

Article

Digital Economy Development and Green Total Factor Productivity: Evidence from the Yangtze River Delta Region

Jun Ma, Mengqi Sun * and Changgao Cheng

School of Economics and Finance, Hohai University, Changzhou 213200, China; majun1807@163.com (J.M.); changgao95@hhu.edu.cn (C.C.)

* Correspondence: 15385948593@163.com

Abstract

Achieving a balance between economic expansion and environmental preservation is a core challenge of sustainable development. Based on panel data from 41 cities in the Yangtze River Delta region from 2006 to 2023, this study develops a digital economy index, measures GTFP using the SBM-GML framework, and examines the relationship between digital economy development and GTFP. The results show that digital economy development is positively associated with GTFP, and the findings remain robust after a series of robustness and endogeneity tests. Further moderating analysis indicates that industrial structure rationalization, industrial structure advancement, green innovation, and ecological compensation policy strengthen the relationship between digital economy development and GTFP. Heterogeneity analysis shows that this relationship is stronger in high-tier cities, highly urbanized cities, and Broadband China demonstration cities. Spatial analysis further suggests that digital economy development may generate spillover effects through intercity linkages within the Yangtze River Delta. By integrating digital transformation, ecological governance, regional interdependence, and green productivity improvement into a unified analytical framework, this study provides city-level evidence for promoting coordinated green transformation and sustainable regional development.

Keywords: green total factor productivity; digital economy; green innovation; sustainable development; industrial structure

1. Introduction

Growing pressure from resource constraints and environmental governance has made the transition toward greener and more sustainable development an important issue for China's regional economies. Against this backdrop, the expansion of digital technologies has created new opportunities for improving production efficiency and supporting economic restructuring. However, traditional extensive growth models, while promoting economic expansion, have also led to severe challenges such as resource depletion and ecological degradation, thereby constraining sustainable development. Under these circumstances, balancing economic growth with environmental protection and promoting a green transition have become critical challenges worldwide.

Under China's current development strategy, digitalization and green transition are being promoted simultaneously, with increasing attention given to the coordination between technological progress and environmental governance. As China continues to advance low-carbon development, digital technologies are increasingly influencing the operation of economic activities and industrial systems. The application of digital platforms and



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information technologies has also created new possibilities for improving resource allocation and environmental performance [1]. Green total factor productivity (GTFP) is widely used to assess the quality of economic growth while taking resource consumption and environmental costs into account. It reflects the combined performance of output expansion and pollution reduction under given input conditions, and thus provides an important measure of whether regional development has achieved a green transition [2–4]. The digital economy and GTFP are closely linked. With its strong penetration, spillover effects, and networked characteristics, the digital economy provides new opportunities to reconcile economic efficiency with environmental protection, thereby generating new momentum for improving GTFP. In turn, GTFP offers a useful criterion for assessing whether digital economy development contributes to high-quality and sustainable growth.

The Yangtze River Delta region provides a particularly relevant context for examining the relationship between the digital economy and GTFP. As one of China's most economically dynamic and institutionally integrated regions, the Yangtze River Delta has relatively advanced digital infrastructure, dense industrial networks, and frequent intercity flows of capital, labor, technology, and information. Meanwhile, ongoing regional integration and cross-regional ecological governance have strengthened the links among cities in industrial coordination, environmental regulation, and infrastructure construction. These characteristics suggest that the influence of the digital economy may not be confined within local administrative boundaries. Instead, digital economy development may be associated with GTFP not only through local efficiency improvement, but also through spatial spillovers generated by technology diffusion, industrial linkages, digital infrastructure connectivity, and coordinated ecological governance. Therefore, examining the Yangtze River Delta helps reveal how digitalization and green productivity interact within a highly connected urban system.

However, the region still faces resource and environmental constraints, as well as substantial pressure to reduce pollution [5]. Although the Yangtze River Delta has made considerable progress in digital transformation and regional integration, differences remain across cities in digital infrastructure, industrial structure, innovation capacity, and environmental governance intensity. These differences may shape the extent to which digital economy development is associated with GTFP [6]. In this sense, the Yangtze River Delta is not only a representative case of China's green and digital transformation, but also a useful setting for examining how local digital development, regional spillovers, internal structural conditions, and external policy incentives jointly relate to green productivity improvement.

Existing research has paid considerable attention to the relationship between the digital economy and green total factor productivity (GTFP) [7,8]. From a theoretical perspective, the expansion of digital technologies can facilitate information exchange and optimize the distribution of production factors, which in turn enhances operational efficiency and resource use. In addition, digital technologies provide new approaches for environmental monitoring and industrial management, which may support the transition toward more efficient and low-carbon patterns of economic development [9,10]. In terms of measurement, to better capture productivity under environmental constraints, studies commonly employ SBM and EBM-GML models that incorporate undesirable outputs to evaluate GTFP [11,12]. Empirical research has further extended this topic across multiple dimensions. For instance, public data openness has been found to improve GTFP [13], while firm-level evidence shows that digital transformation is positively associated with GTFP, particularly under stricter environmental regulation [14,15]. In addition, digital economy development can also contribute to greener and more efficient manufacturing activities [16].

Nevertheless, several aspects of this relationship remain insufficiently explored. First, although existing studies have provided important evidence on the digital economy–GTFP

nexus, many of them focus on the average local effect and give limited attention to the spatial dependence among cities. This is particularly important for integrated urban regions, where digital infrastructure, industrial chains, innovation resources, and ecological governance often operate across administrative boundaries. Second, existing studies have explained the digital economy–GTFP relationship from multiple perspectives, but these explanations are often developed in relatively separate analytical settings. Less attention has been paid to how the broader structural, technological, and institutional environment within an integrated urban region jointly shapes the strength and boundary conditions of this relationship. Third, while city-level evidence has gradually increased, the theoretical significance of city-level analysis still requires clearer explanation. In the Yangtze River Delta, cities are embedded in a highly connected regional system. Therefore, city-level analysis can capture not only local differences, but also the regional interdependence generated by spatial spillovers, infrastructure connectivity, and cross-regional ecological coordination.

Motivated by these considerations, this study draws on panel data from 41 cities in the Yangtze River Delta region from 2006 to 2023 to examine the relationship between digital economy development and GTFP. This study constructs a digital economy index, measures GTFP using an SBM-GML framework, and estimates the association between the digital economy and urban GTFP. It further introduces industrial structure rationalization, industrial structure advancement, green innovation, and ecological compensation policy as moderating conditions to examine whether internal structural factors and external policy incentives shape this relationship. In addition, considering the strong intercity linkages within the Yangtze River Delta, this study conducts spatial correlation and spatial spillover analysis to examine whether digital economy development is also associated with GTFP changes beyond the local city.

This study contributes to the literature in three main ways. First, it shifts the analysis from a purely local perspective to a regional interdependence perspective. By incorporating spatial correlation and spillover effects, this study examines whether digital economy development is associated not only with local GTFP, but also with green productivity changes across connected cities. Second, it incorporates industrial structure, green innovation, and ecological compensation policy into a unified framework as moderating conditions. This helps clarify the conditions under which the digital economy is more strongly associated with GTFP. Third, it examines heterogeneity across city tier, urbanization level, and digital infrastructure conditions, offering more targeted evidence on how urban characteristics shape the digital economy–GTFP relationship.

Overall, this study aims to deepen the understanding of how digital economy development is associated with green productivity improvement in a highly integrated urban region. The findings may provide useful implications for coordinating digital transformation, industrial upgrading, ecological governance, and regional integration in the pursuit of sustainable development.

2. Theoretical Framework and Hypotheses

The Yangtze River Delta is not a collection of isolated cities, but a highly integrated regional system. Digital economy development in this region is embedded in dense intercity networks of production, innovation, infrastructure, and environmental governance. Therefore, the digital economy may be associated with GTFP through both local channels and regional spillover effects. At the same time, the strength of this relationship may depend on whether a city has favorable industrial structure, green innovation capacity, and external policy incentives. Based on this logic, this study constructs a theoretical framework centered on the relationship between digital economy development and GTFP. The framework first explains the basic association between the digital economy and GTFP,

and then examines how internal structural conditions and external policy incentives shape the strength of this relationship. Considering the integrated characteristics of the Yangtze River Delta, spatial correlation and spillover effects are further examined in the empirical analysis to provide additional evidence on the regional interdependence of the digital economy–GTFP relationship.

2.1. How the Digital Economy Influences GTFP

Relying on data and information technology, the digital economy advances the shift toward greener development. GTFP measures productivity performance under both resource and environmental constraints, so its improvement depends not only on output expansion, but also on more efficient resource use and the reduction in undesirable outputs. From this perspective, the digital economy may be associated with GTFP through three main aspects.

From the production perspective, the integration of digital technologies changes how firms organize production activities. Digital platforms, intelligent equipment, and data-based management systems improve the collection and processing of production information, allowing firms to adjust production schedules, monitor equipment operation, and manage material and energy inputs more accurately. This helps reduce redundant production links and improves the coordination between factor inputs and output generation. In this process, digital technologies support smart manufacturing [17] and green production transformation [18]. Evidence from pollution-intensive firms also suggests that digital investment can improve environmental performance by enhancing production efficiency [19]. Therefore, digital economy development may help cities improve GTFP by raising production efficiency under resource and environmental constraints.

The digital economy also affects GTFP through resource allocation. In traditional urban economies, information barriers and transaction costs may prevent production factors from moving toward more efficient sectors and firms. Digital technologies weaken these barriers by improving information connectivity among firms, industries, markets, and governments. Through information sharing and factor mobility, the digital economy reduces search costs, promotes the allocation of capital and technology toward high-efficiency and low-energy-consumption sectors, and improves overall resource allocation efficiency [20,21]. Digitization can reduce transaction costs and information asymmetry, which helps improve green productivity performance [22]. Since GTFP reflects the ability to generate desired output with fewer inputs and lower environmental costs, more efficient factor allocation provides an important explanation for the relationship between digital economy development and GTFP.

In the field of environmental governance, digital technologies strengthen monitoring and supervision capacity. Traditional environmental governance often faces information delay and difficulties in identifying pollution sources. By using IoT devices, remote monitoring, big data platforms, and intelligent sensing systems, governments can track energy consumption, pollutant emissions, and environmental risks more accurately. This improves the precision of environmental regulation and helps local governments adopt more targeted governance measures [23]. In addition, the digital economy can interact with environmental regulation by improving information disclosure, reducing regulatory costs, and strengthening the connection between government supervision and firm behavior, thereby contributing to GTFP improvement [24]. Therefore, digital economy development may be linked to GTFP improvement by reducing undesirable outputs and enhancing the efficiency of environmental governance.

Overall, the digital economy helps reconcile economic development with environmental objectives through several pathways, providing new momentum for improving GTFP. On this basis, we formulate the subsequent hypothesis:

H1. *Digital economy development is positively associated with GTFP in the Yangtze River Delta region.*

2.2. Moderating Effects

Industrial structure affects the way digital technologies enter production activities and reshape resource use. The digital economy can improve information transmission and reduce transaction costs, but these advantages need to be embedded in specific industries before they can be reflected in GTFP. Existing studies usually examine industrial structure from two dimensions: rationalization and advancement [25].

Industrial structure rationalization reflects the matching relationship between sectoral output and factor input. A more rational industrial structure means that labor, capital, and technology are distributed more consistently with sectoral productivity and comparative advantages. When this matching relationship is weak, factor misallocation may keep resources in low-productivity or high-emission sectors. Under such circumstances, digital technologies may improve information flow, but their effect on GTFP will be constrained by distorted factor allocation and weak sectoral coordination. Data flows and digital platforms make production demand, factor supply, and industrial collaboration more visible, which helps reduce search costs and strengthen the division of labor among firms [26]. They also promote the allocation of production factors toward sectors with higher efficiency and lower energy intensity [27]. For cities with a more rational industrial structure, digital technologies can be more effectively translated into resource-saving and pollution-reducing outcomes. Therefore, industrial structure rationalization may strengthen the relationship between digital economy development and GTFP.

In the Yangtze River Delta, this logic is also reflected in the regional division of labor. Cities in the region are connected through manufacturing chains, producer services, logistics networks, and technology flows. A more coordinated industrial structure can help digital platforms improve supply-demand matching across cities, reduce repeated low-end production, and support cleaner forms of industrial collaboration. When industrial coordination is weak, the benefits of digitalization may remain concentrated in several leading cities or sectors, limiting its contribution to wider green productivity improvement. Accordingly, the following hypothesis is developed:

H2. *Industrial structure rationalization favorably moderates the relationship between digital economy development and GTFP.*

Industrial structure advancement reflects the shift of an urban economy from resource-intensive and low-value-added activities toward technology-intensive, knowledge-intensive, and service-oriented activities. This shift changes the industrial environment in which digital technologies are adopted and used. Compared with traditional industries, advanced industries rely more on information processing, technological capability, human capital, and supply-chain coordination. These characteristics make them more compatible with digital technologies. As industrial structure advances, firms are more likely to embed digital tools into production management, logistics coordination, product development, and environmental monitoring [28,29].

Advanced industries also provide a stronger industrial basis for green transformation. High-end industries generally have stronger green technology spillover effects and environmental governance capacity [30], which enables cleaner production practices and

green technologies to diffuse along industrial chains [31]. In the Yangtze River Delta, the development of advanced manufacturing, digital industries, and producer services expands the application scenarios of digital technologies, such as intelligent manufacturing, digital logistics, platform-based services, and environmental monitoring. This makes digital economy development more closely connected with resource-saving production and low-carbon industrial coordination. Accordingly, the following hypothesis is developed:

H3. *Industrial structure advancement positively moderates the relationship between digital economy development and GTFP.*

Green innovation affects whether digital technologies can be connected with environmental improvement rather than remaining at the level of general efficiency gains. Digital economy development improves information acquisition, process monitoring, and organizational coordination, but reductions in energy use and pollutant emissions still depend on the availability and application of cleaner technologies. When green innovation capacity is limited, digital tools may mainly improve management efficiency, while their environmental contribution remains constrained. When green innovation capacity is stronger, firms can use digital information to identify resource losses, adjust production processes, and apply cleaner technologies more precisely [32].

At the urban level, green innovation also provides more technical interfaces for digital-enabled green transformation. Energy-saving technologies, cleaner production processes, and environmentally friendly products make it easier for digital tools to be applied to resource management, pollution control, and low-carbon production. Through industrial chains and inter-firm learning, these technologies can further diffuse across production networks [33]. In this sense, green innovation strengthens the conditions under which digital economy development is associated with higher output efficiency, lower resource intensity, and better environmental performance.

H4. *Green innovation positively moderates the relationship between digital economy development and GTFP.*

Ecological compensation policy provides an institutional setting in which digital economy development can be more closely connected with environmental governance. By linking fiscal incentives, ecological protection responsibilities, and regulatory constraints, ecological compensation helps internalize environmental externalities and discourages pollution-intensive development [34,35]. This is particularly relevant in the Yangtze River Delta, where environmental issues are often shaped by cross-city river basins, industrial linkages, and regional ecological coordination rather than by single-city governance alone.

Under ecological compensation policy, local governments and firms face stronger incentives to use digital technologies for pollution monitoring, resource management, and ecological performance evaluation. Digital platforms, remote sensing, and real-time monitoring systems can reduce information asymmetry in ecological governance and improve the transparency of cross-regional supervision. In this context, digital economy development is less likely to remain limited to economic expansion and more likely to be embedded in environmental governance practices.

Therefore, ecological compensation policy may strengthen the relationship between digital economy development and GTFP by providing clearer environmental constraints and stronger governance incentives. In the Yangtze River Delta, this moderating role also reflects the region's need for coordinated ecological protection across administrative boundaries.

H5. *Ecological compensation policy positively moderates the relationship between digital economy development and GTFP.*

Based on the above analysis, Figure 1 presents the theoretical framework for how the digital economy affects GTFP.

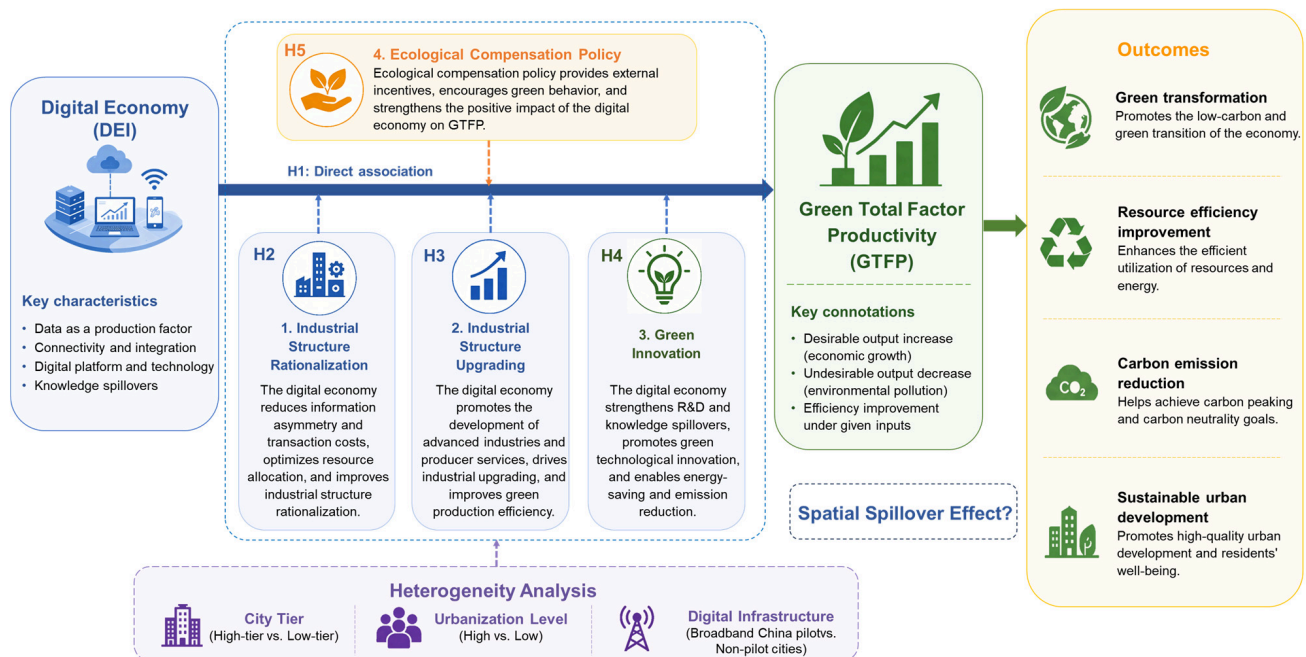


Figure 1. Theoretical Framework.

3. Materials and Methods

3.1. Variables

3.1.1. Dependent Variables

This study uses urban green total factor productivity (GTFP) as the dependent variable. GTFP is measured within a production framework that incorporates factor inputs, desirable economic output, and undesirable environmental outputs [36]. Compared with traditional total factor productivity, GTFP is more suitable for evaluating green development because it considers both economic performance and environmental costs in the production process.

The input indicators include labor, capital, and energy consumption. Labor input is measured by the number of employed persons, reflecting the scale of human resources engaged in urban production activities. Capital input is represented by urban fixed capital stock, which is calculated using the perpetual inventory method [37]. Following this method, capital stock is obtained by adding current real investment to the depreciated capital stock from the previous period, with investment converted into constant-price terms, the detailed procedure is provided in Appendix A. Energy input is measured by total urban electricity consumption, which captures the major resource input in urban economic activities. The desirable output is measured by GDP at constant 2006 prices, reflecting real economic output after excluding price effects. Undesirable outputs include industrial wastewater discharge, industrial sulfur dioxide emissions, and industrial particulate matter emissions, which represent the environmental costs generated during urban production. The complete indicator system is reported in Figure 2.

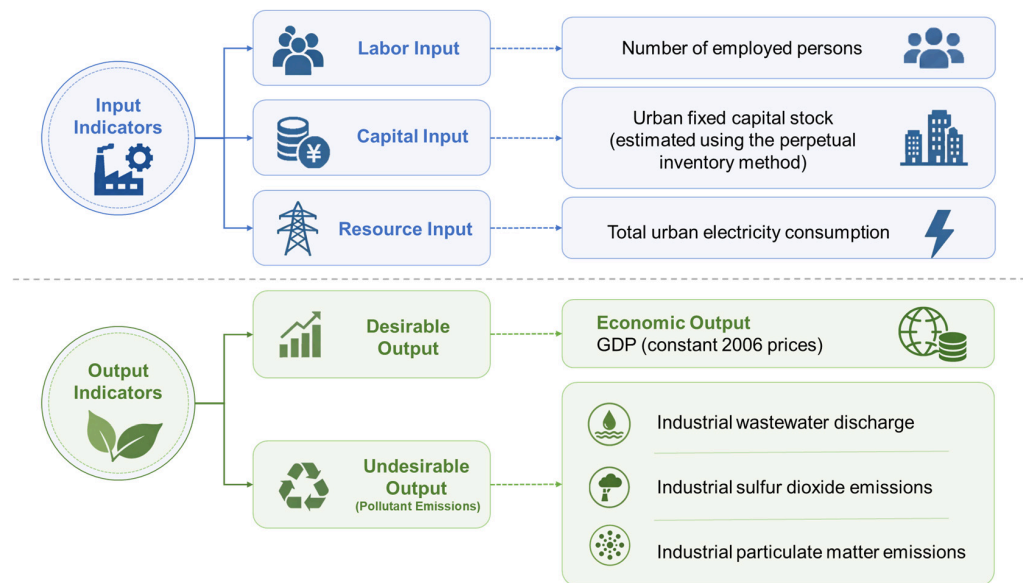


Figure 2. Measurement Indicators of GTFP.

To evaluate GTFP, this study adopts a non-oriented global SBM model with undesirable outputs under the variable returns to scale assumption [38]. In this framework, labor, capital, and energy are treated as inputs, GDP is treated as the desirable output, and industrial wastewater, industrial sulfur dioxide, and industrial particulate matter emissions are incorporated as undesirable outputs. The non-oriented setting allows input contraction, desirable output expansion, and undesirable output reduction to be evaluated simultaneously, while the SBM structure accounts for input and output slacks.

The SBM model with undesirable outputs can be expressed as follows:

$$\begin{aligned}
 \rho = \min & \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{ik}}}{1 + \frac{1}{q_1 + q_2} \left(\sum_{r=1}^{q_1} \frac{s_r^g}{y_{rk}^g} + \sum_{t=1}^{q_2} \frac{s_t^b}{y_{tk}^b} \right)} \\
 & x_k = X\lambda + s^- \\
 & y_k^g = Y^g\lambda - s^g \\
 & y_k^b = Y^b\lambda + s^b \\
 & \lambda \geq 0, s^- \geq 0, s^g \geq 0, s^b \geq 0, \sum_{j=1}^n \lambda_j = 1
 \end{aligned} \tag{1}$$

where ρ denotes the SBM efficiency score; x_k , y_k^g , and y_k^b represent the input, desirable output, and undesirable output vectors of decision-making unit k , respectively; s^- , s^g , and s^b denote input slack, desirable output slack, and undesirable output slack, respectively; λ is the intensity vector; m , q_1 , and q_2 denote the numbers of inputs, desirable outputs, and undesirable outputs. A higher value of ρ indicates better green production efficiency under resource and environmental constraints.

On this basis, the GML productivity index is used to construct the dynamic GTFP series. The global reference technology set improves the comparability of productivity changes across years and avoids the intertemporal inconsistency that may arise from using separate period-specific frontiers. Taking 2006 as the benchmark year, the annual GML indexes are chain-linked to obtain the GTFP values for 2006–2023. As an additional check, GTFP is also recalculated using the EBM-GML approach and used as an alternative dependent variable in the robustness test.

3.1.2. Core Explanatory Variables

The core explanatory variable is the digital economy development index (DEI). Considering the accessibility of city-level data and drawing on previous studies [39], this study evaluates the digital economy from two aspects: Internet development and digital financial inclusion. The former reflects the infrastructure basis, labor support, and service output of urban digitalization, while the latter captures the penetration of digital technologies into financial services and broader economic activities.

Five indicators are selected to construct the DEI: the Digital Financial Inclusion Index of China, Internet broadband users per 100 people, mobile telephone users per 100 people, the share of employees in computer services and software industries and per capita telecommunication business volume. These indicators respectively reflect digital financial inclusion, Internet access, mobile communication use, digital-related employment and digital service output.

The entropy method is used to synthesize the five indicators into a comprehensive DEI. In the calculation, indicator weights are derived from the information variation in the full city-year sample, so that the constructed index remains comparable across cities and over time. Compared with subjective weighting methods, the entropy method reduces arbitrariness in index construction. The indicator system and entropy-based weights are reported in Figure 3. A higher DEI value indicates a higher level of urban digital economy development.

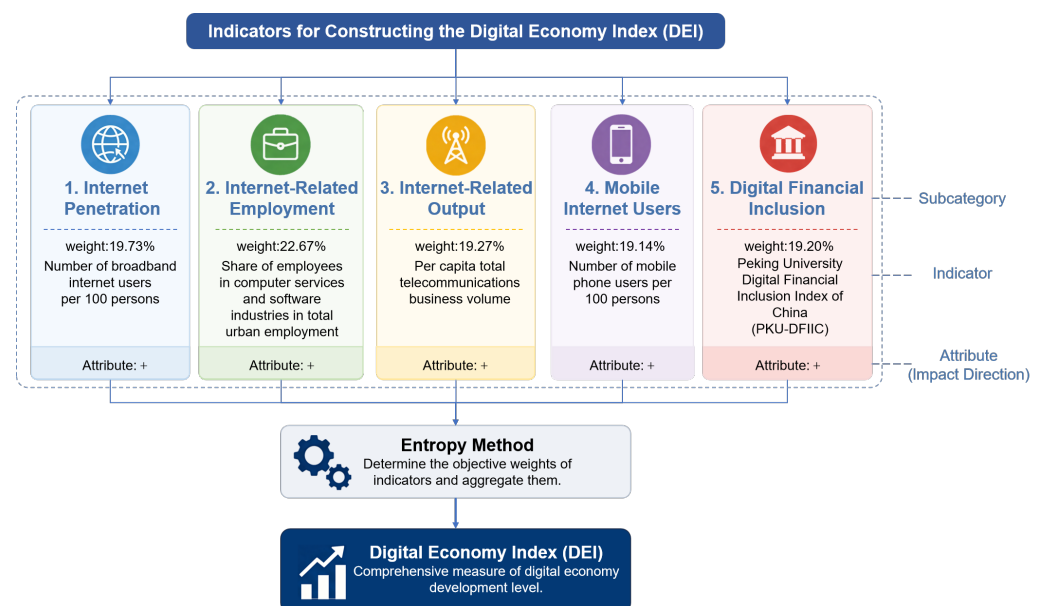


Figure 3. Framework for Constructing the Digital Economy Index.

3.1.3. Control Variables

Several variables are introduced to control for other factors associated with GTFP. Regional economic conditions (*lnpgdp*) are reflected by the logarithm of per capita regional GDP, while financial market development (*lnfina*) is obtained by applying a logarithmic transformation to the ratio between year-end deposits and loans of financial institutions and regional GDP. The openness (*open*) is captured through the proportion of actual utilized foreign direct investment relative to regional GDP. Fiscal investment intensity (*inv*) is reflected by the share of fixed-asset investment in general public budget expenditure. Human capital (*hc*) is reflected by the share of students enrolled in regular higher education institutions within the total population.

3.1.4. Moderating Variables

(1) Rationalization of Industrial Structure (*theil*)

Industrial structure rationalization indicates the extent to which production factors are efficiently allocated among industries, capturing the degree of factor mobility and structural balance within the economy. It provides an important perspective for assessing the performance of the economic system. A more rational industrial structure promotes a more efficient distribution of production resources, thereby enabling digital economy development to generate stronger gains in GTFP.

The Theil index is employed to represent the level of rationalization and is specified as follows:

$$theil_{i,t} = \sum_{m=1}^3 y_{i,m,t} \ln \left(\frac{y_{i,m,t}}{l_{i,m,t}} \right), \quad m = 1, 2, 3 \quad (2)$$

where $theil_{i,t}$ denotes the Theil index for city i at time t ; $y_{i,m,t}$ refers to the proportion of sector m 's output in the GDP of city i at time t ; $l_{i,m,t}$ refers to the employment proportion of sector m in city i during year t . A value of zero corresponds to a completely balanced industrial structure, whereas lower index values indicate a higher degree of rationalization.

(2) Industrial Structure Advancement (*indh*)

This concept describes the process by which the industrial system evolves gradually shifts toward sectors with stronger technological capabilities and higher value creation. It reflects both economic advancement and structural change within the industrial system. With industries shifting toward more advanced sectors, digital technologies can be absorbed and applied more effectively, thereby improving production efficiency and environmental performance while increasing the contribution of digital economy development to GTFP.

The industrial structure advancement index is derived from the relationship between sectoral output and employment [40]. The index is calculated as:

$$indh_{i,t}^* = \sum_{m=1}^3 y_{i,m,t} \left(\frac{Y_{i,m,t}}{L_{i,m,t}} \right) \quad m = 1, 2, 3 \quad (3)$$

where $Y_{i,m,t}$ denotes the economic output generated by sector m in city i during year t , and $L_{i,m,t}$ represents the corresponding number of employees. The variable $y_{i,m,t}$ is defined as in Equation (2), representing the output share of sector m .

To eliminate the influence of units, the Z-score method is used to standardize the ratio $Y_{i,m,t} / L_{i,m,t}$. The standardized index is then normalized to the range [0,1] as follows: $indh = \left[\frac{Z_{i,t}}{\max(Z_{i,t})} \right] \times 0.4 + 0.6$, $Z_{i,t}$ denotes the industrial structure advancement index after standardization. Greater industrial advancement is associated with larger *indh* values.

(3) Green Innovation (*gti*)

Green innovation plays a key role in promoting the synergy between economic growth and environmental improvement. By facilitating the diffusion of environmentally friendly technologies, cities can reduce pollutant emissions while improving production efficiency. This study measures green innovation (*gti*) by the natural logarithm of the number of green invention patent applications at the city level, plus one, which also addresses the issue of zero values [41].

(4) Ecological Compensation Policy (*policy*)

Ecological compensation policy is an important environmental governance instrument that internalizes environmental externalities through fiscal compensation and policy incentives for ecological protection areas. Such policies strengthen green development incentives for local governments and enterprises, enabling digital technologies to play a greater role

in ecological governance. This study measures ecological compensation policy (*policy*) using a dummy variable. The variable takes a value of 1 for cities covered by the ecological compensation pilot program and 0 for all other cities.

3.2. Econometric Framework

3.2.1. Benchmark Model

To assess the relationship between digital economy development and GTFP, the following benchmark model is employed:

$$GTFP_{i,t} = \alpha_0 + \alpha_1 DEI_{i,t} + \alpha_2 X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (4)$$

In Equation (4), $GTFP_{i,t}$ represents the level of green total factor productivity; while $DEI_{i,t}$ captures the corresponding extent of digital economy development. $X_{i,t}$ represents a vector of control variables; μ_i and λ_t correspond to city-specific and year-specific effects, respectively; and $\varepsilon_{i,t}$ captures the error term.

3.2.2. Moderating Effect Model

To examine the moderating effects linking digital economy development and GTFP, interaction terms between DEI and the moderating variables are added to the benchmark model. Specifically, industrial structure rationalization, industrial structure advancement, green innovation, and ecological compensation policy are introduced to capture their moderating effects.

The following models are estimated:

$$GTFP_{i,t} = \beta_0 + \beta_1 DEI_{i,t} + \beta_2 (DEI_{i,t} \times theil_{i,t}) + \beta_3 theil_{i,t} + \beta_4 X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (5)$$

$$GTFP_{i,t} = \gamma_0 + \gamma_1 DEI_{i,t} + \gamma_2 (DEI_{i,t} \times indh_{i,t}) + \gamma_3 indh_{i,t} + \gamma_4 X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (6)$$

$$GTFP_{i,t} = \delta_0 + \delta_1 DEI_{i,t} + \delta_2 (DEI_{i,t} \times gti_{i,t}) + \delta_3 gti_{i,t} + \delta_4 X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (7)$$

$$GTFP_{i,t} = \theta_0 + \theta_1 DEI_{i,t} + \theta_2 (DEI_{i,t} \times policy_{i,t}) + \theta_3 policy_{i,t} + \theta_4 X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (8)$$

In Equations (5)–(8), *theil*, *indh*, *gti*, and *policy* denote the moderating variables capturing moderating effects. The remaining variables follow the definitions provided in Equation (4).

3.2.3. Spatial Econometric Model

Considering the strong intercity linkages within the Yangtze River Delta, this study further introduces a spatial econometric model to examine the spatial association between digital economy development and GTFP. Before estimating the spatial model, Moran's I is used to test whether GTFP shows spatial correlation across cities. The Moran's I statistic is calculated as follows:

$$I_t = \frac{N}{S_0} \frac{\sum_{i=1}^N \sum_{j=1}^N W_{ij} (GTFP_{it} - \overline{GTFP_t}) (GTFP_{jt} - \overline{GTFP_t})}{\sum_{i=1}^N (GTFP_{it} - \overline{GTFP_t})^2} \quad (9)$$

where N denotes the number of cities, W_{ij} is the spatial weight between city i and city j , and $S_0 = \sum_{i=1}^N \sum_{j=1}^N W_{ij}$. A significantly positive Moran's I indicates that GTFP is spatially clustered, which provides a basis for further spatial econometric analysis.

This study then estimates a spatial Durbin model, which can simultaneously incorporate the spatial lag of the dependent variable and the spatial lags of explanatory variables. The model is specified as follows:

$$GTFP_{it} = \rho \sum_{j=1}^N W_{ij} GTFP_{jt} + \alpha DEI_{it} + \theta \sum_{j=1}^N W_{ij} DEI_{jt} + \gamma X_{it} + \delta \sum_{j=1}^N W_{ij} X_{jt} + \mu_i + \lambda_t + \varepsilon_{it} \quad (10)$$

where $GTFP_{it}$ denotes green total factor productivity of city i in year t , DEI_{it} denotes digital economy development, and X_{it} represents the vector of control variables. W_{ij} is the element of the spatial weight matrix. ρ captures the spatial dependence of GTFP, while θ and δ capture the spatial associations of DEI and the control variables, respectively. μ_i and λ_t represent city fixed effects and year fixed effects.

The spatial weight matrix used in this study is an economic–geographic nested matrix, which captures both geographic proximity and economic similarity among cities. The initial spatial weight is defined as follows:

$$w_{ij}^{eg} = \begin{cases} \frac{1}{d_{ij}^{geo}} \times \frac{1}{|\overline{pgdp}_i - \overline{pgdp}_j|}, & i \neq j \\ 0, & i = j \end{cases} \quad (11)$$

where d_{ij}^{geo} denotes the geographic distance between city i and city j , and $|\overline{pgdp}_i - \overline{pgdp}_j|$ denotes the difference in average per capita GDP between the two cities. If the economic distance between two cities equals zero, it is replaced by a very small value to avoid division by zero. The diagonal elements are set to zero. The matrix is then row-standardized as follows:

$$W_{ij}^{eg} = \frac{w_{ij}^{eg}}{\sum_{j=1}^N w_{ij}^{eg}} \quad (12)$$

This matrix assigns larger weights to city pairs that are geographically closer and economically more similar. The SDM is selected because it can capture both local associations and spillover associations through spatially lagged dependent and explanatory variables. This setting is suitable for the Yangtze River Delta, where digital infrastructure, industrial chains, technology diffusion, and ecological governance often operate across administrative boundaries. Based on the SDM, the estimated effects are decomposed into direct effects, indirect effects, and total effects.

3.3. Data Sources and Descriptive Statistics

This study draws on a city-level dataset for the Yangtze River Delta spanning 2006–2023, which includes 41 prefecture-level cities. The sample is determined according to the completeness and consistency of the underlying data. The empirical data are compiled from multiple official statistical sources, including national, provincial, and municipal statistical yearbooks, as well as the EPS database and the China Economic Database.

For variables with occasional missing observations within the sample period, interpolation is applied to preserve the continuity of the city-year panel. Continuous socioeconomic variables are supplemented using linear interpolation when adjacent-year information is available. Since this study covers 2006–2023, the digital financial inclusion component for 2006–2010 is supplemented using predictive mean matching-based multiple imputation. The observed city-level PKU-DFIIC data from 2011 to 2023 are used as the reference sample, and economic development, financial development, and year information are included as auxiliary variables in the imputation model. In the Stata 18.0 implementation, three imputed series are generated. For each missing observation from 2006 to 2010, the final completed value is obtained by averaging the three imputed values. After this component is completed, it is combined with the other four digital economy indicators, and the entropy method is used to construct the final DEI. To reduce concerns about the influence of early-period imputed observations, this study further re-estimates the benchmark model using the 2011–2023 sample, for which the city-level PKU-DFIIC data are directly observed. Table 1 reports the descriptive statistics of the main variables.

Table 1. Descriptive Statistics.

Variable	Definition	Mean	Std. Dev.	Min	Max	Observations
<i>GTFP</i>	Green total factor productivity	1.0566	0.2791	0.3280	2.7131	738
<i>DEI</i>	Digital economy index	0.3081	0.1365	0.0923	0.9490	738
<i>lnpgdp</i>	Economic development level	10.8695	0.8732	8.2849	12.6552	738
<i>lnfina</i>	Financial development level	0.9265	0.3578	0.0507	1.9705	738
<i>open</i>	Openness	0.0044	0.0031	0.0001	0.0209	738
<i>hc</i>	Human capital	0.0211	0.0215	0.0008	0.1272	738
<i>inv</i>	Fiscal investment intensity	6.2668	3.8666	0.8838	28.4107	738
<i>gti</i>	Green innovation	4.9699	1.9078	0	9.3422	738
<i>theil</i>	Industrial structure rationalization	0.2211	0.1832	0.0005	1.2393	738
<i>indh</i>	Industrial structure advancement	0.6782	0.1740	0.3817	1.0000	738

4. Results

4.1. Benchmark Regression

Table 2 presents the benchmark estimates of the relationship between digital economy development and *GTFP*. Columns (1)–(4) correspond to alternative model settings. The *DEI* coefficient is consistently significantly positive at the 1% level across all specifications, suggesting a positive association between digital economy development and *GTFP*. After controlling for additional variables and incorporating city and year fixed effects, the estimated coefficient of *DEI* increases from 0.6949 to 1.4360, and the model fit improves substantially. This result provides preliminary support for H1.

Table 2. Benchmark Regression Results.

Variable	(1) <i>GTFP</i>	(2) <i>GTFP</i>	(3) <i>GTFP</i>	(4) <i>GTFP</i>
<i>DEI</i>	0.6949 *** (3.5011)	1.5932 *** (3.5912)	0.8876 *** (2.8507)	1.4360 *** (3.4025)
<i>lnpgdp</i>			−0.0271 (−0.6636)	−0.0958 (−0.7692)
<i>lnfina</i>			−0.1340 ** (−2.2488)	−0.2837 ** (−2.6467)
<i>open</i>			−4.0651 (−0.5349)	−11.7875 ** (−2.3531)
<i>hc</i>			5.2139 *** (5.2572)	−1.8280 (−0.4975)
<i>inv</i>			−0.0008 (−0.1408)	0.0056 (0.9148)
_cons	0.8425 *** (15.2033)	0.5657 *** (4.1391)	1.1147 *** (3.1819)	1.9736 (1.4601)
City FE	NO	YES	NO	YES
Year FE	NO	YES	NO	YES
<i>N</i>	738	738	738	738
<i>R</i> ²	0.116	0.652	0.218	0.675

Notes: ** $p < 0.05$, *** $p < 0.01$; t-statistics are reported in parentheses. Robust standard errors clustered at the city level are used.

After controlling for city and year fixed effects, the coefficient of *DEI* is still significantly positive, suggesting that the observed relationship is not merely driven by time-invariant city characteristics or common macro-level shocks. In the Yangtze River Delta, digital economy development is closely connected with information transmission, resource allocation, production coordination, and environmental governance capacity, which may help explain its positive association with urban *GTFP*. The control variables capture differences

in economic development, financial conditions, openness, human capital, and fiscal investment intensity across cities. Their coefficients vary across specifications, implying that these socioeconomic factors do not provide a uniform explanation for GTFP changes. The positive coefficient of DEI remains stable after these factors are included, which supports the robustness of the benchmark result.

Overall, the empirical findings provide support for H1.

4.2. Endogeneity Test

Although the benchmark regression controls for city and year fixed effects, potential endogeneity may still arise from reverse causality, omitted variables, and measurement errors in the digital economy index. To address this concern, this study conducts an instrumental-variable estimation using the two-stage least squares method [42].

Following the logic that historical communication infrastructure affects later digital development through technological path dependence, this study constructs two instrumental variables. The first instrument combines each city's total telecommunications business volume in 1984 with the previous year's nationwide internet user scale. The second instrument combines the city-level quantity of postal outlets in 1984 with the previous year's nationwide internet user scale. The historical city-level communication variables capture differences in the early foundation of information infrastructure, while the national Internet user scale introduces time variation in the diffusion of digital technologies. Due to data availability for the instrumental variables, the effective sample size is reduced to 612 observations.

The relevance of the instruments lies in the continuity between traditional communication infrastructure and later digital economy development. Cities with stronger historical communication foundations were more likely to develop information infrastructure, digital services, and Internet-based economic activities during the sample period. At the same time, the exclusion restriction is based on the historical and indirect nature of the instruments. The 1984 communication conditions were formed long before the sample period and before the rise of the digital economy. After controlling for city fixed effects, year fixed effects, and time-varying socioeconomic characteristics, their direct influence on current GTFP is expected to be limited. Their main channel of influence should operate through subsequent digital economy development rather than through current green productivity directly.

Table 3 reports the results of the endogeneity test. The first-stage estimates indicate that both instruments exhibit a strong positive association with the digital economy, satisfying the relevance condition. The K-P rk LM test rejects the null hypothesis of under-identification at the 5% significance level. The K-P rk Wald F value reaches 504.167, well above the corresponding 10% Stock–Yogo critical value, suggesting that weak-instrument concerns are not a serious issue. The Hansen test produces a *p*-value above 0.1, failing to reject the validity of selected instrumental variables.

Table 3. Endogeneity test results.

Variable	(1) First Stage DEI	(2) Second Stage GTFP
IV1	0.2915 *** (17.1476)	
IV2	0.1784 *** (3.1989)	

Table 3. Cont.

Variable	(1) First Stage <i>DEI</i>	(2) Second Stage <i>GTFP</i>
<i>DEI</i>		3.2677 *** (6.8239)
Control variables	YES	YES
City FE	YES	YES
Year FE	YES	YES
N	612	612
K-P rk LM statistic		13.361 [0.001]
K-P rk Wald F statistic		504.167 {19.93}
Hansen J test (<i>p</i> -value)		0.6209

Notes: *** $p < 0.01$; t-statistics are reported in parentheses. Figures in brackets correspond to the *p*-values of the K-P rk LM test. Figures in braces denote the 10% Stock–Yogo critical values.

The second-stage estimates continue to show a positive and significant coefficient for *DEI* at the 1% level, indicating that the relationship remains stable after accounting for endogeneity. Therefore, H1 continues to be supported.

4.3. Robustness Tests

4.3.1. Substitution of the *GTFP*

Considering that the measurement of *GTFP* may vary across different methods, this study recalculates *GTFP* using the EBM–GML index and uses it as an alternative dependent variable for robustness testing. Column (1) of Table 4 shows that the estimated effect of *DEI* is retained after replacing the *GTFP* measure, with significance maintained at the 1% level, corroborating the reliability of the benchmark findings.

Table 4. Robustness test results.

Variable	(1) Alternative Dependent Variable <i>GTFP</i>	(2) Lagged <i>DEI</i> <i>GTFP</i>	(3) Excluding Major Cities <i>GTFP</i>	(4) Adjusted Sample Period <i>GTFP</i>
<i>DEI</i>	0.1099 *** (4.8611)		0.9154 *** (3.3281)	0.9876 ** (2.0480)
Lagged <i>DEI</i>		1.5323 *** (3.9049)		
_cons	1.0120 *** (10.1968)	2.0922 (1.6275)	1.7678 (1.4468)	2.8593 (1.6259)
Control variables	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
N	738	697	684	533
R ²	0.704	0.427	0.394	0.406

Notes: ** $p < 0.05$, *** $p < 0.01$; t-statistics are reported in parentheses.

4.3.2. Temporal Lag Specification

To reduce concerns arising from reverse causality and contemporaneous correlations, the benchmark model is re-estimated using a one-period lag of the core explanatory variable. As reported in Column (2) of Table 4, the estimated effect of *DEI* persists after introducing

the lag structure and remains significant at the 1% level, lending further support to the benchmark findings.

4.3.3. Excluding Shanghai and Provincial Capital Cities

Given the prominent positions of Shanghai and provincial capitals in terms of economic strength, policy support, and innovation resources, retaining these cities in the sample may amplify the estimated effects. Accordingly, the model is re-estimated after excluding Shanghai, Nanjing, Hangzhou, and Hefei. Column (3) of Table 4 shows that the DEI coefficient is still positive and significant, supporting the robustness of the benchmark result.

4.3.4. Adjusting the Sample Period

Since the city-level observations of the Peking University Digital Financial Inclusion Index are directly available from 2011 onward, this study further restricts the sample period to 2011–2023 to reduce the possible influence of early imputed observations from 2006 to 2010. The benchmark model is then re-estimated using the post-2011 sample. Results in Column (4) of Table 4 continue to support the benchmark findings.

4.4. Moderating Effect Analysis

The benchmark estimates indicate a significant positive association between the digital economy and GTFP. To further explore the underlying moderating effects, four variables are considered: industrial structure rationalization, industrial structure advancement, green innovation, and ecological compensation policy, representing internal structural dynamics and external policy incentives. Interaction terms between DEI and each variable are introduced to assess their respective roles, with the results presented in Table 5.

Table 5. Moderating effect results.

Variable	Industrial Structure Rationalization (1) GTFP	Industrial Structure Advancement (2) GTFP	Green Innovation (3) GTFP	Ecological Compensation Policy (4) GTFP
$DEI \times theil$	−2.5817 *** (−2.8244)			
$DEI \times indh$		3.5863 *** (4.7090)		
$DEI \times gti$			0.3845 *** (5.9233)	
$DEI \times policy$				1.0403 *** (4.2978)
DEI	1.6499 *** (4.5068)	−1.8945 *** (−2.9726)	−1.9459 *** (−3.3360)	0.5337 (1.1494)
$_{cons}$	0.3975 (0.2677)	1.8432 * (1.6893)	1.2496 (1.0120)	1.7069 (1.4470)
Control variables	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
N	738	738	738	738
R^2	0.447	0.520	0.500	0.454

Notes: * $p < 0.1$, *** $p < 0.01$; t-statistics are reported in parentheses.

4.4.1. Industrial Structure Rationalization

Column (1) of Table 5 reports the moderating effect of industrial structure rationalization. The interaction term between DEI and industrial structure rationalization carries

a significantly negative coefficient. Given that industrial rationalization is proxied by the Theil index, larger values correspond to a lower level of rationalization, and this result suggests that industrial structure rationalization strengthens the positive association between DEI and GTFP.

This finding is consistent with the role of industrial coordination in improving resource allocation. When the allocation of labor, capital, and output across industries becomes more balanced, digital technologies can be more effectively applied to production coordination, factor matching, and resource management. In this case, the digital economy is more closely connected with improvements in green productivity. Therefore, H2 is supported.

4.4.2. Industrial Structure Advancement

Column (2) of Table 5 examines the moderating role of industrial structure advancement. A significantly positive coefficient is observed for the interaction term between DEI and industrial structure advancement, which implies that industrial advancement strengthens the positive association between DEI and GTFP.

A more advanced industrial structure provides better conditions for the application of digital technologies. As industries move toward higher value-added and less resource-intensive activities, digital tools are more likely to be embedded in production processes, service systems, energy management, and environmental governance. This enables the digital economy to be more effectively linked with efficiency improvement and pollution reduction. Therefore, H3 is supported.

4.4.3. Green Innovation

Column (3) of Table 5 reports the moderating effect of green innovation. The coefficient of the interaction term between DEI and green innovation is positive and statistically significant, suggesting that green innovation strengthens the positive association between DEI and GTFP.

Green innovation improves the technological capacity of cities to transform digital advantages into green productivity gains. When green innovation capacity is stronger, firms are more able to use digital technologies for cleaner production, energy saving, emission reduction, and pollution control. In this setting, digital economy development is less likely to remain limited to information transmission or transaction efficiency, and more likely to be connected with green production practices. Therefore, H4 is supported.

4.4.4. Ecological Compensation Policy

Column (4) of Table 5 examines the moderating role of ecological compensation policy. The interaction term between DEI and policy is significantly positive, indicating that ecological compensation policy reinforces the contribution of the digital economy to GTFP.

Ecological compensation policy creates clearer environmental constraints and governance incentives. Under this policy setting, local governments and firms face stronger motivation to use digital technologies for environmental monitoring, ecological performance assessment, and resource management. In the Yangtze River Delta, where ecological issues are closely related to cross-city industrial linkages and watershed governance, this institutional setting may further strengthen the relationship between digital economy development and green productivity. Therefore, H5 is supported.

4.4.5. Marginal Effect Analysis

To further interpret the interaction effects, this study calculates the marginal effects of DEI under different levels of the moderating variables. Figure 4 reports the results with 95% confidence intervals, providing a clearer view of how the DEI–GTFP relationship changes under different conditions.

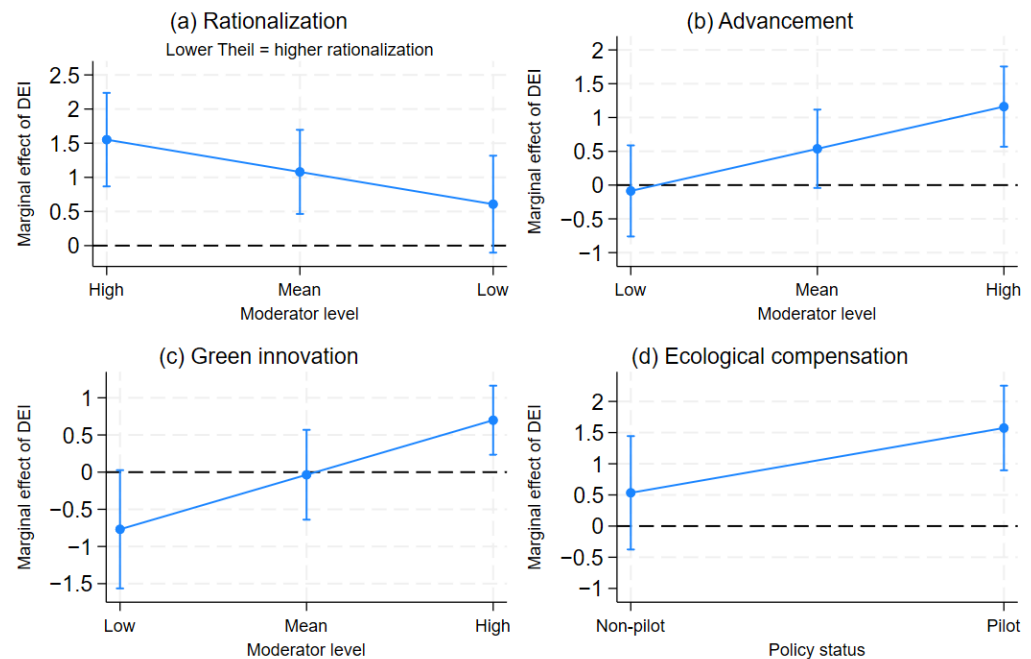


Figure 4. Marginal Effects of DEI under Different Moderating Conditions: (a) Industrial structure rationalization measured by the Theil index; (b) Industrial structure advancement; (c) Green innovation; (d) Ecological compensation policy. Note: The vertical lines represent 95% confidence intervals. Low and high levels of continuous moderators are defined as one standard deviation below and above the sample mean.

Figure 4a shows that the marginal effect of DEI is larger when industrial structure rationalization is higher. Since rationalization is measured by the Theil index, lower values indicate a more rational industrial structure. Figure 4b shows that the marginal effect of DEI increases with industrial structure advancement. Figure 4c indicates that higher green innovation is associated with a stronger marginal effect of DEI. Figure 4d shows that the marginal effect is larger in ecological compensation pilot cities than in non-pilot cities.

Overall, the marginal-effect results are consistent with the interaction-term estimates, suggesting that the DEI–GTFP relationship becomes more evident under more favorable industrial, technological, and policy conditions.

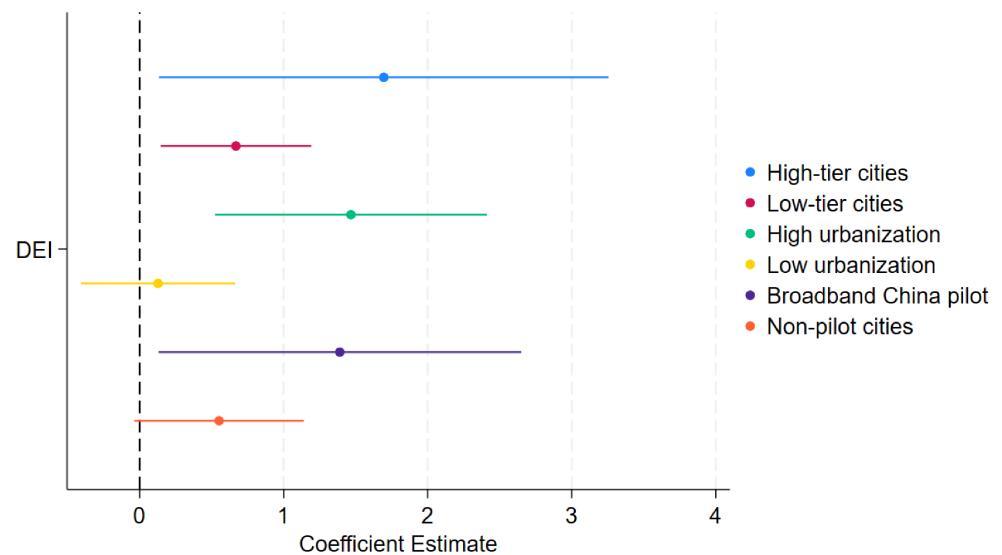
4.5. Heterogeneity Analysis

To examine whether the association between digital economy development and GTFP differs across cities with different characteristics, this study first conducts subgroup regressions by city tier, urbanization level, and digital infrastructure condition. However, separate subgroup regressions only show the estimated DEI coefficients within each group and do not directly test whether the coefficients are statistically different across groups. Therefore, this study further estimates pooled interaction-term models to formally test the differences in DEI coefficients across groups. Table 6 presents the subgroup regression results, while Figure 5 illustrates variations in the estimated effects across cities with different characteristics. Table 7 further tests whether the DEI coefficient differences observed in the subgroup regressions are statistically significant. The interaction terms are significantly positive, indicating that the DEI coefficients differ significantly across the corresponding groups, and the direction of the differences is consistent with the subgroup regression results. The insignificant coefficient of DEI only reflects the relatively weak DEI–GTFP association in the lower-level group, rather than the absence of a digital economy effect across all cities.

Table 6. Heterogeneity analysis results.

Variable	City Tier		Urbanization Level		Digital Infrastructure	
	High (1)	Low (2)	High (3)	Low (4)	Demonstration Zones (5)	Non-Demonstration Zones (6)
<i>DEI</i>	1.6955 ** (2.3310)	0.6687 ** (2.6360)	1.4671 *** (3.2192)	0.1281 (0.4906)	1.3900 ** (2.3295)	0.5519 * (1.8949)
<i>_cons</i>	−0.6236 (−0.2075)	1.7667 (1.1297)	1.2822 (0.5936)	1.2538 (0.7571)	−0.9161 (−0.2632)	3.6812 *** (2.8314)
Control variables	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
<i>N</i>	270	468	369	369	162	576
<i>R</i> ²	0.717	0.653	0.719	0.693	0.894	0.632

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$; t-statistics are reported in parentheses.

**Figure 5.** Heterogeneity in the Impact of the Digital Economy on GTFP.**Table 7.** Tests for coefficient differences across heterogeneous groups.

	(1) GTFP	(2) GTFP	(3) GTFP
<i>DEI × High – tier cities</i>	0.8204 ** (2.6786)		
<i>DEI × High urbanization</i>		1.1821 *** (5.3721)	
<i>DEI × Demonstration zones</i>			1.1206 *** (4.8085)
<i>DEI</i>	0.7240 * (2.0019)	0.2939 (0.9405)	0.5472 * (1.7213)
Control variables	YES	YES	YES
City FE	YES	YES	YES
Year FE	YES	YES	YES
<i>N</i>	738	738	738
<i>R</i> ²	0.691	0.712	0.697

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$; t-statistics are reported in parentheses.

4.5.1. Heterogeneity by City Tier

According to the 2023 China Urban Commercial Attractiveness Ranking, cities classified as second-tier or above are defined as high-tier cities, while the remaining cities are categorized as low-tier cities. Columns (1)–(2) of Table 6 report the results for the two city-tier groups. In high-tier cities, the DEI coefficient is positive and statistically significant, indicating a significant positive association between digital economy development and GTFP. In low-tier cities, the DEI coefficient is also positive, but its magnitude is relatively smaller. This stems from the fact that high-tier cities possess better digital foundations, denser industrial networks, and greater innovative potential, which create favorable conditions for popularizing digital technologies within eco-friendly production links. Low-tier cities may also benefit from digitalization, but their digital infrastructure, factor mobility, and technological diffusion capacity may still affect the extent to which digital development is linked with green productivity improvement.

4.5.2. Urbanization Rate

Urbanization is proxied by the share of the non-agricultural population in the registered population. Cities are classified into two groups according to whether their urbanization levels are above or below the sample median. Columns (3)–(4) of Table 6 indicate that DEI remains significant at the 1% level among highly urbanized cities, whereas no significant relationship is observed in less urbanized cities. The role of the digital economy in driving GTFP appears to be stronger in highly urbanized areas. Higher urbanization is associated with better infrastructure, more efficient factor allocation, and stronger information diffusion, which enhance the spillover effects of digital technologies. By comparison, cities with lower levels of urbanization are less able to capitalize on the benefits brought by digital economy development.

4.5.3. Digital Infrastructure

Considering that the “Broadband China” policy represents a major digital infrastructure initiative, the sample is additionally grouped according to whether a city is designated as a “Broadband China” demonstration zone. Columns (5)–(6) of Table 6 indicate a positive and significant DEI coefficient in demonstration cities, whereas the DEI coefficient is relatively smaller in non-demonstration cities. The demonstration group exhibits larger coefficient estimates and stronger statistical significance, indicating a more prominent role of the digital economy in improving GTFP where digital infrastructure is better developed.

4.6. Spatial Correlation and Spillover Effects

The preceding analysis mainly identifies the association between digital economy development and local GTFP. However, cities in the Yangtze River Delta are not independent units. The region is characterized by close geographical proximity, strong intercity economic linkages, intensive infrastructure connectivity, and increasingly coordinated ecological governance. Under such conditions, the digital economy may affect GTFP not only within a city, but also through cross-city spillovers. Ignoring this spatial interdependence may underestimate the regional meaning of digital transformation and may also obscure why the Yangtze River Delta provides a distinct setting for examining the digital economy–GTFP relationship.

To capture these regional linkages, this study selects the bidirectional fixed-effects spatial Durbin model to analyze spatial spillover effects and constructs a geo-economic nested spatial weight matrix. The geographic component reflects spatial proximity among cities, while the economic component is measured using each city’s average GDP over the period 2006–2023. This matrix is more consistent with the spatial organization of

the Yangtze River Delta than a purely geographic matrix, because the diffusion of digital technologies, green innovation, industrial collaboration, and environmental governance pressure is shaped not only by physical distance but also by the intensity of economic connections. In this sense, the spatial analysis helps examine whether the relationship between the digital economy and GTFP is also reflected in regional spillover patterns under the integrated development of the Yangtze River Delta.

4.6.1. Global Moran's I

Before estimating the spatial econometric model, this study first calculates the global Moran's I of GTFP to examine whether green productivity exhibits spatial correlation across cities. As shown in Table 8, the Moran's I values are not significant in the early years of the sample. This may be related to the relatively fragmented spatial structure of green development in the early sample period. Intercity factor flows and industrial linkages had not yet formed a sufficiently stable spatial network, and the green productivity performance of each city was more dependent on its own industrial foundation, resource endowment, and local environmental regulation. Therefore, the spatial correlation of GTFP was relatively weak in the early period.

Table 8. Moran's I of GTFP.

Year	Moran's I	<i>p</i> -Value
2023	0.4158 ***	0.001
2022	0.4462 ***	0.001
2021	0.4625 ***	0.001
2020	0.3886 ***	0.001
2019	0.4442 ***	0.001
2018	0.4300 ***	0.001
2017	0.4328 ***	0.001
2016	0.2433 **	0.012
2015	0.2345 **	0.010
2014	0.0830	0.428
2013	0.2227 **	0.016
2012	0.2995 ***	0.003
2011	0.2975 ***	0.004
2010	0.1409	0.142
2009	0.1402	0.156
2008	−0.0734	0.430
2007	−0.0557	0.417
2006	—	—

Notes: ** $p < 0.05$, *** $p < 0.01$; t-statistics are reported in parentheses. The Moran's I for 2006 is not reported because GTFP is normalized in the base year, leaving no cross-city variation.

The Moran's I values are generally positive after 2009 and become more stable and significant after 2015. In particular, from 2017 to 2023, the Moran's I values remain relatively high and are significant at the 1% level, indicating that GTFP in the Yangtze River Delta shows a clear positive spatial clustering pattern. This evolution is consistent with the deepening of regional integration in the Yangtze River Delta. With the improvement of digital infrastructure, the strengthening of intercity industrial collaboration, and the

gradual development of cross-regional ecological governance, green productivity is no longer determined only by local conditions. Instead, it increasingly reflects the influence of neighboring and economically connected cities. The significant positive spatial autocorrelation therefore provides an empirical basis for further examining the spatial spillover effects of digital economy development.

4.6.2. Spatial Spillover Effect Analysis

Table 9 reports the spatial spillover results based on the geo-economic nested matrix. The estimated spatial autoregressive term is significantly positive, indicating that GTFP in the Yangtze River Delta exhibits spatial dependence. This suggests that the green productivity performance of a city is related not only to its own development conditions, but also to the green productivity level of geographically and economically connected cities. Such a result is consistent with the fact that cities in the Yangtze River Delta are closely linked through industrial division, factor mobility, infrastructure networks, and environmental governance cooperation.

Table 9. Spatial Spillover Results.

Variable	GTFP
ρ	0.321 *** (0.050)
<i>DEI</i>	1.178 *** (0.160)
$W \times DEI$	0.778 ** (0.316)
σ^2	0.023 *** (0.001)
Direct effect	1.266 *** (0.164)
Indirect effect	1.622 *** (0.388)
Total effect	2.888 *** (0.428)
Control variables	YES
City FE	YES
Year FE	YES
<i>N</i>	738

Notes: ** $p < 0.05$, *** $p < 0.01$; t-statistics are reported in parentheses.

The estimated coefficient of *DEI* remains significantly positive after spatial dependence is taken into account. This indicates that local digital economy development is still associated with higher local GTFP. This result is consistent with the benchmark regression. Digital economy development may reduce information costs, improve the efficiency of resource allocation, enhance production and management processes, and strengthen environmental monitoring capacity, thereby supporting green productivity improvement within the city.

The spatially lagged *DEI* is also significantly positive, suggesting that digital economy development in geographically or economically connected cities has a positive spillover effect on local GTFP. This result shows that the influence of digital economy development is not confined to local administrative boundaries. In the Yangtze River Delta, digital infrastructure, industrial chains, innovation resources, and environmental governance practices are closely connected across cities. Therefore, digital development in one city may generate external effects through technology diffusion, industrial collaboration, supplier upgrading, information sharing, and policy learning.

The decomposition of spatial effects further confirms the existence of both local and spillover effects. The direct effect indicates that digital economy development is associated with the improvement of local GTFP, while the indirect effect suggests that its influence can extend to other cities through regional linkages. The significant total effect shows that the overall relationship between the digital economy and GTFP should be understood from a regional perspective rather than only from the perspective of individual cities.

Overall, the spatial results show that digital economy development is associated with GTFP through both local improvement and cross-city spillover. This provides a more specific explanation for the regional characteristics of the Yangtze River Delta. In a highly integrated urban agglomeration, the digital economy affects green productivity not only as a local technological and economic factor, but also as a factor that strengthens intercity resource allocation, industrial coordination, and environmental governance linkages.

5. Discussion

The findings indicate that digital economy development is positively associated with GTFP across cities in the Yangtze River Delta. Given its strong economic foundation and advanced level of development, the Yangtze River Delta possesses relatively favorable conditions for the diffusion and application of digital technologies. By improving resource allocation, reducing information barriers, and enhancing production efficiency, digitalization provides new momentum for the coordinated advancement of economic growth and environmental performance [4,16,43]. The positive coefficient obtained in the baseline regression supports the view that digital development is closely related to urban green transformation. However, the result should not be understood only as a general digitalization effect. In the Yangtze River Delta, cities are closely connected through industrial chains, transport networks, digital infrastructure, and environmental governance arrangements. These regional linkages make digital technologies more likely to influence production organization, factor flows, and pollution control beyond the boundary of a single city. Therefore, the Yangtze River Delta provides a suitable context for understanding how digital economy development is related to green productivity in an integrated urban region.

This finding is generally consistent with previous studies showing that digital economy development is positively associated with green productivity and environmental performance. Existing research has mainly explained this relationship from the perspectives of information efficiency, resource allocation, technological innovation, and environmental governance [15,18,42,43]. Our results support this general argument, but also provide several extensions. First, compared with studies that focus mainly on the average relationship between digitalization and GTFP, this study further considers the roles of industrial structure, green innovation, and ecological compensation policy in shaping the DEI–GTFP relationship. Second, by focusing on the Yangtze River Delta, this study highlights the regional context in which digital infrastructure, industrial chains, technology flows, and ecological governance are closely connected across cities. Third, the spatial analysis further shows that the relationship between digital economy development and GTFP may extend beyond local cities through intercity linkages. Therefore, this study not only supports the conclusions of the existing literature, but also extends them by showing the moderating conditions and spatial linkages of the DEI–GTFP relationship in an integrated urban region.

The moderating results indicate that the DEI–GTFP relationship is shaped by structural and institutional conditions. Industrial structure rationalization and advancement strengthen the association between digital economy development and GTFP by improving the conditions under which digital technologies are applied to production and resource management. Green innovation provides the technological basis for transforming digital advantages into cleaner production and emission reduction. Ecological compensation

policy offers external constraints and governance incentives, making digital tools more closely connected with environmental monitoring and ecological performance evaluation. These results suggest that digital economy development does not automatically translate into green productivity improvement. This relationship depends on whether cities have suitable industrial, technological, and policy conditions.

The heterogeneity analysis also shows that the relationship between digital economy development and GTFP differs across city types. High-tier cities, cities with higher urbanization levels, and broadband demonstration cities show stronger DEI–GTFP associations. This may be because these cities have better digital infrastructure, stronger innovation capacity, more advanced industrial systems, and greater ability to apply digital technologies to environmental governance. By contrast, lower-level cities may face weaker infrastructure support, limited industrial upgrading capacity, and insufficient green innovation resources, which restrict the green productivity gains associated with digital economy development. This finding implies that narrowing the digital infrastructure gap and improving the absorptive capacity of less-developed cities are necessary for achieving more balanced regional green development.

The further spatial analysis provides additional evidence from the perspective of regional interdependence. In an integrated urban system, digital economy development may affect neighboring cities through information diffusion, industrial collaboration, technology spillovers, and cross-regional ecological governance. This result responds to the regional characteristics of the Yangtze River Delta, where economic activities and environmental problems are not confined to individual administrative boundaries. It also suggests that policies aimed at promoting the digital economy and green transformation should pay attention to intercity coordination rather than relying only on isolated city-level measures.

This study extends the existing literature by placing this relationship in the context of the Yangtze River Delta, where cities are connected through dense industrial linkages, digital infrastructure networks, and cross-regional environmental governance. Rather than treating the digital economy–GTFP relationship as a uniform process, this study further shows that the strength of this relationship depends on structural conditions, technological capacity, and policy incentives. In this sense, the results provide additional evidence on how digital economy development is associated with green productivity improvement in an integrated urban region. In addition, by incorporating spatial spillover analysis, this study further shows that the digital economy–GTFP relationship is not confined to individual cities, but may also operate through intercity linkages, technology diffusion, and regional coordination within the Yangtze River Delta.

Despite these findings, several limitations should be acknowledged. First, the study uses city-level panel data, which cannot fully capture firm-level or industry-level differences in digital technology adoption and green transformation. Firms may differ in digital capabilities, production technologies, environmental management capacity, and incentives for green investment. Future research can use micro-level data to examine how firms in different industries respond to digitalization. Second, although the DEI covers Internet development and digital financial inclusion, it may not fully reflect newer forms of digital activity, such as platform economy, data elements, artificial intelligence applications, and industrial Internet systems. Future studies can construct more refined indicators to capture the depth of digital technology application in production, governance, and environmental management. Third, some early city-level data require interpolation or imputation due to data availability constraints. Although robustness checks are conducted, future studies can further verify the findings using more detailed and continuous datasets.

6. Conclusions and Policy Implications

Using city-level panel data covering 41 cities in the Yangtze River Delta over 2006–2023, this study examines the relationship between digital economy development and GTFP.

- (1) Digital economy development is positively associated with GTFP in the Yangtze River Delta. This finding remains stable after a series of robustness and endogeneity tests.
- (2) The contribution of the digital economy varies across cities. The estimated effect is more evident in high-tier cities, highly urbanized areas, and Broadband China demonstration cities. These results suggest that local development conditions influence the extent to which digitalization can be translated into green development outcomes.
- (3) The DEI–GTFP relationship is shaped by industrial structure, green innovation, and ecological compensation policy. These factors create favorable conditions for translating digital development into improvements in green productivity.
- (4) The further spatial analysis suggests that the DEI–GTFP relationship is not confined to local cities. Digital economy development may generate spatial spillover effects through intercity industrial linkages, technology diffusion, infrastructure connectivity, and regional environmental governance.

The findings carry several policy implications.

- (1) Digital economy development should be integrated with green productivity-oriented urban governance. Local governments should not only expand digital infrastructure, but also promote the application of digital technologies in production coordination, energy management, pollution monitoring, and resource allocation. In the Yangtze River Delta, where cities are closely connected through industrial chains and factor flows, digital infrastructure planning should be coordinated at the regional level. Cross-city data sharing, unified digital standards, and integrated environmental monitoring platforms can help reduce information barriers and improve the efficiency of regional green governance. Meanwhile, data security and network protection should be considered in the construction of cross-city digital governance platforms [44,45].
- (2) The green productivity effect of the digital economy depends on industrial and technological conditions. Cities should promote industrial structure rationalization and advancement while accelerating digital transformation. For cities with a weak industrial foundation, policy support should focus on improving factor allocation efficiency and reducing resource mismatch across sectors. For cities with more advanced industries, digital technologies should be further embedded in high-end manufacturing, producer services, cleaner production, and intelligent environmental management. At the same time, green innovation should be strengthened by encouraging firms to apply digital tools to energy saving, emission reduction, process optimization, and pollution control.
- (3) Ecological compensation policy should be combined with digital governance tools. Ecological compensation can provide external constraints and incentives for green development, while digital technologies can improve the transparency and accuracy of ecological monitoring, performance evaluation, and policy implementation. In the Yangtze River Delta, environmental issues often cross administrative boundaries, especially in river basins and industrially connected areas. Therefore, ecological compensation mechanisms should be coordinated across cities, and digital platforms should be used to support joint monitoring, information disclosure, and cross-regional accountability.
- (4) Differentiated policies are needed for different types of cities. High-tier cities, highly urbanized cities, and broadband demonstration cities can further use their digital and industrial advantages to lead regional green transformation. Lower-tier cities and

cities with weaker digital infrastructure should receive more support in broadband access, digital public services, industrial digitalization, and green innovation capacity. Narrowing the digital infrastructure gap and improving the absorptive capacity of less-developed cities are important for preventing the digital economy from widening regional disparities in green development.

- (5) Policy design should pay attention to spatial spillover effects. Since digital economy development may influence neighboring cities through technology diffusion, industrial collaboration, and regional governance networks, local policies should not be designed in isolation. The Yangtze River Delta should strengthen intercity coordination in digital infrastructure construction, green technology cooperation, ecological compensation, and environmental regulation. This can help transform local digital economy development into broader regional gains in green productivity.

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Appendix A. Estimation of Urban Fixed Capital Stock

Urban fixed capital stock is estimated using the perpetual inventory method, following related studies on urban GTFP measurement. The basic formula is expressed as follows:

$$K_{it} = (1 - \delta)K_{i,t-1} + I_{it}$$

where K_{it} denotes the fixed capital stock of city i in year t , $K_{i,t-1}$ denotes the fixed capital stock in the previous year, δ is the depreciation rate, and I_{it} denotes real fixed asset investment. The depreciation rate is set at 9.6%. Nominal fixed asset investment is converted into constant 2006 prices using the fixed asset investment price index. For occasional missing observations in fixed asset investment or price index data, linear interpolation is applied when adjacent-year information is available. The estimated fixed capital stock is then used as the capital input in the GTFP calculation.

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