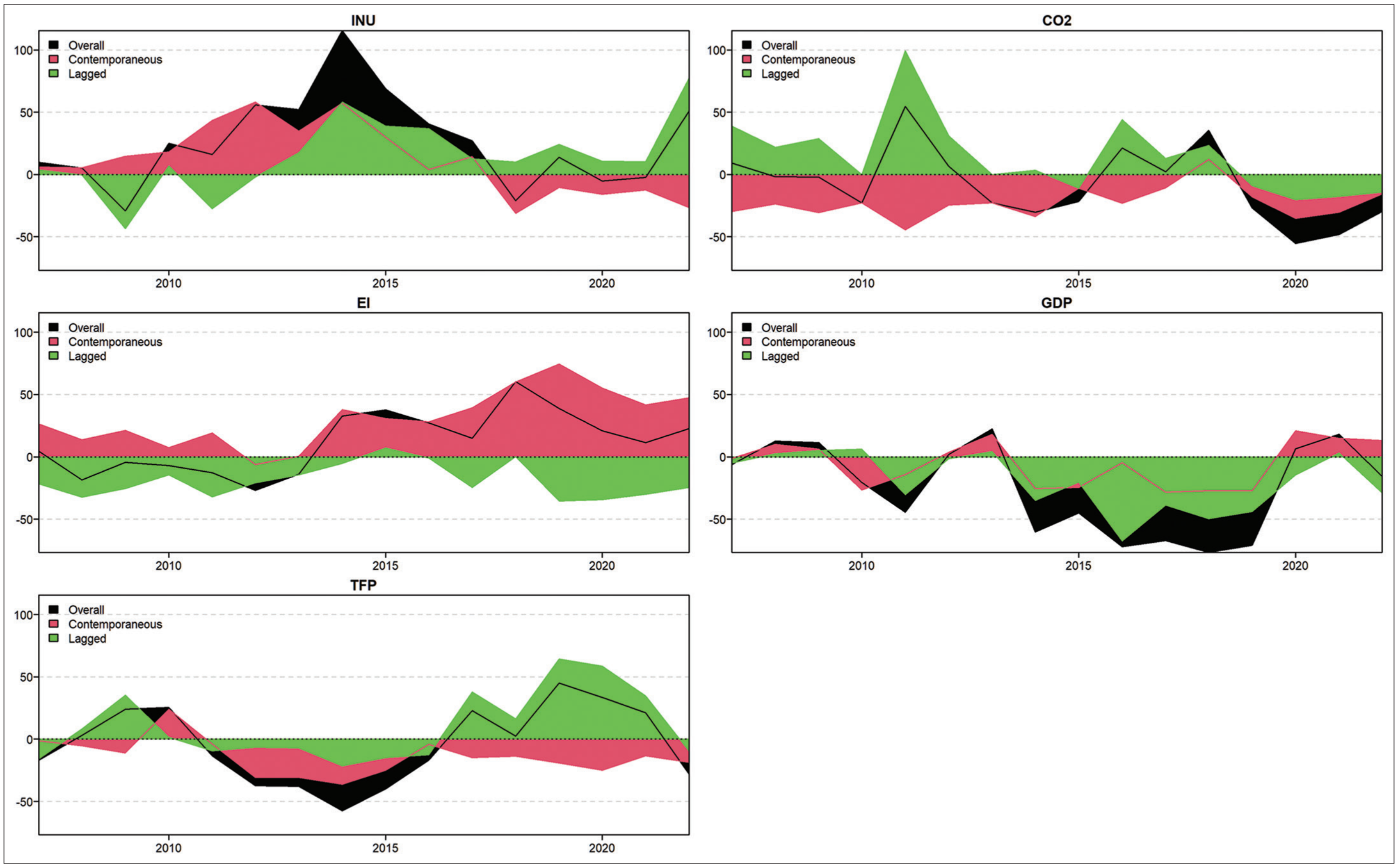
Subsequently, Figure 3 provides an illustration of the time-varying net total directional connectedness, shedding light on the roles of environmental innovation, digitalization, and TFP in agriculture utilizing both dynamic contemporaneous and lagged linkages.

Digitalization has consistently acted as a strong net shock transmitter, particularly from 2012 to 2017, through both contemporaneous and lagged linkages. For example, during this period, the rapid adoption of digital technologies, driven by government initiatives such as the National Broadband Plan, significantly impacted the agricultural sector by enhancing productivity and efficiency (ITU, 2012). In contrast, before 2012, lagged linkages showed a different dynamic, and after 2018, contemporaneous linkages played a more prominent role. This shift highlights the evolving nature of digitalization's impact on the sector over time.

Conversely, TFP in agriculture has primarily been a net shock receiver, especially from 2011 to 2016, influenced by both contemporaneous and lagged connections. This period saw significant improvements in TFP due to various policy interventions and technological advancements. For instance, the Agricultural Restructuring Plan focused on enhancing productivity and competitiveness in agriculture, which had a substantial impact on TFP (Linh and Thang, 2015). After 2016, contemporaneous dynamics continued to play a critical role in influencing TFP, as evidenced by the continued adoption of modern agricultural practices and technologies. However, before 2011 and after 2016, lagged linkages primarily influenced TFP, reflecting the delayed effects of earlier policies and technological changes.

Environmental innovation was a net shock transmitter before 2012 and from 2013 to the end of the period in contemporaneous dynamics. On the other hand, environmental innovation was a net shock receiver before 2015 and from 2016 to the end of the period, in the lagged linkage. The roles of contemporaneous and lagged environmental innovation were generally opposed, as it was predominantly the contemporaneous dynamic, highlighting the limitations and slow development of environmental innovation in Vietnam. This slow progress can be attributed to several factors, including insufficient funding, a shortage of skilled labor, and outdated technology. For instance, Vietnam has struggled with limited financial resources dedicated to research and development in green technologies. Phan (2024) reported that Vietnam's R&D expenditure as a percentage of GDP remained below 1%, significantly lower than the global average. Additionally, there has been a lack of skilled professionals in the field of environmental science and technology, which has hampered the adoption and innovation of sustainable practices. Moreover, the rapid industrialization and economic growth in Vietnam have often come at the expense of environmental protection, as industries prioritized short-term economic gains over long-term sustainability (Raihan et al., 2024).

Figure 3: Time-variant of net total directional connectedness



After 2017, the roles of contemporaneous and lagged linkages among environmental innovation, digitalization, and total factor productivity (TFP) in agriculture became increasingly complex and often opposed each other. This period highlights the multifaceted influence of these variables over time. In the long term, digitalization continued to play a pivotal role in promoting environmental innovation and agricultural TFP. However, in the short term, digitalization was subject to the impact of other variables. Significant progress was made in Vietnam's digital infrastructure with the implementation of various digitalization initiatives. For example, the launch of the Vietnam Digital Transformation Alliance aimed to foster digital innovation and enhance the country's digital economy (Cameron et al., 2019). During the COVID-19 pandemic, digitalization accelerated rapidly, driven by the necessity to adapt to new challenges. The pandemic spurred the adoption of digital tools and technologies in agriculture, such as remote sensing, drone technology, and online marketplaces, which significantly improved agricultural productivity and resilience (Thi, 2024). These developments underscore the crucial role of digitalization in both the immediate response to crises and long-term agricultural innovation. Environmental innovation also saw notable advancements from 2014 onwards. In 2014, the Vietnamese government launched the Green Growth Strategy, aimed at promoting sustainable development and reducing greenhouse gas emissions. This strategy facilitated the integration of environmentally friendly technologies and practices in agriculture, contributing to improvements in agricultural productivity and environmental sustainability (Open Development Vietnam, 2024). Additionally, in 2019, the government implemented the National Program on Sustainable Development Goals, further enhancing the role of EI in the agricultural sector (Phong, 2020). Total factor productivity (TFP) in agriculture experienced significant events in 2010-2011 and 2016. During 2010-2011, the adoption of the Agricultural Restructuring Plan aimed at improving productivity and competitiveness in the agricultural sector. This plan focused on restructuring crop and livestock production systems, promoting advanced technologies, and enhancing supply chain efficiency. In 2016, the implementation of the National Agricultural Extension Center's programs further boosted TFP by providing farmers with access to modern agricultural practices and technologies (World Bank, 2016). These initiatives highlight the critical role of TFP in driving agricultural productivity and sustainability.

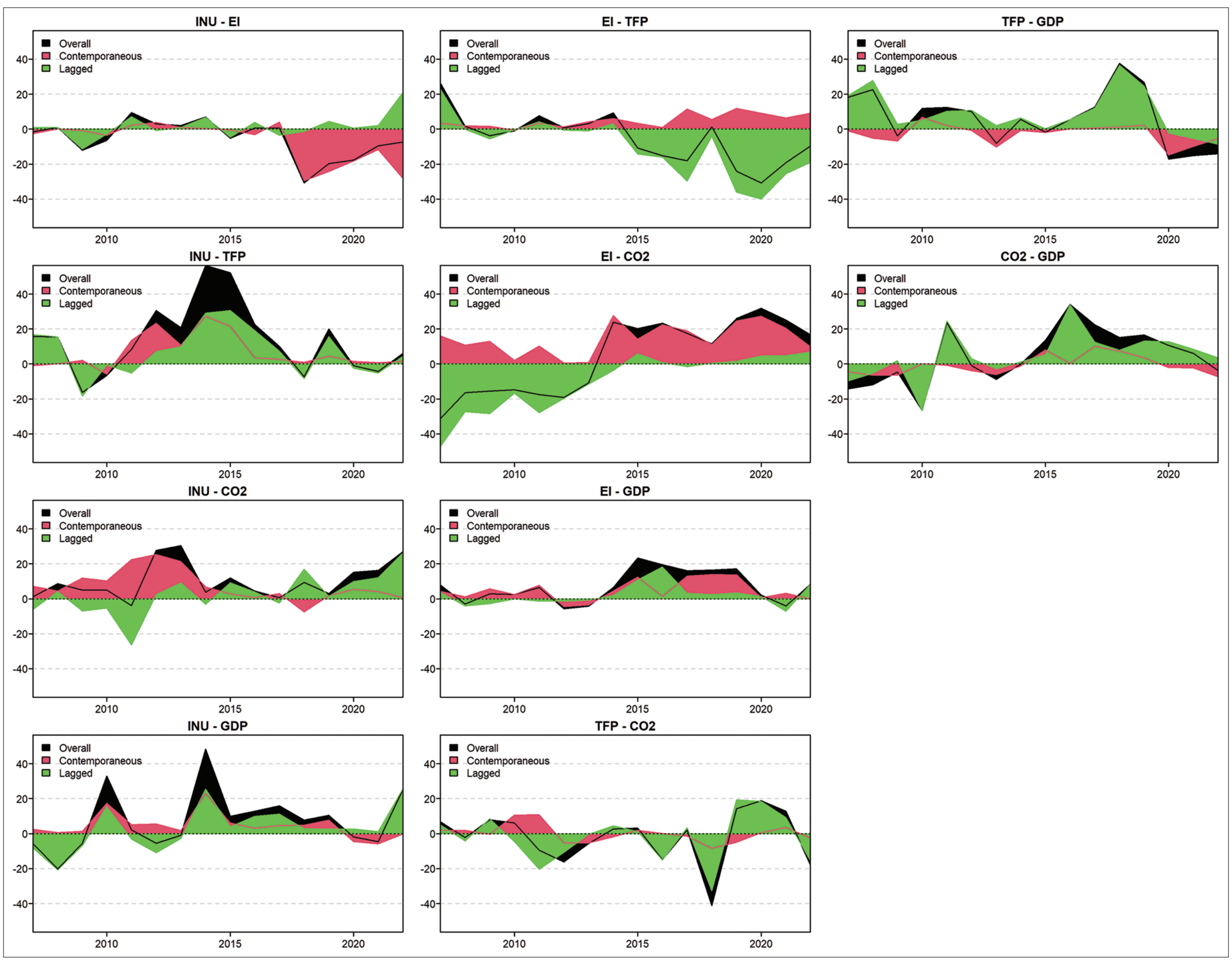
CO_2 emissions were generally consistent net shock receivers throughout the period, with some short durations of being net shock transmitters in the lagged linkage. It reflects Vietnam's struggle with balancing industrial growth and environmental sustainability. The rapid industrialization and urbanization in Vietnam have led to increased greenhouse gas emissions, contributing to air pollution and environmental degradation. For example, the expansion of coal-fired power plants to meet the rising energy demands has significantly increased CO_2 emissions despite efforts to promote renewable energy sources (Open Development Vietnam, 2024). GDP was mainly a net shock receiver throughout the period, especially from 2014 to 2021, when its impact increased significantly. The robust economic growth following Vietnam's deeper integration into the global economy and significant foreign direct investment flows played a crucial role in driving this trend. An example is the surge in GDP growth due to the manufacturing boom driven by multinational corporations establishing operations in Vietnam, which brought technology transfer, job creation, and economic diversification (Anwar and Nguyen, 2010).

4.4. Net Pairwise Dynamic Connectedness

Figure 4 illustrates the dynamic net pairwise directional connectedness. On the one hand, digitalization weakly dominated environmental innovation from 2010 to 2015 and 2022, in the lagged linkage. However, a reversal role was observed from 2008-2010 in the lagged linkage, especially from 2018 to the end of the period in the contemporaneous dynamic. On the other hand, digitalization controlled TFP in agriculture before 2008 and from 2019 to 2020 in the lagged linkage, especially from 2010 to 2016 in both linkages. Some short durations also observed the reversal role, particularly from 2008 to 2010. Regarding environmental innovation, TFP in agriculture mainly dominated from 2014 to the end of the period, in the lagged linkage, while it was also controlled at the same time observed by the contemporaneous dynamic.

Since 2017, environmental innovation in Vietnam has been increasingly dominated by digitalization, underscoring the critical role of digital technologies in driving the country's digital transformation. Key examples of environmental innovations leveraging digital technology include precision agriculture systems, which utilize satellite imagery, drones, and sensors to monitor soil health, crop conditions, and resource usage. These systems enable farmers to optimize inputs and enhance productivity by providing real-time, data-driven insights (Duong, 2022). Additionally, digital platforms for environmental monitoring, such as those developed for tracking air and water quality, have been instrumental in improving environmental management and regulatory compliance (Vietnam+ (VietnamPlus), 2024). The adoption of such technologies demonstrates how digital innovations are pivotal in advancing Vietnam's environmental and agricultural sectors. Digitalization has significantly enhanced agricultural TFP since 2010. The integration of digital technologies into agriculture has facilitated substantial improvements in efficiency and output. For example, the use of Internet of Things (IoT) devices for precision irrigation and automated farming equipment has streamlined operations, reduced waste, and increased crop yields (Vietnam+ (VietnamPlus), 2023). The adoption of big data analytics for predicting weather patterns

Figure 4: Dynamic net pairwise directional connectedness



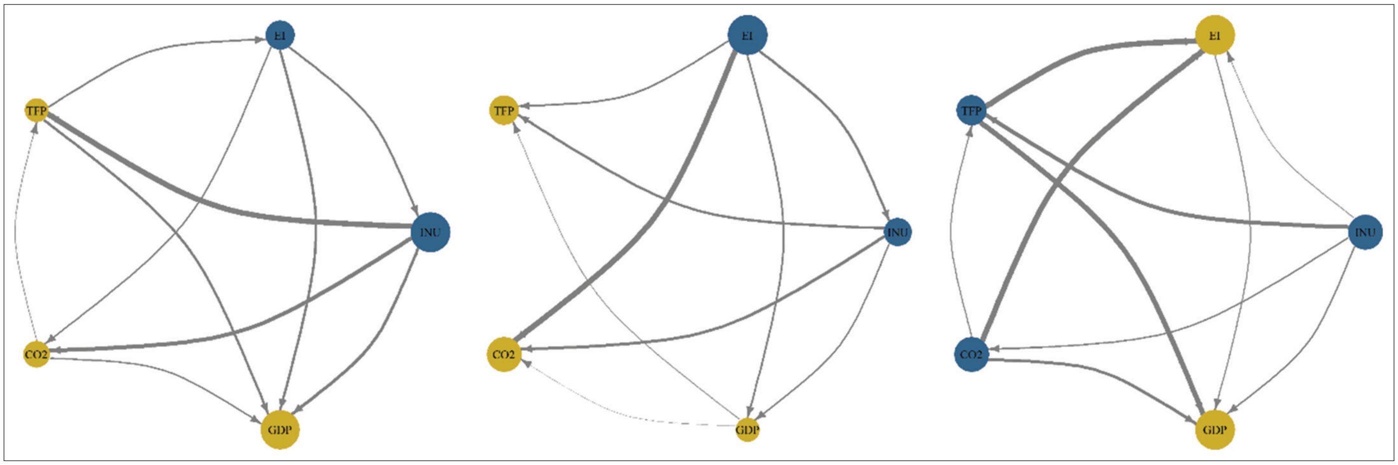
and managing crop production has further optimized agricultural practices, contributing to greater productivity and sustainability (Vietnam News, 2023). These advancements highlight how digital transformation has been crucial in driving agricultural growth and efficiency in Vietnam. From 2014 onward, the relationship between contemporaneous and lagged linkages between EI and agricultural TFP has been characterized by a predominance of lagged effects. In the short term, environmental innovations have positively impacted agricultural TFP by enhancing productivity through immediate technological improvements (Giang et al., 2019). For instance, innovations such as digital pest management and smart irrigation systems have provided immediate benefits in terms of crop yield and resource efficiency. In contrast, the long-term growth in agricultural TFP has stimulated further advancements in environmental innovation. Increased agricultural productivity creates demand for more sophisticated technological solutions and sustainable practices, thereby driving continuous innovation in the sector (Thi, 2024). For example, the development of advanced data analytics tools and environmental monitoring systems reflects the evolving needs and increased capabilities in the agricultural sector, leading to further environmental innovations (Vietnam+ (VietnamPlus), 2024).

In general, digitalization dominated CO_2 emissions, particularly through contemporaneous linkages in the first half of the studied period and subsequently through lagged linkages. During this time, digitalization's control of CO_2 emissions was most pronounced in the short term, reflecting the immediate effects of technological advancements on environmental factors. For instance, the introduction of advanced digital technologies and policies aimed at reducing emissions likely contributed to these observed effects (World Bank, 2019). Between 2002 and 2009, CO_2 emissions had more significant control over digitalization through lagged linkages. This period highlights how the environmental impact of CO_2 emissions influenced the pace and nature of digitalization efforts. The lagged effects suggest that the broader environmental context and regulatory pressures may have shaped the development and implementation of digital technologies during this time (United Nations Environment Programme, 2020). Similarly, digitalization was also controlled in driving economic growth, particularly from 2009 to 2011, through both contemporaneous and lagged linkages. During this period, rapid technological advancements and increased digital infrastructure investments significantly boosted economic growth. The effects of digitalization on economic growth were evident as new technologies facilitated business operations, improved productivity, and fostered innovation (OECD, 2021). From 2013 to 2018, digitalization continued to be a key driver of economic growth through lagged linkages, reflecting the long-term benefits of earlier digital investments and technological improvements. This period demonstrates how the ongoing evolution of digital technologies continued to influence economic growth, with delayed but significant impacts on productivity and development (The World Bank In Viet Nam, 2024). In contrast, before 2009, lagged linkages showed that economic growth was more strongly controlled by digitalization. This reverse relationship indicates that the earlier stages of digital development had a notable effect on economic performance, shaping the growth trajectory prior to the observed period of rapid advancement and investment (Binh and Phuong, 2020).

Before 2018, environmental innovation primarily controlled economic growth, particularly from 2014 to 2018. During this period, various environmental innovations, supported by both foreign aid and domestic policies, contributed to economic growth through enhanced productivity and job creation in green sectors. For instance, the adoption of energy-efficient technologies in industrial sectors not only reduced operational costs but also spurred economic activities by attracting investments in clean technologies (Hoa et al., 2023). However, after 2018, economic growth began to exert a strong control on environmental innovation. This shift reflects the increased focus on economic expansion, which drove demand for environmental innovations as part of broader industrial and infrastructural development efforts. The growing economic activities necessitated advancements in environmental technologies to address the impacts of increased industrial output and urbanization (International Trade Administration, 2024). Overall, environmental innovation was controlled by CO_2 emissions before 2014, in the lagged linkage, indicating a slower spillover effect. Prior to 2014, the rapid industrialization and associated increase in CO_2 emissions necessitated innovations to mitigate environmental impacts. For example, the introduction of cleaner production technologies and stricter environmental regulations aim to reduce industrial emissions and improve air quality (Herr et al., 2016). Conversely, environmental innovation dominated CO_2 emissions before 2010 and from 2013 to the end of the period in contemporaneous dynamics. This dominance indicates that advancements in environmental technologies significantly impacted CO_2 emissions and human development outcomes. For example, during these periods, the introduction of advanced emission control technologies and sustainable practices led to substantial reductions in industrial emissions and improved environmental quality (Asian Development Bank, 2013; Li and Qamruzzaman, 2023).

TFP in agriculture was dominated by CO_2 emissions from 2010 to 2018, particularly through lagged linkages. This period reflects the delayed impact of CO_2 emissions on agricultural productivity. The negative effect of CO_2 emissions on TFP can be attributed to the environmental degradation and climate change associated with increased greenhouse gas emissions, which can adversely affect agricultural output and efficiency (Masson-Delmotte et al., 2021). For example, the intensified focus on reducing carbon emissions and addressing climate change through various policies and regulations during this period likely influenced agricultural practices and productivity (UNFCCC, 2018). Conversely, the reverse relationship between CO_2 emissions and TFP was observed primarily from 2010 to 2011 through contemporaneous dynamics and from 2019 to 2021 through lagged linkages. During 2010-2011, immediate interactions between CO_2 emissions and TFP were evident, possibly due to short-term fluctuations in environmental policies and technological advancements affecting agricultural productivity (World Bank, 2019). The resurgence of this relationship from 2019 to 2021 through lagged linkages may be linked to the cumulative effects of recent environmental regulations and sustainability practices on agricultural productivity

Figure 5: Network connectedness. Overall (left), contemporaneous (center), and lagged (right) network connectedness. Overall (left), contemporaneous (center), and lagged (right) network connectedness



(World Bank, 2022). In contrast, TFP in agriculture dominated GDP before 2020, particularly through lagged linkages. This indicates that improvements in agricultural productivity had a more significant impact on overall economic performance over time. The lagged influence suggests that advancements in agricultural efficiency and output gradually contributed to GDP growth, reflecting the delayed effects of productivity improvements on the broader economy (Asian Development Bank, 2022). However, some shorter periods exhibited a reversal in this dynamic, with TFP in agriculture showing a more immediate influence on GDP through contemporaneous dynamics. For example, during certain periods of rapid technological advancements and agricultural reforms, the immediate effects of increased agricultural productivity on GDP growth were more pronounced (Vu and Nguyen, 2021).

Furthermore, we present the averaged contemporaneous, lagged, and overall network connectivity metrics in Figure 5. The overall and lagged models both observed that digitalization dominated TFP in agriculture, economic growth, and CO_2 emissions. On the one hand, environmental innovation controlled digitalization, economic growth, and CO_2 emissions in the overall and contemporaneous dynamics. On the other hand, TFP in agriculture took control over environmental innovation in the overall and lagged linkages. Additionally, as the dominant one, environmental innovation was controlled by both TFP and digitalization in the lagged linkage.

5. CONCLUSIONS AND POLICY IMPLICATIONS

Employing the R^2 decomposed linkage method, the primary objective of our study is to elucidate associations, with a specific focus on distinguishing between contemporaneous and lagged linkages. This novel methodology is applied to scrutinize the transmission of returns among environmental innovation (EI), Individuals using the Internet (% of the population) (INU), Index of Agricultural Total Factor Productivity (TFP in agriculture), CO_2 emissions (CO_2), gross domestic product (GDP) in Vietnam from 1994 to 2022.

Our results show that digitalization had a minimal impact on environmental innovation between 2010 and 2015 and in 2022, with a notable reversal observed from 2008-2010 and especially from 2018 onwards. Additionally, digitalization influenced TFP in agriculture before 2008 and from 2019 to 2020, with significant effects from 2010 to 2016. Environmental innovation predominantly affected TFP from 2014 through the end of the study period, exhibiting both immediate and delayed impacts. Since 2017, digitalization has increasingly driven environmental innovation, with advancements in precision agriculture and environmental monitoring technologies. These developments have significantly boosted agricultural TFP by enhancing efficiency and productivity through digital tools and data analytics. Overall, the findings underscore the essential role of digital technologies in improving agricultural productivity and environmental sustainability, highlighting the need for ongoing investment in digitalization to support growth and innovation in the sector.

ACKNOWLEDGMENT

This research is funded by the Ministry of Education and Trainning under grant number B2023-KSA-07. This paper is the result of the ministerial – level research project “Researching the impact of institutions on the development of private firms in Vietnam based on science, technology, and innovation in the new context”. This research is funded by the University of Economics Ho Chi Minh City, Vietnam.

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