

Digital Economy Development and Green Total Factor Productivity: Influence Mechanisms and Empirical Evidence

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Abstract: This study investigates the dynamic interplay between digital transformation and sustainable development in contemporary China. Utilizing panel data spanning 30 provincial-level administrative units (2006-2021), this investigation establishes a comprehensive evaluation framework to quantify regional disparities in both digital economy maturity and green productivity performance. Through rigorous empirical analysis, we systematically examine the structural mechanisms through which digital advancement catalyzes green total factor productivity (GTFP) enhancement, while conducting phased comparative assessments aligned with critical junctures in China's digital evolution trajectory. Key findings reveal three critical insights: First, digital economy development demonstrates statistically significant positive externalities on GTFP optimization, with effect magnitude exhibiting temporal sensitivity to national digital strategy implementation phases. Second, mechanism analysis identifies provincial environmental regulatory intensity as a pivotal moderating variable that positively amplifies the digital-GTFP nexus. Third, asymmetrical interprovincial openness patterns exacerbate regional disparities across multiple dimensions - including resource allocation efficiency, industrial composition characteristics, and environmental governance capacity, which consequently induce differentiated spatial effects of digital development on ecological productivity improvement.

Keywords: digital economy, green total factor productivity, environmental regulation

1. Introduction

Contemporary conceptualizations of digital economic systems derive from two authoritative frameworks. The G20 summit [1] characterizes this paradigm as "an economic ecosystem where digitized intellectual capital serves as primary productive inputs, interconnected information infrastructures function as operational substrates, and strategic ICT deployment drives systemic efficiency optimization and productive forces restructuring." Building upon this foundation, China's plan for digital economy development [2] subsequently positions it as the dominant economic paradigm succeeding agrarian and industrial eras, instigating fundamental transformations across production modalities, societal operations, and governance architectures, while emerging as a critical mechanism in reconfiguring global resource distribution dynamics. Empirical validation comes from an official research report [3], documenting sectoral expansion to 53.9 trillion RMB in 2023, constituting 42.8% of national GDP with a 66.45% contribution rate to aggregate economic growth - metrics underscoring its transformative macroeconomic impact.

Following four technological revolutions, human society has entered an era of "intelligent and green transformation" characterized by advanced productive forces. The innovative integration of digital technologies with traditional and emerging industries has reshaped production relations aligned with these new forces, propelling advancements in multifactor productivity. The digital economy, through the introduction of disruptive technological innovations, grants industries the capacity to realize more resilient and eco-friendly sustainable development, facilitates corporate intelligent and green transitions, gradually reforms energy-intensive, wasteful, and structurally imbalanced production models, reduces negative externalities of economic activities, promotes healthy regional economic growth, and boosts green total factor productivity (GTFP). As China's digital transformation deepens, green development is transitioning from an aspirational goal to a tangible reality. The nexus between digitalization progress and eco-efficiency enhancement constitutes a critical research frontier. Utilizing sixteen-year provincial datasets (2006-2021), this investigation applies dynamic panel regression to decode the spatial-temporal evolution patterns of digital-driven productivity gains, while identifying key moderating variables in interprovincial development contexts. Innovatively, the paper introduces environmental regulation intensity as a moderating variable and accounts for provincial disparities in openness, thereby complementing the missing "green development" dimension in the analysis of digital economy growth alongside economic and ecological benefits. It also clarifies how inherent provincial heterogeneity leads to differentiated effects on GTFP. The study's contributions are twofold: first, it enriches the theoretical framework of interactions among the digital economy, factor allocation optimization in industrial ecosystems, green development, and advanced productive forces, providing a foundation for advancing digital economy growth and green transitions; second, it quantifies regional historical experiences, offering actionable pathways for provinces to tailor digital economy strategies and enhance GTFP.

2. Theoretical analysis and research hypotheses

In recent years, breakthroughs in 5G, artificial intelligence, big data, and other technologies have accelerated the development of data factor markets, refined the digital economy industrial system, and enabled greener, more efficient digital technologies to reshape production modes [4], invigorating market entities' creativity and dynamism [5]. From a technological perspective, the deep penetration of digital technologies optimizes production processes through intelligent and precise transformations, breaking traditional constraints on factor inputs. This directly reduces resource consumption and environmental burdens while accelerating the iteration and diffusion of green technologies, creating a virtuous cycle between technological and environmental efficiency [6]. Structurally, the digital economy reorients production factors toward knowledge-intensive and service-oriented sectors. By fostering cross-industry digital integration and displacing outdated industries, it reshapes energy dependency in economic development, weakens path-locking effects in high-carbon industries, and enables low-carbon transitions in growth drivers. Digital technological progress fosters new economic growth poles through bidirectional integration: digitizing traditional industries while materializing digital innovations into productive forces, advancing industrial upgrading and green transformation [7]. Furthermore, the unique attributes of data elements optimize resource allocation mechanisms. Through information integration and algorithmic matching, they mitigate information asymmetry, reduce market frictions, enhance capital mobility, and resolve resource misallocation caused by environmental externalities, thereby increasing the marginal returns of green economic activities [8][9]. Additionally, the digital economy reconstructs innovation ecosystems [10], lowering R&D costs, expanding collaborative boundaries, and strengthening intellectual property incentives to build sustainable green innovation capabilities. By establishing a networked governance framework, it aligns decentralized actors under unified green objectives, coordinates micro-level behaviors with

macro-level policies through data flows and algorithmic rules, and reduces systemic transition costs. In summary, the digital economy elevates efficiency, accumulates green productivity, and fosters innovation at the micro level; reshapes growth pathways through meso-level structural optimization; and ultimately achieves dynamic equilibrium between economic growth and green constraints at the macro level, driving paradigm upgrades in GTFP [11].

Based on this, we propose:

Hypothesis 1: The development of digital economy can promote the improvement of green total factor productivity.

The pursuit of green development and exploration of green transitions have positioned environmental regulation as a critical governance tool, balancing "incentives" and "constraints" with significant provincial heterogeneity [12]. Moderate environmental regulation drives provincial green transitions through policy pressures and institutional innovation: on one hand, local governments optimize resource allocation under emission reduction targets, fostering deep integration of digital infrastructure and green technologies [13]; on the other hand, market-based regulatory tools (e.g., cross-regional carbon trading, provincial green finance pilots) leverage price signals and fiscal incentives to steer industries toward cleaner practices, accelerating spatial spillovers of green innovation. However, if regulatory intensity exceeds a region's capacity to absorb green technologies or its resource endowment, policy implementation may become distorted [14]. Excessive reliance on administrative interventions to meet short-term targets could stifle industrial upgrading and stagnate GTFP growth. Moreover, the choice of regulatory instruments is closely tied to provincial characteristics: command-based regulation forcibly phases out high-pollution industries but risks suppressing innovation in regionally distinctive sectors, while market-based regulation synergizes economic incentives with digital governance to stimulate endogenous motivation for green development [15]. Thus, environmental regulation is both a product of green development and a factor influencing its trajectory. Its net effect on GTFP depends on the alignment between policy intensity and regional digital economy maturity, resource endowments, and governance capabilities.

Therefore, we propose:

Hypothesis 2: In the process of promoting the improvement of green total factor productivity through the development of digital economy, the intensity of environmental regulation plays an important regulatory role.

3. Model construction

3.1. Model specification

This study creates a baseline model to analyze, through empirical methods, how the level of digital economy development in provinces affects green total factor productivity (GTFP).

$$GTFP_{i,t} = \beta_0 + \beta_1 Digital_{i,t} + \sum_{j=1}^n k_j CV_{i,t} + P_i + \theta_t + \varepsilon_{i,t} \quad (1)$$

Among them, i and t represent the province and year respectively. After excluding regions with missing data, 30 provincial-level administrative regions were retained in the province sample. $GTFP_{i,t}$ represents the green total factor productivity of province i in year t , $Digital_{i,t}$ represents the level of digital economic development in province i in year t , P_i represents the province fixed effect, θ_t represents the time fixed effect, $\varepsilon_{i,t}$ represents the random error term, and $CV_{i,t}$ represents other control variables.

According to the previous analysis, it can be seen that the environmental regulation intensity of each province plays a moderating role in the impact of the level of digital economic development on green total factor productivity. Therefore, by introducing the environmental regulation intensity

($Env_{i,t}$) and its interaction term $ED_{i,t}$ with the level of digital economic development ($Digital_{i,t}$), a model is constructed as follows:

$$ED_{i,t} = Env_{i,t} \times Digital_{i,t} \quad (2)$$

$$GTFP_{i,t} = \beta_0 + \beta_1 Digital_{i,t} + \beta_2 Env_{i,t} + \beta_3 ED_{i,t} + \sum_{j=1}^n k_j CV_{i,t} + P_i + \theta_t + \varepsilon_{i,t} \quad (3)$$

3.2. Variable selection and data sources

3.2.1. Explained variable: GTFP

The explained variable in this study is green total factor productivity ($GTFP$). Drawing on the measurement methodology from the paper [16], we incorporate undesirable environmental pollution outputs into a Data Envelopment Analysis (DEA) framework. The Malmquist index is employed to comprehensively account for outputs and inputs, yielding the final $GTFP$ values. The raw data indicators used are listed in the table below (see Table 1), with data sourced from the CSMAR Database and EPS Database.

Table 1: Explanation of input output indicators

	Indicator type	Indicator description
Output	Desirable outputs	GDP of each province (in billions of yuan)
	Undesirable outputs	Total amount of industrial wastewater discharge (10,000 tons)
		Total industrial sulfur dioxide emissions (10,000 tons)
		Industrial smoke and dust emissions (10,000 tons)
Input	Capital input	Fixed investment (100 million yuan)
	Labor input	Year-end employment (10,000 people)
	Energy input	Electricity consumption (100 million kilowatt hours)

3.2.2. Core explanatory variable: digital economy development level

This study measures the digital economy development level ($Digital$) by synthesizing two dimensions—internet development and digital financial inclusion—based on the indicator selection framework from the paper. By means of Principal Component Analysis (PCA), we diminish the dimensionality of five metrics: internet penetration rate, proportion of personnel in related industries, per capita telecommunications business volume, mobile phone penetration rate and China Digital Inclusive Finance Index. The raw data for these indicators are sourced from the *China City Statistical Yearbook* and the *China Digital Inclusive Finance Index*.

3.2.3. Other variables

This article divides the other variables involved into two parts.

(1) Moderator Variable: Environmental Regulation Intensity (Env). Drawing on the measurement method from [17], this study employs the proportion of investment in industrial pollution control relative to industrial value-added across provinces as an indicator of environmental regulatory stringency.

(2) Control Variables. Following existing studies, we select the following control variables: Urbanization level (Urb): Measured as the proportion of urban population to total provincial population. Education development level (Edu): Represented by the average years of education in each province. The openness level (Fdi): determined by dividing the actual FDI used by the provincial GDP. Human capital investment (Hum): measured by the ratio of spending on science and education

to fiscal expenditures in each province. The level of social consumption (*Soc*): described as the ratio of total consumer goods retail sales to provincial GDP. Unemployment rate (*Une*): Measured by the urban registered unemployment rate. All data are obtained from the EPS Database, CSMAR Database, and provincial statistical yearbooks.

3.2.4. Descriptive statistics

To clarify the distribution of variables, we calculate several key distribution characteristics for each variable. The descriptive statistics are presented in Table 2.

Table 2: Descriptive statistics of variables

Variable	N	Mean	SD	Min	p50	Max
<i>Digital</i>	480	0.0800	0.0900	0.0100	0.0500	0.470
<i>Urb</i>	480	0.560	0.140	0.300	0.550	0.890
<i>Edu</i>	480	8.970	1	6.790	8.900	12.43
<i>Fdi</i>	480	0.0200	0.0200	0	0.0200	0.100
<i>Hum</i>	480	0.180	0.0300	0.120	0.180	0.250
<i>Soc</i>	480	0.380	0.0600	0.240	0.380	0.550
<i>Une</i>	480	0.0300	0.0100	0.0100	0.0300	0.0400
<i>GTFP</i>	480	1.010	0.100	0.780	1.020	1.560
<i>Env</i>	480	0	0	0	0	0.0200

4. Empirical analysis

4.1. Benchmark regression

Initially, this article conducts regression analysis on model (1) to evaluate the preliminary impact of the provincial digital economy's development stage on green total factor productivity. The outcomes of this regression are presented in Table 3.

Table 3: Benchmark regression and robustness test results

	(1)	(2)	(3)
<i>Digital</i>	0.360*** (0.105)	0.430*** (0.119)	0.445** (0.216)
<i>Urb</i>		-0.122 (0.227)	-0.365 (0.478)
<i>Edu</i>		-0.000506 (0.0281)	-0.0341 (0.0396)
<i>Fdi</i>		-0.101 (0.366)	-0.0191 (0.480)
<i>Hum</i>		-0.576 (0.378)	-0.399 (0.625)
<i>Soc</i>		-0.0952 (0.111)	-0.0648 (0.147)
<i>Une</i>		-1.470 (1.318)	-2.021 (1.562)
_cons		1.127** (0.342)	1.656** (0.648)

Table 3: (continued).

<i>Prov</i>	Yes		
<i>Year</i>	Yes		
<i>N</i>	480	480	270
<i>R</i> ²	0.340	0.351	0.349
adj. <i>R</i> ²	0.272	0.274	0.221

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.001$

Table 3 presents two columns of regression results: the first column does not include any control variables, while the second column includes control variables and displays prominently positive regression coefficients. The primary regression findings suggest that the advancement of the digital economy positively influences the improvement of green total factor productivity, thereby confirming hypothesis 1.

4.2. Robustness test

The year 2013 marks the inception of Internet finance. With the release of national policies, the layout of China's mobile Internet has gradually improved, the cloud computing ecosystem has been established, and the layout of big data applications has accelerated. In this context, the digital economy has emerged as a hot spot for industry innovation, and its integration with various industries is gradually accelerating, penetrating into every corner of the economy and society. Therefore, in the robustness testing stage, this article changes the sample observation time and uses 2013 as the boundary to test the regression results of green total factor productivity against the advancement in digital economy spanning from 2013 to 2021, as detailed in line (3) of Table 3. It reveals that the regression results from 2013 to 2021 are significantly positive, in agreement with benchmark regression results. This underscores the substantial positive influence of digital economy growth on the enhancement of green total factor productivity.

4.3. Moderating effect

The above studies and data analyses demonstrate that the advancement of digital economy substantially enhances the growth of green total factor productivity. Nevertheless, this stimulatory effect manifests heterogeneity contingent not only on provincial disparities in digital economic development levels, but also moderated by geographical differences in environmental regulatory stringency. As evidenced in Table 4, empirical investigations incorporating environmental regulation intensity adjustments to baseline regressions reveal significant spatial variations in this developmental relationship. Furthermore, this article uses the variable $ED_{i,t}$ to represent the interaction term between $Digital_{i,t}$ and $Env_{i,t}$, which is calculated by multiplying $Digital_{i,t}$ and $Env_{i,t}$. The meaning is that environmental regulation intensity has a moderating effect on the interaction between digital economy development and green total factor productivity, and the regression coefficient of this interaction term is also shown in table 4. The analytical outcomes derived from modified econometric models accounting for regulatory interventions confirm the contextual nature of digital economy's productivity-enhancing mechanisms.

Table 4: Moderating effect results

	(1)	(2)
<i>Digital</i>	0.442*** (0.120)	0.372** (0.122)
<i>Env</i>	-1.663 (2.037)	-5.200** (2.433)
<i>Urb</i>	-0.149 (0.229)	-0.138 (0.228)
<i>Edu</i>	-0.00122 (0.0281)	-0.00558 (0.0279)
<i>Fdi</i>	-0.0969 (0.366)	-0.124 (0.364)
<i>Hum</i>	-0.582 (0.378)	-0.434 (0.379)
<i>Soc</i>	-0.0894 (0.112)	-0.125 (0.112)
<i>Une</i>	-1.536 (1.321)	-1.647 (1.313)
<i>ED</i>		92.60** (35.39)
<i>_cons</i>	1.161*** (0.345)	1.195*** (0.342)
<i>Prov</i>	Yes	
<i>Year</i>	Yes	
<i>N</i>	480	480
<i>R²</i>	0.352	0.362
adj. <i>R²</i>	0.273	0.283

The statistical findings delineated in Table 4 demonstrate that comprehensive environmental regulatory frameworks significantly accelerate the evolution of digital economic systems while optimizing ecological efficiency metrics. This empirical evidence highlights the moderating effect of environmental regulation intensity on the progress of green total factor productivity driven by the development of digital economy, indicating that systematically enforced environmental compliance mechanisms not only catalyze the sustainable transition pathways of digital industries, but also amplify resource-utilization effectiveness in green productivity paradigms. Such observations reinforce the criticality of institutionally embedded environmental accountability measures in reconciling technological modernization with ecological preservation objectives, offering policymakers empirical validation for designing dual-target strategies aligned with sustainable development goals. Hypothesis 2 has been validated.

4.4. Heterogeneity analysis

The development of different regions may exhibit differentiation characteristics due to differences in resource endowment, local policies, and the ability to absorb and transform factors. Provincial disparities in environmentally-adjusted productivity metrics are predominantly determined by region-specific economic compositions, particularly the sectoral configuration and technological sophistication of industrial ecosystems. As China's openness to international markets continues to

broaden and the digital economy drives the transformation and upgrading of industrial structures, a synergistic effect between these two forces may progressively come into view, that is, in the process of "bringing in" and "going out", fully releasing the strong vitality and resilience of the digital economy, gradually optimizing the industrial structure in the process of absorbing foreign investment and outward investment, and driving the optimization of sustainable factor efficiency through innovation-driven resource allocation mechanisms. In view of this, based on the median of the selected observation sample's level of openness (*Ofdi*), this article divides each province into two categories: low and high levels of openness to the outside world, and conducts heterogeneity analysis accordingly. The regression results are shown in Table 5, where column (1) corresponds to provinces that are less open, and column (2) corresponds to provinces that are more open.

Table 5: Heterogeneity regression results of provinces

	(1)	(2)
<i>Digital</i>	0.567 (0.393)	0.435** (0.166)
<i>Env</i>	-5.654 (3.510)	-2.149 (5.004)
<i>ED</i>	52.64 (83.45)	112.7** (48.39)
<i>Urb</i>	-0.708 (0.749)	-0.330 (0.335)
<i>Edu</i>	0.0145 (0.0389)	-0.0493 (0.0478)
<i>Fdi</i>	-0.388 (1.270)	-0.282 (0.514)
<i>Soc</i>	-0.0697 (0.174)	-0.208 (0.225)
<i>Hum</i>	-0.278 (0.510)	-0.361 (0.681)
<i>Une</i>	-1.655 (1.798)	-0.843 (2.311)
_cons	1.276** (0.426)	1.815** (0.589)
<i>Prov</i>	Yes	
<i>Year</i>	Yes	
<i>N</i>	240	240
<i>R</i> ²	0.375	0.404
adj. <i>R</i> ²	0.238	0.262

Geographic zones exhibiting heightened external connectivity demonstrate substantially amplified catalytic effects from digitalization initiatives on eco-efficiency advancements, attributable to technology-driven cross-border synergies and knowledge spillover dynamics. However, in provinces with lower levels of openness, this promotion effect is not sufficiently pronounced. The possible reasons for this are: firstly, this phenomenon fundamentally stems from the synergistic convergence between global integration and technological progressiveness. Regions characterized by advanced external engagement exhibit enhanced economic dynamism, which systematically translates into (a) strategic prioritization of digital transformation agendas through institutional innovation frameworks,

(b) systematic capital deployment into digital infrastructure development and frontier technology incubation ecosystems, and (c) paradigmatic advancements in sustainable productivity metrics through cross-border knowledge diffusion channels. Such multi-stakeholder ecosystems effectively harness globalization dividends to accelerate socio-technical transitions toward low-carbon economic paradigms. Secondly, open provinces can more efficiently integrate external resources and local innovation factors, thereby amplifying the promoting effect of the digitalization on GTFP. On one hand, this high-level opening up has hastened the integration of digital technology through channels such as cross-border technology cooperation and foreign direct investment, accelerating corporate ecological modernization and regional green development; On the other hand, the market competition pressure under an open economic system can force local enterprises to achieve green upgrading through digital transformation, which in turn prompts the government to improve the construction of the digital economic system and green supply chain. Hence, provinces that exhibit a strong tendency towards embracing the global market tend to experience more rapid advancement in digital economy and eco-friendly total factor productivity. This also equips them with enhanced abilities and a wider scope to align digital economy strategies with goals of sustainable green development. The knowledge flow and talent aggregation brought about by opening up to the outside world further strengthen this process. This multidimensional resource integration capability enables open economies to strategically optimize the latent capabilities of digitalized economic systems in optimizing resource allocation, improving energy efficiency, and innovating pollution control, ultimately achieving coordinated development of economic growth and ecological improvement.

5. Conclusions and policy implications

This research employs longitudinal datasets spanning 2013-2021 to analyze the developmental impacts of digitalization processes on sustainable productivity indicators across 30 provincial-level regions in China, with particular focus on the moderating role of local environmental governance frameworks. Core analytical outcomes demonstrate that:

(1) The digital economy's growth has had a noteworthy effect on the enhancement of green total factor productivity in various Chinese provinces, demonstrating that it can harmonize economic and ecological advantages, bolster the Chinese economy's high-grade development, and aid China's green revolution. In the meantime, the practical test findings on the moderating effect model highlight the crucial role played by the level of environmental regulation in boosting the enhancement of green total factor productivity in the digital economy. Enhanced stringency in environmental governance frameworks exhibits a dose-responsive relationship with eco-efficiency gains attributable to digitalization initiatives, where progressive regulatory rigor correlates positively with sustainable productivity optimization.

(2) There is a variation among provinces in terms of how the digital economy affects green total factor productivity. Regions characterized by greater openness demonstrate statistically significant eco-efficiency gains through digital transformation initiatives, whereas provincial jurisdictions with constrained cross-border engagement currently lack discernible productivity improvements from regional digitalization efforts.

This study provides some insights on how China can cultivate neo-quality productivity forces, achieve productivity-enhancing progression, and realize green transformation in such a digital economy era.

(1) Persistently advance the development of digital infrastructure and refine the enabling ecosystem for digital economic growth. We must broaden the range of digital infrastructure, bridge the voids in less developed areas, narrow the digital economy gap among provinces and promote coordinated growth in green total factor productivity. Meanwhile, we must begin with the digital components themselves and concentrate on the entire process and connections of their production,

gathering, processing, and transmission. In order to foster resilient and sustainable production relationships that support the advancement of green total factor productivity, it is essential to expand the avenues for converting digital components into innovative productivity, while also establishing an external atmosphere that is favorable for the growth of the digital economy. This will cater to the requirements of new quality productivity development and facilitate continuous enhancement of green total factor productivity.

(2) Improve environmental regulations and related government governance, and establish an effective policy system. Effective environmental regulatory measures can positively regulate the enhancing impact of digital economic development on advancing green total factor productivity. Therefore, government departments should accelerate the construction of a multidimensional environmental regulatory framework to seek a balance between the economy and the environment with reasonable standards. What's more, government departments need to innovate governance tool combinations, strengthen intelligent regulatory capabilities, develop a government-guided contemporary ecological governance framework, with enterprise entities and social participation, and promote precise implementation of efficient decision-making and regulation.

(3) Enhance the openness to the external world and attain more effective resource distribution. In the new era of opening up to the outside world, efforts need to be made to create a new highland of "institutional opening up". Government departments must optimize the foreign investment service system, devise factor allocation systems that are novel, strengthen cross-border and cross-regional production capacity collaboration, foster digital trade transformation and upgrade regional industrial structure, as well as enhance and refine the reserve route of intangible capital. Through talent introduction, technology introduction and other means, the problem of mismatch between development needs and development capabilities should be solved. Furthermore, the government needs to attach importance to education investment and technological innovation, cultivate more versatile and professional talents, consolidate the endogenous driving force of local talent supply, get rid of excessive dependence on external resources, and advance environmentally sustainable growth in the digital sector from its origins while accelerating China's ecological modernization.

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