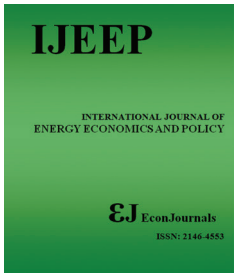

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Digital Transformation, Human Capital Upgrading, FDI Spillover and Green Total Factor Productivity: Evidence from Vietnamese Provinces

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ABSTRACT

The study examines the relationship between FDI spillover and green total factor productivity (GTFP) at the provincial level, as well as exploring the roles of digital transformation and human capital upgrading in this relationship using the global Malmquist-Luenberger index, system generalized methods of moments (S-GMM) combined with threshold model. Using a panel data from 63 Vietnamese provinces from 2011 to 2022, the research findings show that the FDI spillover has contributed significantly to province-level GTFP enhancement and both digital transformation, human capital upgrading positively moderate the effect of FDI spillover on provincial GTFP. Besides, the positive influence of FDI spillover on GTFP has a significant double threshold effect when advanced human capital is used as the threshold variable. These findings emphasize the significance of encouraging FDI spillover, enhancing digital transformation, and strengthening high-quality human capital as viable strategies for improving GTFP.

Keywords: FDI Spillover, Digital Transformation, Human Capital Upgrading, Green Total Factor Productivity, Provincial Level, Vietnam.
JEL Classifications: C13, Q50

1. INTRODUCTION

Considering the growing worldwide tensions between environmental preservation and economic development caused by massive use of fossil fuel in economic activities (Satrianto et al., 2025), how to ensure sustainable development and mitigate negative impacts of global warming and climate change has become a global concern (Raihan et al., 2022). Green total factor productivity (GTFP), a critical criterion for assessing environmental performance and economic development, has been widely used in recent studies (Zhang et al., 2024; Yu et al., 2022; Wang et al., 2022) to reflect sustainable development. Consequently, how to enhance GTFP has become a critical concern for governments and scholars around the world.

FDI spillover is the externality of knowledge and technology from FDI to the host country (Sjöholm, 1999). The spillover includes not only the technology inherent in the subsidiary's locally produced goods or services, or the technology required for such production (Dussaux et al., 2022), but also non-technical knowledge relating to management (Wang and Kafouros, 2020). As productivity growth is largely dependent on the transfer of technical and scientific information among economic agents (Romer, 1994), it is practical and logical to investigate if and to what extent FDI spillovers can assist GTFP enhancement.

Prior study has mostly explored the relationship between FDI presence and GTFP, but the findings are inconclusive (Liu et al., 2023; Qiu et al., 2021). Xie and Zhang (2021) serve as an exemplary, showcasing the crucial role of China's OFDI in facilitating GTFP in "Belt and Road" Initiative countries. In contrast, Lin and Chen (2018) discovered that FDI had a large negative spillover effect on Chinese GDP growth. What's more, using China's province panel data from 2001 to 2019, Liu et al.

(2023) discovered that the influence of FDI inflows on GTFP follows an asymmetric inverted U-shape, rising at first and then dropping at the same time.

Although previous research has established the impact of FDI spillover on domestic productivity, the research is mostly conducted at the two levels of industry and enterprises (Mai Lan et al., 2024; Wang et al., 2023). The literature addressing the mechanisms of FDI spillover on GTFP at the provincial level is very limited. As a matter of fact, a province is not only a location where industrial, and enterprise economic activities are implemented but also a place where local government agencies issues policies and regulations which may be able to affect the behaviors of firms operating within that location. This distinction is theoretically vital because regional operations differ from firm-level operations in various ways, which in turn affects how provinces benefit from FDI spillover. Furthermore, few studies have looked at FDI productivity spillover from digital transformation and human capital development perspectives, even though digitalization and upgrading human capital are significant moderator variables in FDI spillover. Third, the nonlinear effect of FDI spillover on GTFP is typically overlooked in study. The impacts of FDI spillover on GTFP are most likely to vary by advanced human capital structure. because of the significant differences in advanced human capital amongst Vietnamese regions.

To fill these research gaps, this research adopts 63 provinces in Vietnam as the research object, using a comprehensive provincial panel dataset covering the 2011-2022 period. The research aims are twofold: first, to explore the direct impact of FDI spillover on provincial GTFP, and second, to investigate the moderating effects of digital transformation and human capital upgrading on the above relationship.

This research is embedded in Vietnam, an emerging country which had previously sacrificed its environment to seek economic prosperity but recently has shown a strong commitment for sustainable economic development (Tran and Lai, 2022). Despite its impressive economic success, Vietnam's environmental concerns have become increasingly serious. According to the International Energy Agency (IEA), Vietnam's carbon emissions increased by 548% from 2000 to 2022. Furthermore, air pollution in Vietnam has prompted a call for action, with IQAir's yearly assessment ranking the country as the second most polluted in the ASEAN region and the 22nd worst in the world (IQAir, 2024). It is also noticeable that even though there is a considerable disparity in sustainable development across regions in Vietnam (Nguyen et al., 2025), there is currently no investigation into how FDI spillover affects these discrepancies.

This study makes three significant contributions to existing literature by achieving its research objectives. First, it advances the literature of productivity by investigating the relationship between FDI spillover and province-level GTFP. Second, this study contributes to the literature of FDI spillovers by elucidating the moderating impacts of digital transformation and human capital upgrading in order to explain their catalytic role in the dissemination of FDI knowledge. Third, this study echoes the call for additional research in developing countries, inquiring not just whether spillovers exist but also how they arise by looking inside the "black box" (Demena and Murshed, 2018) by unveiling the threshold effect of FDI spillover on GTFP

The structure of this paper is as follows: Section 2 includes a thorough literature review, followed by research hypotheses based on a full theoretical examination in Section 3. Section 4 focuses on calculating the GTFP indicator, establishing three empirical models, and performing a descriptive statistical analysis. Section 5 summarizes the findings from baseline regression, moderating regression, and threshold regression. The final section summarizes the research findings and conclusions while making pertinent policy recommendations.

2. LITERATURE REVIEW

GTFP is an indicator used to quantify green growth, which combines economic expansion with environmental preservation to gauge high-quality economic development, this index has been employed extensively (Tian and Feng, 2022).

GTFP is measured in the literature using both parametric and nonparametric approaches (Choi et al., 2012; Chen et al., 2014; Şeker and Saliola, 2018; Wang and Feng, 2021), with the latter is more popular (Tone, 2001) since it does not necessitate the construction of a specific production function and variable distribution (Battese and Coelli, 1995; Chung et al., 1997; Habib and Ljungqvist, 2005; Greene, 2010).

Numerous studies have concentrated on how different factors affect GTFP. On the one hand, scholars focus on policy issues and investigate how laws and public policies affect GTFP (Chen et al., 2021). Zhang et al. (2024) serves as an exemplar, showcasing the vital role of local government attention in raising GTFP in Chinese cities. Furthermore, Yu et al. (2022) reveal the importance of carbon emission trading programs in facilitating agricultural GTFP in pilot cities. Meanwhile, Wang et al. (2022) explored that smart city construction considerably boosts GTFP and has a beneficial spillover effect on non-pilot cities. On the other hand, non-policy elements have been taken into account, including green innovation, digital financial inclusion, artificial intelligence and industrial agglomeration (Luo et al., 2023). Hunjra et al. (2024) confirmed that green innovation can promote GTFP. Cheng et al. (2023) discovered that by encouraging green innovation and entrepreneurship, the expansion of digital financial inclusion contributes to GTFP growth. In contrast, Lin and Chen (2018) observed that factor market distortion negatively influences GTFP growth.

Prior studies (Guo et al., 2023; Qiu et al., 2021) provide valuable insights into how FDI presence affects GTFP. However, past research has failed to achieve a consistent conclusion. On the one hand, the *"pollution paradise"* hypothesis argues that to attract FDI, developing countries relax environmental regulations early on, resulting in increased energy consumption and pollution technologies transferred, exacerbating environmental pollution in the host country (Wagner and Timmins, 2009). Lin and Chen (2018) discovered that FDI had a large negative spillover

effect on Chinese GDP growth. On the other hand, according to the *"pollution halo"* hypothesis, FDI can reduce carbon emissions in the manufacturing and energy sectors by improving management systems and controlling energy consumption rates (Guo et al., 2023). Xie and Zhang (2021) show that China's OFDI is green rather than accompanied by pollution transfer, which can promote GTFP in "Belt and Road" Initiative countries. Similarly, using a newly built dynamic threshold panel model with GMM characteristics and panel data from 46 "Belt and Road" nations from 2003 to 2016, Wu et al. (2020) found that when China boosted its OFDI, the GTFP of the B&R countries improved considerably.

FDI spillover is the externality of knowledge and technology from FDI to the host country (Sjöholm, 1999). Although existing research have established the impact of FDI spillover on domestic productivity (Motta et al., 2001; Bernard et al., 2000; Sjöholm, 1999), the productivity in these studies is mainly measured by TFP, a conventional measure that ignores environmental and energy factors (Wang et al., 2023). Recently, Mai Lan et al. (2024) stands out as one of the few studies demonstrating the impact of FDI spillover on GTFP. However, the study focuses on enterprise level and measures FDI spillover using input-output data from Vietnam.

In terms of province-level approaches, Liu et al. (2023) utilized China's province panel data from 2001 to 2019 and discovered that the impact of FDI inflows on GTFP is an asymmetric inverted U-shape, rising at first and then dropping at the same time. In a similar vein, Qiu et al. (2021) found regional variation in the influence exerted by FDI on GTFP and revealed that FDI originated from China had a "pollution heaven" effect on GTFP in the eastern and central regions, but a "pollution halo" effect on GTFP in the western region.

Some limitations have been identified, even though helpful references from earlier research have been used. First, there is a lack of emphasis on the GTFP improvement generated by FDI spillover. Most prior articles centered on the relationship between FDI presence and GTFP. Nevertheless, there is a shortage of available literature paid attention directly to the relationship between FDI spillover and GTFP. Second, digitalization and human capital upgrading are important moderator variables in FDI spillover. Still, few studies examine the FDI productivity spillover from the digital transformation perspective and human capital development perspective. Third, research usually ignores the nonlinear impact of FDI spillover on GTFP. Given the considerable variations in advanced human capital among Vietnamese regions, the effects of FDI spillover on GTFP varied according to the advanced human capital structure. Finally, even though significant distinct characteristics of provinces' context will affect how provincial productivity benefited from FDI spillover, research on FDI spillover at provincial remains somewhat limited Therefore, to empirically investigates the effect of this FDI spillover on GTFP while considering the role of digital transformation and human capital upgrading, this research analyzes panel data based on 63 Vietnamese provinces from 2011 to 2022.

3. THEORETICAL MECHANISM AND HYPOTHESIS DEVELOPMENT

3.1. FDI Spillover and GTFP

The theory of endogenous growth emphasizes knowledge spillovers as an essential factor in explaining domestic production. FDI is considered as a channel for spillovers, via which technological breakthroughs and knowledge about themselves can be transferred and changed to fit local demands (Ali et al., 2016). The influence it exerts on GTFP can be observed from four following channels: (1). Knowledge-technology spillover effect. Local businesses can gain superior production technologies and managerial skills., particularly pollution control technologies originated from FDI firms, by absorbing, copying, and modifying them into management techniques and industrial technologies with unique regional features. (Motta et al., 2001). This will foster industrial technical growth in the area while also reducing environmental pollution, proving the province GTFP. (2) Competitive boosting effect. The introduction of foreign-invested firms with advanced production technology and management experience has put domestic businesses under a great deal of competitive pressure, forcing them to either increase domestic technological research and development or buy and learn foreign superior technology, thereby increasing productivity (Bernard et al., 2000). (3) Synergistic effect. Local counterparts can benefit from technology and scale synergy by creating forward and backward connections with foreign-invested businesses, promoting resource optimization and pollution reduction, resulting in an increase in province GTFP. (4) Labor mobility effect. The movement of qualified staff from foreign-funded firms to local enterprises will increase knowledge spillover and turn the return from human capital into a catalyst for low-carbon growth. (Arkolakis et al., 2018). Therefore, the following hypothesis is put out in this paper:

Hypothesis 1. Increasing the FDI spillover will significantly improve provincial GTFP

3.2. The Role of Digital Transformation

The global economy has undergone a significant digital revolution in recent years, with more integration and synergy between the digital and real economies. Digital transformation is an effective catalyst for generating competitive advantage among organizations. In business, digital transformation promotes enterprise innovation through technological applications, business model innovation, and industrial collaboration (Zhou et al., 2023). Technologically, firms are offered a wide range of advanced technologies like big data, cloud computing, and blockchain. Industrially, the integration of traditional industries with digital technologies facilitates knowledge and information sharing (Zhu, 2025), thus fostering FDI spillovers. Furthermore, the introduction of digital transformation enhances the security and efficiency of cross-border transfer of technology-intensive assets (Xu et al., 2024) thereby fostering technological diffusion from FDI.

In addition, prior research has established that digital transformation helps to reduce carbon emission by enhancing productivity, conserving energy, and optimizing industrial structure. This, in turn, leads to a significant improvement in GTFP. Specifically, by optimizing resource utilization through automation, IoT

sensors, and data analytics, digital technologies increase resource efficiency. By reducing trash production, water use, and energy consumption, this optimization can raise GTFP (Zhong and Ma, 2024). Moreover, as digital transformation makes it easier to work remotely and telecommute, it eliminates the need for daily commutes, which lowers traffic and carbon emissions and, ultimately, increases GTFP. Accordingly, the hypothesis is proposed:

Hypothesis 2. The relationship between FDI spillover and provincial GTFP growth is positively moderated by digital transformation.

3.3. The Role of Human Capital Upgrading

Human capital upgrading refers to the strategic evolution of a nation's or region's human capital from basic level to advanced competencies to satisfy the changing needs of social and economic growth (Liu et al., 2024). Advanced human capital facilitates talent support for the absorption of FDI spillover, yet it possesses limited capacity in production allocation, technical innovation, and downward compatibility (Arkolakis et al., 2018).

Additionally, after high-tech green productions are implemented, a province with a high level of advanced human capital will be able to comprehend fully and adopt the cleaner production technology. Cutting-edge science and technology, along with highly skilled human resources, may help transform and effectively deploy new technologies, increasing productivity and having significant effects on GTFP.

To put it briefly, a more educated human capital structure contributes to the diffusion of technology from FDI, which in turn influences the green productivity of FDI spillovers. In contrast, FDI spillovers will contribute less to the increase of provincial green productivity if the human capital structure is less advanced. As a result, the hypothesis is proposed:

Hypothesis 3. The relationship between FDI spillover and provincial GTFP growth is positively moderated by human capital upgrading.

However, issues like over-education and a misalignment between the industrial and human capital structures lead to a mismatch between the two. This occurs when the supply of high-quality labor exceeds the demand for innovation in the region, and numerous highly skilled human resources with the capacity to innovate move into monopoly divisions that lack innovation (Zheng et al., 2020; Jiang and Guo, 2022). As a result, improving human capital could result in societal loss rather than regional change. Accordingly, the hypothesis is proposed:

Hypothesis 4. Upgrading human capital has a threshold effect on how FDI spillover affects provincial GTFP.

To validate the above hypotheses, the following research framework is put forward in Figure 1

4. METHODOLOGY AND DATA

4.1. Calculation of Provincial GTFP

The optimal production practice limits are established, and the production possibility sets of n provinces are produced. Based on the approach suggested by Fare et al. (2007), it is assumed that in t = 1, 2,…, T periods, province k = 1, 2,…, K employs $x^{t,k}$, $y^{t,k}$ and $b^{t,k}$ as input factor vectors, desirable output vectors, and undesirable output vectors, respectively. Afterwards, the DEA approach can be used to determine the current production possibilities of n provinces.

$$P^t(x^t)=\left\{\begin{array}{l}\left(y^t,b^t\right):\sum_{k=1}^{K}z_k^t y_{km}^t\geq y_{km}^t,\forall m;\sum_{k=1}^{K}z_k^t b_{ki}^t=b_{ki}^t,\forall i;\\ \sum_{k=1}^{K}z_k^t x_{kn}^t\leq x_{kn}^t,\forall n;\sum_{k=1}^{K}z_k^t=1,z_k^t>0,\forall k\end{array}\right\} \quad (1)$$

where z_k^t is each province's weight; the DEA approach can be used to produce formular (2) as follows.

$$P^G(x)=\left\{\begin{array}{l}\left(y^t,b^t\right):\sum_{t=1}^{T}\sum_{k=1}^{K}z_k^t y_{km}^t\geq y_{km}^t,\forall m;\\ \sum_{t=1}^{T}\sum_{k=1}^{K}z_k^t b_{ki}^t=b_{ki}^t,\forall i;\\ \sum_{t=1}^{T}\sum_{k=1}^{K}z_k^t x_{kn}^t\leq x_{kn}^t,\forall n;\\ \sum_{k=1}^{K}z_k^t=1,z_k^t\geq 0,\forall k\end{array}\right\} \quad (2)$$

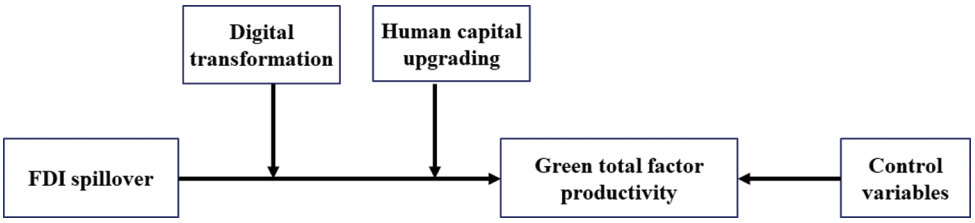
$$\overrightarrow{D_0}(x,y,b,g)=\max\left\{\beta:\left(y,b\right)+\beta g\in P(x)\right\} \quad (3)$$

Oh (2010) {Citation}defines the global Malmquist-Luenberger (GML) index as follows:

$$GML^{t,t+1}\left(x^t,y^t,\mathrm{b}^t,x^{t+1},y^{t+1},b^{t+1}\right)=\frac{1+\vec{D}^G(x^t,y^t,\mathrm{b}^t)}{1+\vec{D}^G(x^{t+1},y^{t+1},\mathrm{b}^{t+1})} \quad (4)$$

where the GTFP measured in this research is denoted by the GML index. $GML^{t,t+1}$ is the multiple of the productivity in t+1 compared to that in t. If GML > 1, GML = 1, GML < 1 indicate that the GTFP is improved, unchanged, and declined, respectively.

Figure 1: Research framework on FDI spillover affecting provincial GTFP



4.2. Model Estimation

This work presents the first-order lag terms of GTFP based on formula (5) to build a dynamic panel model because of the inertia of the green economy.

$$GTFP_{it} = \alpha_0 + \alpha_1 GTFP_{it-1} + \alpha_2 FS_{it} + \sum_{i=3}^{k} \alpha_i X_{it} + \mu_i + \mu_t + \epsilon_{it} \quad (5)$$

where i^{th} is the province i in year t; GTFP is model's explanatory variable; FS is primary explanatory variable; X represents a set of control variables including markelization (MAR), industrial structure (IS), energy consumption structure (ES), trade openess (OPEN), and gorvement ownership (OWS), μ_i and μ_t are fixed effect in region and time, respectively.

The moderating influence of digitalization and human capital upgrading is then examined by adding two interaction terms. The following is how the model is expressed:

$$GTFP_{it} = \delta_0 + \delta_1 GTFP_{it-1} + \delta_2 FS_{it} + \delta_3 M_{it} + \delta_4 M_{it} \times FS_{it} + \sum_{i=5}^{k} \delta_n X_{it} + \mu_i + \mu_t + \epsilon_{it} \quad (6)$$

where M refers to the moderating factors of improving human capital and digitization, respectively. Other symbols like those found in Equation (5).

Additionally, FDI spillover may have a threshold effect on GTFP because of Vietnam's uneven distribution of high-quality human capital across areas. Eq. (7) illustrates a threshold model developed by Hansen (1999):

$$GTFP_{it} = \alpha_i + \beta_1 FS_{it} I(c < h_1) + \beta_2 FS_{it} I(ch_1) + \sum_{i=3}^{k} \beta_i X_{it} + \mu_i + \mu_t + \epsilon_{it} \quad (7)$$

where c is the threshold variable and h_1 indicates the precise threshold value. Other symbols like those found in Equation (5).

4.3. Variables and Data Source

The samples used in this study are taken from panel data covering 63 Vietnamese provinces between 2011 and 2022. Firstly, the Vietnam Statistical Yearbook and the relevant annual Vietnamese Provincial Statistical Yearbook both state that FDI stock is determined using information on FDI flow. Furthermore, the International Energy Agency (IEA) is the source for energy consumption and carbon emissions. The yearly Statistical Yearbook, Report on Labor Force Survey, and for each province provide the input and output for the GTFP computation, moderating and control variables' calculations

4.3.1. Dependent variable

The global Malmquist Luernberger index is used to mearsure the GTFP of 63 provinces in Vietnam from 2011 to 2022 in this paper. The following are the specifics of the input and output indicators in the DEA measure for GTFP:

Input indicators include capital, labor, and energy (Yu et al., 2021; Feng et al., 2024). (1) Capital input is the province's actual capital stock, as determined using Goldsmith's perpetual inventory method (1951), Labor input is the product of employed labor and labor quality at the end of the year. This study uses the Human Development Index as a proxy for labor quality. (3) Energy input. Based on total energy consumption in the whole country provided by the IEA, energy consumption of each province is calculated with output weight. In particular, the proportion of the total energy consumption of firms and residentials in the province to the total energy consumption of the entire country are calculated, respectively.

Output indicators include both desired and undesired outputs. (1) According to Feng et al. (2024) the desired output variable is the gross regional domestic product (GRDP). In a similar manner, the deflator index derived from historical GDP is used to convert the nominal GRDP to a constant price based on 2010. This removes the effect of inflation. (2) CO_2 emissions are chosen as an indicator of output that is undesired. Like the case of energy input, data of CO_2 emission is not available at the provincial level. Therefore, this study constructs CO_2 emission of each province based on total Vietnam's CO_2 emission provided by the IEA. According to the organization, CO_2 emissions in Vietnam come from two primary sources: business and household activities. The former is further separated into three subcategories: agriculture, industry, and service. The following are the specific steps involved in calculating CO_2 emissions.

First, determine the province's percentage of the nation's total output and population in the year t.: $per_{it} = Q_{it}/Q_t$, where $aper_{it}$, $iper_{it}$, $sper_{it}$ is the weight of agricultural, industrial, and service output respectively; Q_{it} and Q_t are the gross domestic products from agriculture/industries/services in province i and the whole country in year t, Meanwhile, the weight of the ith province's population in year t is written as: $pper_{it} = POP_{it}/POP_t$, where POP_{it} and POP_t are total population of province i and whole country in year t, respectively.

Second, calculate total CO_2 emissions of the i th province in the year t: Based on the relationship between economic growth and CO_2 emissions (Eldowma et al., 2023), CO_2 emissions of each province is calculated through three sources of production and from residentials as follows:

$$CO_{2it} = aper_{it} \times CO_{2agri,t} + iper_{it} \times CO_{2indus,t} + sper_{it} \times CO_{2ser,t} + pper_{it} \times CO_{2residential,t} \quad (8)$$

where CO_{2it} is the CO_2 emissions of province i in year t; $CO2_{agri,t}$, $CO_{2indus,t}$, $CO2_{sert}$, $CO_{2residential,t}$ are the country's total CO_2 emissions from agriculture, industries, services and residential, respectively.

Core independent variable. This study uses the following formula to calculate the extent of FDI spillover, in accordance with the methodology put forth by (Zamani and Tayebi, 2022):

$$FS = \frac{FDI_{it} \times EXPEND}{DI} \quad (9)$$

where FDI_{it} is province I's FDI stock in year t, EXPEND is the govenemtal budget for science and techonolgoy, DI is the total social fixed investment.

4.3.2. Control variables

(1) Marketlization degree (MAR). The ratio of employees of non-state-owned businesses to all employees in a province is a proxy for marketization since it can increase the allocation and utilization efficiency of production factors (Yu et al., 2021). (2) Industrial strutrure (IS) Changes in a province's industrial structure are reflected in the added value of the service sector as a percentage of GDP. (3) Trade openness (OPEN). The proportion of GDP to total goods imported and exported serves as a proxy for trade openness. (4) Energy consumption struture (ES). The provincial energy consumption structure is represented in this article by the percentage of coal consumption that is converted to standard coal relative to the total energy consumption (Ren, 2020). (5) State ownership (OWS). The ratio of state-owned enterprises' turnover to GDP is proxied to state ownership.

4.3.3. Moderator variables

(1) Digital transformation is represented by the Information and Communication Technology (ICI) Index, evaluated by the Ministry of Information and Communications in collaboration with the Vietnam Informatics Association. (2) Human capital upgrading. In accordance with Liu et al. (2024), advanced human capital structure serves as a stand-in for human capital upgrading in this study. It is constructed using the space vector angle formula and education data from labor force surveys conducted in Vietnam.

The result of descrptive statisitics are in Table 1.

Table 1 shows the model variable's descriptive statistics. Total 756 observations from Vietnam's 63 provinces between 2011 and 2022 make up the final sample. Significant differences in green production between provinces and years are indicated by the mean GTFP value of 1.002, which ranges from a minimum of 0.906 to a maximum of 1.077. With a standard deviation of 129.9745 and an average level of FDI spillover (FS) of 44.980, there appear to be notable regional variations in the way FDI has spread. The mean values for human capital upgrade (HC) and digitization (DIGITAL) are 55.15 and 0.4274, respectively, showing significant variation among provinces and years.

Table 1: Descriptive statistics

Variable	Obs.	Mean	Std. Dev.	Min.	Max.
GTFP	756	1.002	0.0131	0.906	1.077
FS	756	44.980	129.9745	0.000	1151.205
DIGITAL	756	0.4274	0.1280	0.0855	0.9407
HC	756	55.15	10.3709	19.74031	74.5272
MAR	756	92.118	31.6316	46.417	930.986
IS	756	1.11E-05	0.0001	6.92E-08	0.003
ES	756	21.256	6.2206	6.127	48.840
OPEN	756	173.684	549.4547	5.11E-07	9627.540
OWS	756	12.218	11.63185	0.029	84.364

5. FINDINGS AND DISCUSSION

5.1. Baseline Analysis

First, equation (5) is estimated using the ordinary least squares (OLS) and fixed-effect models, as described in the methods section. It is then estimated using the feasible generalized least squares (FGLS) method, which relaxes the assumption of independent and identically distributed random perturbation terms to account for the impact of potential heteroscedasticity and autocorrelation of provincial individual perturbation terms on estimation results.

Additionally, equation (5) is estimated using the System GMM. The AR (2) and Hansen test statistics are provided by the regression findings, which are used to evaluate the reliability of the tools employed in GMM regressions. Table 2 demonstrates the validity of all of the instrument variables used in this model, as the results of the Hansen and AR (2) tests are not rejected at the 10% significance level.

The system GMM regression findings show that the first lagged GTFP's coefficient is strongly negative at the 1% level, suggesting that the prior period will have an impact on the Vietnamese provinces' GTFPP and that dynamics must be included. These findings also show that, under the same conditions, the provincial GTFP rose by 0.003% on average for every 1% rise in FDI spillover. This suggests that FDI spillover improves the province's GTFP performance, which supports Hypothesis 1. In this sense, foreign direct investment (FDI) inflows have the potential to not only support clean production by local businesses through the effects of knowledge-technology spillover, competitive strengthening, synergy, and labor mobility, but also to enhance resource utilization efficiency and the green development process in Vietnamese provinces.

Table 2: Results of baseline regression

Variables	Dependent variable: GTFP			
	(1)	(2)	(3)	(4)
	POLS	FE	FGLS	System GMM
FS	0.002**	0.002*	0.001***	0.003**
	(0.0009)	(0.0010)	(0.0005)	(0.0014)
MAR	−0.007	−0.007	−0.003	−0.004**
	(0.0057)	(0.0060)	(0.0040)	(0.0022)
IS	0.002**	0.002*	0.002***	0.002*
	(0.0007)	(0.0008)	(0.0005)	(0.0011)
ES	0.028***	0.029***	0.026***	0.024***
	(0.0039)	(0.0041)	(0.0042)	(0.0047)
OPEN	0.000	0.000	−3.39e-05	0.003***
	(0.0002)	(0.0002)	(0.0004)	(0.0011)
OWS	0.001	0.002	0.003*	0.002
	(0.0015)	(0.0015)	(0.0015)	(0.0015)
L.GTFP				−0.182***
				(0.0618)
Constant	−0.001	−0.001	0.001	−0.001
	(0.0008)	(0.0009)	(0.0009)	(0.0004)
Rsq/Wald-Test	0.087	0.087	91.55***	91.55***
AR (1)				0.000
AR (2)				0.952
Hansen test				0,191
N	693	693	693	630

***P<0.01, **P<0.05, *P<0.1. In parenthesis there are standard errors

Additionally, most of the control variables have significant regression coefficients. The coefficients of trade openness and industrial structures are particularly favorable, implying that trade opening and industrial structure optimization are essential factors in improving GTFP. This is similar with the results of Yu et al. (2021) and the current economic development stage, as the country's manufacturing and processing sectors continue to be the main drivers of economic growth. In the meantime, the structure of energy consumption has a positive effect on GTFP, showing that Vietnam's economic growth still depends heavily on natural resources like coal, meaning that rising coal consumption continues to contribute to GTFP. This result is comparable to the findings of Ren (2020). On the other hand, the marketization degree has impeded the improvement of provincial GTFP, as indicated by the significantly negative coefficient of marketization (MAR). This could be due to the insufficient connection between private firms and other sectors of the Vietnamese economy. Finally, despite being positive, the coefficient of ownership (OWS) is not statistically significant, most likely because of the state-owned enterprises' unclear performance, resilience, and supervision.

5.2. Moderating Effect Analysis

This study investigates whether digital transformation and advanced human capital structure play moderating roles in the FDI spillover effect on provincial GTFP. The specific technique is to enhance the benchmark model with the interaction terms of the two primary explanatory variables, $FS_{it} \times DIGITAL_{it}$ and $FS_{it} \times AHCS_{it}$, respectively. The interaction term is evaluated logarithmically to avoid a large gap in data between factors that could affect the outcome. Table 3 displays the regression findings. While column (1) displays the baseline regression without the interaction term, columns (2) and (3) display the interaction term between digitalization and FDI spillover and the interaction term between human capital upgrading and FDI spillover, respectively.

Column (2) shows that the interaction term between digital transformation (DIGITAL) and FDI spillover (FS) has a regression coefficient that is significantly positive. This suggests that digital transformation has a positive regulatory influence on provincial GTFP of FDI spillover. Thus, digitization helps to mitigate the link between FDI spillover and GTFP, supporting hypothesis 2. According to the results, which support theoretical claims, digitalization may enhance the beneficial effects of FDI spillover on provincial green total factor production. Furthermore, the FS coefficient rose from 0.003 to 0.004 after adding the moderator factor, showcasing that digitalization enhances the impact of FDI spillover on GTFP.

Since the incorporation of digital tools and processes into production can help transfer the environmentally best practices and green technologies from foreign-funded companies to local firms, the crucial importance of digitalization in promoting green innovation and sustainable production processes can be explained (Zhang et al., 2021). Additionally, data-driven strategies, artificial intelligence, and big data analytics can help businesses improve their environmental performance and resource efficiency.

The interaction term of FDI spillover (FS) and human capital upgrading (HC) has a significantly positive regression coefficient, as shown in column (3), indicating that advanced human capital structure enhances the positive effect of FDI spillover on GTFP. As a result, hypothesis 3, according to which the positive correlation between FDI spillover and GTFP is moderated by advanced human capital structure, is supported. This research shows that qualified human capital increases the benefits of foreign direct investment in increasing GTFP, highlighting the significance of having high-quality human capital as a positive modulator.

Table 3: Results from regression with a moderating effect

Dependent variable GTFP	System GMM		
	(1)	(2)	(3)
L.GTFP	−0.182***	−0.244***	−0.237***
	(0.0618)	(0.0172)	(0.0358)
FS	0.003**	0.004***	0.003*
	(0.0014)	(0.0016)	(0.0014)
FS×DIGITAL		0.003*	
		(0.002)	
FS×HC			0.076***
			(0.0227)
DIGITAL		−0.007**	
		(0.0029)	
HC			−0.022***
			(0.0060)
MAR	−0.004**	−0.004***	−0.003**
	(0.0022)	(0.0010)	(0.0013)
IS	0.002*	0.002***	0.002**
	(0.0011)	(0.0002)	(0.0010)
ES	0.024***	0.028***	0.023***
	(0.0047)	(0.0023)	(0.0043)
OPEN	0.003***	0.003***	0.003***
	(0.0011)	(0.0004)	(0.0007)
OWS	0.003	0.002***	0.001
	(0.0015)	(0.0006)	(0.0011)
Constant	−0.001	−0.007**	−0.000
	(0.0004)	(0.0029)	(0.0004)
Arrellano-Bond AR (1)	0.000	0.000	0.000
Arrellano-Bond AR (2)	0.952	0.359	0.773
Hansen test	0.191	0.671	0.427

***P<0.01, **P<0.05, *P<0.1. In parenthesis there are standard errors. AR (1), AR (2), and Hansen test show P values

High-quality human capital can help to boost both the rates of technical innovation in domestic production and the rate at which domestic technology imitates and catches up to that of technologically advanced countries (Benhabib and Spiegel, 1994). This may speed up the absorption and diffusion of FDI investments, hence explaining the importance of advanced human capital structure.

5.3. Analysis of the Threshold Effect

Based on Hansen's (1999) methodology, a threshold model is built for analysis to more correctly and intuitively reflect the influence of FDI spillover on GTFP at various levels of human capital. First, the threshold effect test, which is displayed in Table 4, indicates the presence of a double threshold.

A 300-time self-sampling test of the threshold effect of human capital is then conducted using the panel threshold regression model (9). Table 5 presents the regression results.

Table 4: Results of the threshold test

Threshold variable	Threshold type	F-value	P-value
Human capital upgrading	Single	17.40	0.0100
	Double	12.54	0.0533
	Triple	5.04	0.4867

Table 5: Threshold regression results

Variable	Coefficient
LFS (c<−0, 1872)	−0.023*** (0.0047)
LFS (−0,1872≤c≤−0,0871)	0.015** (0.0059)
LFS (c>−0,0871)	0.002* (0.0011)
Cons	−2.93e-05 (0.0007)
Control variables	YES
R-sq	0.449
N	630

***P<0.01, **P<0.05, *P<0.1. In parenthesis there are standard errors

When the advanced human capital structure is less than the threshold value of −0.1872, FDI spillover reduces GTFP. When the threshold value is exceeded and falls between −0.1872 and −0.0871, improving the advanced human capital structure has a strong positive impact on GTFP. This suggests that a more sophisticated human capital structure may more effectively leverage FDI investment for R&D spending, increase R&D efficiency and technological innovation, and so greatly boost the GTFP benefit of FDI spillover.

However, when the threshold value rises above −0.0871, the advanced human capital structure increases, and the impact of FDI spillover on provincial GTFP performance becomes considerable but diminishes. One possible explanation is that when human capital upgrading surpasses the threshold value, issues like overeducation and a misalignment between the industrial and human capital structures lead to a large influx of advanced human capital into inefficient firms, which in turn causes a dislocation between the human capital structure and regional needs (Zheng et al., 2020; Jiang and Guo, 2022). This, in turn, inhibits the provincial GTFP of FDI spillover.

5.4. Regional Heterogeneity Test

There are substantial disparities in terms of sustainable economic development across regions in Vietnam (Nguyen et al., 2025). While the analysis conducted previously has confirmed that FDI spillover has a major impact on increasing green total factor production, it is unknown whether this outcome varies among regions. As a result, this analysis seeks to investigate whether the impact of FDI spillover on GTFP differs between regions.

Based on six official socio-economic regions in Vietnam, these regions are combined into three major regions, including Northern, Central, and Southern region (Le, 2024).

Upon examining Table 6, it is observed that the FS coefficient in the central region subsample is positive but not statistically significant (0.0013). In contrast, the regression coefficients of FDI spillover in the northern and southern areas are 0.0028 and 0.0063, respectively, demonstrating significance and a positive relationship. This implies that FDI spillover has a negligible impact

Table 6: Regional heterogeneity

Variable	(1)	(2)	(3)
	Northern provinces	Central provinces	Southern provinces
L.GTFP	−0.2070***	−0.1870***	−0.1820***
	(0.0681)	(0.0637)	(0.0650)
FS	0.0028*	0.0013	0.0063*
	(0.0016)	(0.0024)	(0.0035)
MAR	−0.0042**	−0.0045**	−0.0040*
	(0.0020)	(0.0021)	(0.0021)
IS	0.0021	0.0022*	0.0020*
	(0.0012)	(0.0011)	(0.0011)
ES	0.0249***	0.0236***	0.0236***
	(0.0055)	(0.0053)	(0.0048)
OPEN	0.0027**	0.0030***	0.0030***
	(0.0012)	(0.0011)	(0.0011)
OWS	0.0024	0.0023	0.0022
	(0.0018)	(0.0016)	(0.0016)
Cons	−0.0002	−0.0002	−0.0006
	(0.0004)	(0.0003)	(0.0005)
N	250	190	190
AR (1)	0.0000	0.0000	0.0000
AR (2)	0.880	0.944	0.771
Hansen	0.101	0.134	0.108

***P<0.01, **P<0.05, *P<0.1. In parenthesis there are standard errors

on GTFP in the central region, though the effect is significant in both the northern and southern regions.

As highlighted by Nguyen et al. (2025), the Northern and Southern areas, which are distinguished by favorable geographic positions, solid infrastructure, and strategic investments in green initiatives, demonstrate a greater level of sustainable economic development than the Central region. In contrast, Central provinces with low levels of economic growth, poor infrastructure, and a lack of technical expertise may encounter considerable challenges to effectively implementing innovative foreign technologies (Herzer, 2025).

5.5. Robustness Test

To verify the accuracy of the findings, such as that FS encourages provincial GTFP, this research conducts three robustness tests (Table 7). The following three sections describe specific robust tests and related findings.

(1) Re-measure the dependent variable. The DEA model re-measured the province GTFP before integrating it into the regression model by using PM2.5, a crucial air quality metric, as an additional undesired outcome that was taken from the NASA SEDAC website. Column (1) shows that even after the GTFP indicator is replaced, FS is still quite beneficial.

(2) Substitute other techniques of measuring. The method used to assess the core independent variable (FS) is changed in this study since the way indicators are measured may have an impact on the regression results. The percentage of employment in foreign businesses in a region compared to the total number of jobs in that region is used to quantify FDI spillover, as suggested by Belitski et al. (2023). Column (2) demonstrates that although the FS coefficient decreased to 0.002, which is less than the baseline results (i.e., 0.003), the regression results remain positive at 10% significance,

Table 7: Robustness tests

Variable	(1) Re-measure GTFP	(2) Replace FS indicator	(3) Change estimation method
FS	0.002*	0.002*	0.008***
	(0.0014)	(0.0009)	(0.0023)
Control variables	Yes	Yes	Yes
Observations	630	630	630
AR (1)	0.015	0.000	0.000
AR (2)	0.777	0.822	0.128
Hansen test	0.154	0.352	0.125

***P<0.01, **P<0.05, *P<0.1. In parenthesis there are standard errors

indicating that the FDI spillover continues to have a substantial impact on GTFP.

(3) Change the technique for estimating models. The regression coefficient of FDI spillover, which remains strongly positive after applying differential GMM, is consistent with the results of the benchmark regression.

6. CONCLUSION AND IMPLICATIONS

Resource utilization efficiency and pollution control emissions are crucial to a country or region's competitiveness. To maintain competitive advantages, it has become vital to create GTFP by integrating ecological and environmental conservation with economic and social development (Zhang et al., 2024; Yu et al., 2022; Wang et al., 2022). This study examined how host provinces might boost GTFP when FDI inflows, digital transformation, and human capital upgrading are present in the local business environment.

We first contributed to the FDI spillovers literature by outlining the link between FDI externalities and provincial GTFP. By looking at provincial GTFP, which combines economic growth with resource use and environmental preservation (Tian and Feng, 2022), this study resolves the contradicting data and offers a plausible explanation of a region's high-quality economic development.

Our data suggests that there is a positive FDI spillover on province-level GTFP. Local businesses benefit from an expanded pool of cutting-edge production technology and management expertise provided to their area by FDI-invested businesses, which encourages resource optimization and pollution control and raises the province's gross domestic product. This result validates the significance of FDI inflow for green growth and is in line with the findings of Xie and Zhang (2021) and Wu et al. (2020). In addition, the promotion of effect of FDI spillover on provincial GTFP is mainly observed in the northern and southern regions.

Our second contribution is to expand the research on FDI spillovers by elucidating the moderating impacts of digital transformation and human capital upgrading to explain their catalytic role in the dissemination of FDI knowledge. As a source of knowledge transfer, FDI spillovers do rely on interpersonal connections and the degree of environmental integration of recipient enterprises (Ning et al., 2016). Although earlier research has mostly focused on the impact of technological gaps, institutions, and absorptive capacity on productivity (Mai Lan et al., 2024; Li et al., 2020; Razzaq et al., 2021), little is known about the moderating effects of digital transformation and human capital upgrading, both theoretically and empirically. This study examined the moderating impacts of digital transformation and human capital upgrading on FDI productivity spillover, drawing on the literature on digitalization and human capital (Zhong and Ma, 2024; Zheng et al., 2020; Jiang and Guo, 2022).

Our empirical results suggest that the association between FDI spillover and GTFP is moderated by digitalization, indicating that areas with greater digital advancement are more likely to gain from the development in GTFP brought about by FDI's green technologies and environmental best practices. Similarly, improvements in human capital have reinforced the effect of FDI spillovers on GTFP, suggesting that a skilled workforce can help FDI inflows be absorbed and dispersed.

Our third contribution is that the study supports the need for additional research in developing countries, inquiring not just whether spillovers exist but also how they arise by looking inside the "black box" (Demena and Murshed, 2018). Given the significant differences in advanced human capital between Vietnamese areas, the effects of FDI spillover on GTFP may differ depending on the advanced human capital structure, even though previous research typically ignores the nonlinear influence of FDI spillover on provincial GTFP.

The results show that the beneficial effect of FDI spillover on provincial GTFP has a discernible double threshold effect when human capital upgrading changes. Specifically, when the advanced human capital structure is below the first threshold value, FDI spillover inhibits GTFP; nevertheless, when the structure's value surpasses the first threshold, the GTFP of FDI shows a marginally expanding feature. However, the effect of FDI spillover on GTFP exhibits a somewhat declining tendency when the structure is beyond the second threshold value.

The study has significant implications for scholars and policymakers who want to promote green growth and get a better understanding of the effects of foreign direct investment on the environment and economy. In order to attract foreign capital with advanced technology, high added value, and a high management level, policymakers should first concentrate on fostering a business environment that would further encourage the amount of foreign investment in the green environmental protection sector. Second, in order to benefit from digital transformation, it is imperative to prioritize investments in digital infrastructure and the development of digital skills. Thirdly, policymakers should focus particularly on developing skilled labor, making sure that workers have the credentials and abilities needed to assimilate and spread FDI's technology and best practices. Additionally, labor development initiatives should be thoughtfully crafted to prevent over-education and a misalignment between the industrial and human capital structures. Finally, policymakers should acknowledge regional disparities in the impact of FDI spillover on GTFP and devise specific measures to address each region's distinct difficulties

and potential. Policies in the northern and southern areas must encourage innovation and the use of modern green technologies in production. In the central region, efforts should be made to improve the transport infrastructure and socio-economic structure to leverage FDI inflow for long-term sustainable development.

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