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HOW DOES ICT CAPITAL STOCK AFFECT HIGH-QUALITY ECONOMIC GROWTH? EVIDENCE FROM CHINA

Pengfei GUO[1,2]✉, Zihua HU[3], Xinyun HU[4]✉✉

[1] *Institute for Chengdu-Chongqing Economic Zone Development, Chongqing Technology and Business University, Chongqing, China*
[2] *Chengdu-Chongqing Economic Zone Data Analysis and Intelligent Decision Making Laboratory, Chongqing Technology and Business University, Chongqing, China*
[3] *School of Economics, Yunnan University, Kunming, China*
[4] *School of Management, Chongqing University of Science and Technology, Chongqing, China*

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Abstract. As an essential driving force to promote industrial upgrading and technological innovation, ICT has gradually become the technological support for high-quality economic growth. This paper adopts the improved perpetual inventory method and entropy weight TOPSIS method to measure China's ICT capital stock and economic high-quality growth index, respectively, and experimentally examines the ef-fect of the former on the latter. The findings show that the south has a more extensive ICT capital stock than the north, and the coastal region has a better high-quality growth index than the inland region. Meanwhile, high-quality economic growth, which has increased since 2009 and is incredibly robust in the south, positively correlates with ICT capital stock. Further research finds that ICT capital stock can boost high-quality economic growth by raising marketization and human capital. The results provide policy recommendations for enhancing high-quality economic growth.

Keywords: ICT capital stock, high-quality economic growth, marketization, human capital.

JEL Classification: E22, O11, R11.

✉Corresponding author. E-mail: ***13350382420@163.com***
✉✉Corresponding author. E-mail: ***huxinyun0717@163.com***

1. Introduction

The 19th CPC National Congress report notes that China's economy has moved from a rapid growth phase to a high-quality development phase. New-generation information and communication technology (ICT) not only increases transaction efficiency and promotes industrial upgrading by replacing other capitals and allowing technology to permeate many industrial sectors (Higón, 2012; Murphy et al., 2014; Tang & Konde, 2020; Yan et al., 2021) but also progressively becomes a significant factor in the promotion of high-quality economic growth (Behera et al., 2024; Hussain et al., 2023; Kurniawati, 2022). As of June 2022, China had 1.051 billion Internet users, with an increasing Internet penetration rate of 74.4%, according to the Statistical Report on China's Internet Development (China Internet Network Information Center, 2022). Hence, it is imperative to investigate the comprehensive impact of ICT investment on high-quality economic growth, which is of great practical significance and due value.

However, existing studies mainly focus on the impact of ICT on economic growth quantity (Erumban & Das, 2016; Hazuki, 2015; Jorgenson & Stiroh, 1999; Shahiduzzaman & Alam, 2014; Vu, 2013), and there is limited scholarly research on the influence of ICT on high-quality economic growth. Simultaneously, most academics agree that technical advancement and innovation should be recognized as the main drivers of quality economic growth (Higón, 2012; Marszk & Lechman, 2021). However, exploring its impact factors from the standpoint of technological inputs has not been extensively studied in research. ICT has become a potent force reshaping the world's economic structure in the current global technological revolution and industrial change. Existing studies suggest that ICT can help businesses gain a competitive edge by drastically lowering transaction costs (Kang et al., 2022). Furthermore, it can stimulate technological innovation and industrial structure upgrading, thereby exerting a significant impetus to achieving high-quality economic growth (Higón, 2012; Murphy et al., 2014; Yan et al., 2021). Thus, the effect of ICT capital investment on high-quality economic growth needs to be experimentally tested.

Unfortunately, the existing literature about ICT for high-quality economic growth has three shortcomings. First, most studies do not measure ICT investments but utilize the ICT index consisting of mobile communication, Internet, and fixed broadband instead (Appiah-Otoo & Song, 2021; Bakry et al., 2023). Alternatively, some studies use investment flows rather than capital stock when quantifying ICT investments (Seo et al., 2009). Although some researchers utilize self-measured ICT capital stock data, the use of the unimproved perpetual inventory method (PIM) limits the measurement to only the ICT net capital stock, which makes it difficult to accurately represent the actual productive capacity and service efficiency of ICT capital (Cho et al., 2007). Second, previous research on the heterogeneous effects of ICT investment on economic growth in China primarily categorizes the data into eastern, central, and western areas or developed and underdeveloped regions (Li & Wu, 2022; Wen et al., 2023), with few scholars examining the heterogeneity between the north and south. Finally, since there is a shortage of research linking the ICT capital stock to high-quality economic growth, we can only speculate about its possible mechanisms based on related studies. Most academics argue that ICT increases social productivity through industrial structure upgrading and technological innovation (Higón, 2012; Murphy et al., 2014; Yan et al., 2021), but few scholars have studied it from the perspective of the marketization degree and human capital.

To summarize, this study seeks to make the following contributions. First, this paper utilizes the improved PIM to assess the ICT productive capital stock instead of relying on actual quantities, investment flows, or net capital stock as previous literature has done. Second, compared to the previous literature that focused mainly on the impact of ICT on economic growth quantity, this paper further captures the heterogeneous effect of ICT capital stock on high-quality economic growth from different development periods and regions, especially exploring the differences between the north and the south[1]. Finally, in contrast to the prior literature, which primarily examined mediating mechanisms from the perspectives of

[1] Bounded by the Qinling Mountains and Huaihe River, Jiangsu, Anhui, Shanghai, Zhejiang, Fujian, Jiangxi, Hubei, Hunan, Chongqing, Yunnan, Guizhou, Sichuan, Guangxi, Guangdong, and Hainan are the southern region, and the remaining part is the northern region.

industrial structure and technological innovation, this study explores the mediating roles of marketization degree and human capital, which contributes to a deeper comprehension of the mechanisms by which the ICT capital stock influences high-quality economic growth.

Subsequent sections are organized as follows. Section 2 displays the theoretical analysis and research hypotheses. Section 3 presents the data and method. Section 4 shows the empirical results. Section 5 discusses the results. Section 6 outlines the conclusions and policy recommendations.

2. Theoretical analysis and research hypotheses

This study showcases the influence of the ICT capital stock on high-quality economic growth. The theoretical framework and hypotheses are shown in Figure 1.

2.1. Direct effects

The generation of new production factors accompanies every significant change. ICT, as the basis for developing the information age, has been juxtaposed with traditional factors like land, labor, and capital. In the early days, it was difficult for data to generate value due to technological constraints, and ICT development has led to a fundamental change in the uselessness of data. During the agricultural economy, labor and land were indispensable production factors. During the industrial economy, capital and technology gradually declined the labor force proportion and became essential production factors. In the current information age, ICT has become an important production factor.

Integrating industry and ICT enables traditional industries to develop towards digitalization and intelligence, which reduces pollution emissions, protects the environment, and better supervises and manages enterprises (Lahouel et al., 2021). High-quality economic growth is facilitated by the technological support provided by the development of ICT for digital transformation and supply-side structural reform. Specifically, according to Keynesian Investment Multiplier Theory, an increase in investment causes an exponential increase in income.

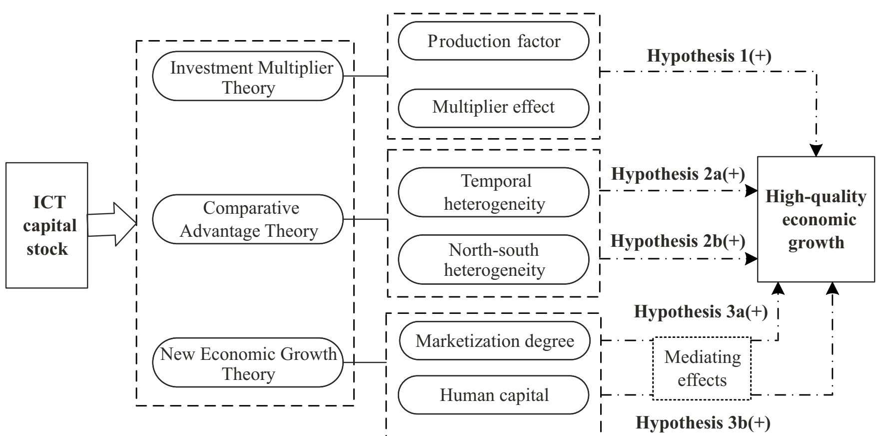

Figure 1. The theoretical framework and hypotheses

The same is true of ICT investment, which can sustainably drive economic growth (Hazuki, 2015). Moreover, with the globalization of the economy, data is growing at a geometric rate. ICT is driving high-quality economic growth by substituting other capitals, penetrating technology into various industrial sectors, and enhancing synergies between factors in the production process due to its ability to effectively utilize the data element (Bartel et al., 2007; Fueki & Kawamoto, 2009; Ketteni, 2009). Therefore, we propose:

H1: *The ICT capital stock has a positive direct effect on high-quality economic growth.*

2.2. Heterogeneous effects

The rapid development of the terminal industry was caused by the issuance of 3G licenses by China at the end of 2008, which compelled the three leading operators-China Mobile, China Unicom, and China Telecom-to enter the market for the construction of large-scale networks and the enrichment of value-added services. A new era of mobile Internet is being introduced with the introduction of 3G, a new-generation mobile communication system that integrates wireless and multimedia communications. The accelerated development of 3G has facilitated the accumulation of ICT capital. The accumulation of ICT capital can improve labor productivity and transaction efficiency and redistribute production factors among industries without the "productivity paradox" phenomenon (Li & Wu, 2022; Rajkhowa & Baumüller, 2024). At the same time, ICT capital accumulation helps economies access wider knowledge networks, enabling them to shift from labor-intensive to skill-intensive production through the knowledge accumulation effect (Zhu et al., 2021), thus enhancing the quality of economic growth. As a result, we claim:

H2a: *The ICT capital stock has a more substantial positive effect on high-quality economic growth after 2009.*

Regional development disparities are a typical phenomenon of the development process. With economic development, regional development policies have shifted from "being first rich" to "being rich altogether," but the problem of regional development disparities still exists. Despite the gradual reduction in the gap between eastern, central, and western China, the gap between northern and southern China has become more pronounced. At present, the north-south gap is generally characterized by higher economic growth, output, and per capita levels in the south than in the north, with technology-intensive industries focusing on the south (Chen & Xu, 2023; Wang et al., 2023). In terms of total economic output, from 2010 to 2020, the absolute gap between the GDP of the north and the south has been increasing, with the south's total GDP accounting for 65.98% of the country's total from 61.25%, which is about twice as much as the north's total economic output.

The difference in the capital stock's growth rate is the primary reason affecting the north-south gap. The north has a high proportion of traditional industries, sluggish investment growth, and slow growth of capital stock. According to the Comparative Advantage Theory, with factor mobility and trade flows, disparities in economic development have emerged between different countries or regions due to inconsistencies in resource endowments and factor inputs (Costinot & Donaldson, 2012). The impact of ICT capital stock on high-quality economic growth varies across the north and south due to different economic policies and factor endowments. Consequently, we contend that:

H2b: *The ICT capital stock has a more substantial positive effect on high-quality economic growth in the south than in the north.*

2.3. Mediating effects

While China has increasingly come to recognize the market's pivotal role in resource allocation following its reform and opening up to the outside world, there are still market barriers of varying degrees in various places, and the market-oriented reform has still not been completed (Poncet, 2005; Xu et al., 2022). The 20th National Congress Report proposes accelerating the construction of a unified national market. ICTs can break down market segmentation and enhance local marketization activity by facilitating data flow and other production factors (Jensen, 2007). In addition, ICT capital investment can improve the productivity of enterprises by transforming the way they produce and reducing the costs of production, information gathering, and communication, thereby promoting cross-regional trade markets for products (Barbero & Rodriguez-Crespo, 2018). Short-term benefits of increased local marketization for enterprises include a rise in transaction frequency and a decrease in transaction costs, which improve transaction efficiency and promote high-quality economic growth (Behera et al., 2024). In the long term, the increased marketization will result in a more diversified organizational structure of enterprises and a closer economic connection between regions. A unified domestic market will be more conducive to market competition and generate economies of scale, significantly influencing high-quality economic growth (Liu et al., 2024). Hence, we further propose:

H3a: *The ICT capital stock can indirectly facilitate high-quality economic growth by increasing the degree of marketization.*

ICT capital investment contributes to human capital accumulation in three main ways. First, ICT and related technologies facilitate more efficient information access and encourage complete knowledge sharing within regional innovation systems. People may swiftly pick up new information and skills using ICT applications, which speed up human capital development across various industries (Oluwatobi et al., 2016). Second, incorporating ICTs into production and management processes prompts innovators to acquire new skills and gain experience, which helps to raise the knowledge and proficiency of the workforce (Khalifa, 2019). Finally, ICT capital investment can accelerate human capital accumulation by expanding the speed and scope of labor mobility and increasing the proportion of highly skilled labor that meets employment needs (Hedberg et al., 2014). The New Economic Growth Theory believes that human capital accumulation is the inexhaustible driving force of economic growth (Barro, 2001). Human capital accelerates technological innovation and application, promotes industrial restructuring, and transforms the economic growth model from extensive to intensive. Meanwhile, human capital accumulation can alleviate the supply and demand problems in the talent market, optimize the employment structure, and expand the output of enterprises, thus promoting high-quality economic growth. Correspondingly, we argue:

H3b: *The ICT capital stock can indirectly promote high-quality economic growth by enhancing human capital.*

3. Data and method

3.1. Data

This paper uses panel data covering 30 Chinese provinces (excluding Tibet and Hong Kong, Macao, and Taiwan) from 2003 to 2020. Original data sources include the China Statistical Yearbook, China Fixed Asset Investment Yearbook, China Statistical Yearbook in Investment Field, Local Statistical Yearbook (above from the China Economic and Social Big Data Research Platform, n.d.; China Economic Information Network, n.d.; EPS database, n.d.). The linear interpolation method is used to fill in some missing data.

3.2. Variables

3.2.1. High-quality economic growth

The dependent variable is high-quality economic growth (*Heg*). The academic community has not yet harmonized the definition of high-quality economic growth. Quality and quantity are two aspects of economic growth, but there is a difference between the two, with quality being a product of quantitative growth at a particular stage. Currently, there are two main methods for measuring high-quality economic growth. The first method is to measure it using labor productivity or total factor productivity (Edquist & Henrekson, 2017; Wang & Guo, 2023). The second method establishes a multidimensional system of indicators from structure, stability, welfare distribution, resource environment, and national quality. Drawing on the studies of Chen and He (2022), Lin and Zhou (2022), and Kong et al. (2022), this paper constructs a high-quality economic growth indicator system from the following five dimensions, given that using a single indicator is difficult to reflect the efficiency of factor allocation.

(1) Economic growth structure. On the one hand, it is imperative to maintain supply-side reform as the primary objective and continue to promote the structural upgrading of domestic industry, investment, and consumption. On the other hand, optimizing the balance-of-payments structure and eliminating reliance on foreign technology providers is necessary. (2) Economic growth stability. In the post-epidemic era, high-quality economic growth requires that output volatility and price volatility be within a reasonable range. (3) Welfare changes and distribution. High-quality economic growth should enable people to obtain appropriate welfare protection to reduce premature mortality caused by major chronic diseases and bridge the gap between urban and rural areas. (4) Resources and environment. High-quality economic growth cannot focus solely on the quantity of economic growth but requires better regulation of resource utilization and harmful emissions. (5) National economy quality. High-quality economic growth requires not only upgrading the hardware environment of the national economy, such as increasing the construction of highways, high-speed railways, postal outlets, and other infrastructures, but also upgrading the soft environment of the national economy, such as accelerating investment in R&D and enhancing innovation capacity. Table 1 presents the high-quality economic growth indicator system.

Table 1. High-quality economic growth indicator system

Dimension	Secondary indicator	Tertiary indicator	Indicator attribute		
			Positive	Negative	Moderate[2]
Economic growth structure	Industrial structure	Industrialization rate	√		
		Industrial structure upgrading index	√		
	Investment and consumption structure	Incremental capital output rate		√	
		Demand structure	√		
	Balance-of-payments structure	External trade dependence	√		
Economic growth stability	Output volatility	GDP index[3]			√
	Price volatility	Consumer price index[4]			√
		Retail price index[5]			√
Welfare changes and distribution	Welfare changes	Population mortality rate		√	
	Welfare distribution	Urban-rural consumption gap		√	
		Labor compensation ratio	√		
Resource and environment	Resource consumption	Electricity consumption per unit of GDP		√	
	Environmental pollution	Sulfur dioxide emissions per unit of GDP		√	
		Total industrial wastewater discharge per unit of GDP		√	
		Emission of general industrial solid waste per unit of GDP		√	
National economy quality	Infrastructure quality	Highway mileage	√		
		Railroad mileage	√		
	Informatization quality	Postal outlets	√		
		Express delivery volume	√		
	R&D quality	Share of science and technology expenditure in fiscal expenditure	√		

We further calculate the high-quality economic growth index using the entropy-weighted TOPSIS method, which involves the following steps:

Standardizing the data in both positive and negative directions is the first step; that is, Equation (1) and Equation (2), where max (X_{ij}) and min (X_{ij}) represent the maximum and minimum of variables, i and j represent provinces and indicators.

$$X'_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})}; \tag{1}$$

[2] The absolute value inverse method is used to normalize the moderate indicator into a positive indicator.

[3] The moderate value is set as the average value of the GDP index over the sample period.

[4] The moderate value is set at 100.

[5] The moderate value is set at 100.

$$X'_{ij} = \frac{\max(X_{ij}) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})}. \tag{2}$$

Equation (3) calculates the information entropy of each indicator, where n represents the number of provinces.

$$D_j = -\ln\frac{1}{n}\sum_{i=1}^{n}\left[(X'_{ij} / \sum_{i=1}^{n} X'_{ij})\ln(X'_{ij} / \sum_{i=1}^{n} X'_{ij})\right]. \tag{3}$$

Equation (4) is used to determine the weight of each indicator, where m represents the number of indicators.

$$W_j = \left(1 - D_j\right) / \sum_{j=1}^{m}\left(1 - D_j\right). \tag{4}$$

Equation (5) is used to construct a weighting matrix of indicators of high-quality economic growth.

$$R = \left(r_{ij}\right)_{n\times m},\ r_{ij} = W_j \times X'_{ij}. \tag{5}$$

Based on the weighting matrix, we can determine the optimal solution in Equation (6) and the worst solution in Equation (7).

$$G_j^+ = \left(\max r_{i1}, \max r_{i2}, \cdots, \max r_{im}\right); \tag{6}$$

$$G_j^- = \left(\min r_{i1}, \min r_{i2}, \cdots, \min r_{im}\right). \tag{7}$$

Equations (8)–(9) are adopted to compute the Euclidean distances of the optimal and worst solutions d_j^-.

$$d_i^+ = \sqrt{\sum_{j=1}^{m}\left(G_j^+ - r_{ij}\right)^2}; \tag{8}$$

$$d_i^- = \sqrt{\sum_{j=1}^{m}\left(G_j^- - r_{ij}\right)^2}. \tag{9}$$

The distance from the ideal solution to each observed solution is the high-quality economic growth index of province i shown in Equation (10).

$$Heg_i = \frac{d_i^-}{d_i^+ + d_i^-}. \tag{10}$$

3.2.2. ICT productive capital stock

The ICT capital stock (*Ict*) is the independent variable. Recently, some researchers have tried to estimate the ICT capital stock of each country using the perpetual inventory method pioneered by Goldsmith (1951). Due to differences in the availability of fixed capital consumption (FCC) data, there are two approaches to measuring capital stock using PIM: unimproved and improved PIM (Guo et al., 2022, 2023; Organization for Economic Co-operation and Development, 2009; Zhao et al., 2022). The unimproved PIM follows the idea of "gross capital stock (GCS) → FCC (obtained directly by assuming an asset depreciation function) → net capital stock (NCS)." The improved PIM follows the idea of "GCS→NCS→FCC," i.e., we first obtain the GCS through the asset retirement function, then set the average age-efficiency/

retirement function to obtain the productive capital stock (PCS), and then combine the average age-efficiency/retirement function with the asset value formula to obtain the average age-price/retirement profile, which can be used to obtain the NCS, and finally indirectly obtain the fixed capital consumption. Hence, the improved PIM not only integrates capital stock and capital services into a unified framework, obtaining GCS, NCS, and PCS, balancing the dual attributes of wealth and production of the asset but also calculates stock and flow data based on the average age efficiency/retirement function, ensuring consistency between stock and flow. Given this, this paper uses an improved PIM to measure the ICT and non-ICT PCS of each province in China from 2003 to 2020, reflecting their capital inputs.

First, the GCS measurement formula is as follows:

$$GCS_t = GCS_{t-1} + I_t - R_t = \sum_{\tau=0}^{T} S_\tau I_{t-\tau}, \tag{11}$$

where I_t denotes the amount of new fixed asset investment in year t after price deflator, R_t denotes the replacement demand of capital goods in year t, and S_τ denotes the residual value rate of capital goods when they reach τ years of service, and R_t and S_τ are mainly dependent on the retirement pattern of the capital goods. Considering that the bell-shaped retirement pattern is more consistent with the retirement process of the ICT capital goods than the simultaneous, linear, and delayed linear retirement patterns, the lognormal frequency distribution model of the bell-shaped retirement pattern is finally selected in this paper:

$$f_\tau = \frac{1}{\sqrt{2\pi} \times \sigma} \times \frac{1}{\tau} \times \exp\left(-\frac{(\ln\tau - \mu)^2}{2\sigma^2}\right),\ \sigma = \sqrt{\ln\left(1 + 1 / \left(m/s\right)^2\right)},\ \mu = \ln m - 0.5\sigma^2, \tag{12}$$

where τ is the age of the asset, σ is the standard deviation of the lognormal function, and μ is its mean, m, and s are the mean and the standard deviation of the underlying normal distribution. The lognormal frequency distribution is commonly used in the EU to measure the capital stock. Standard deviation s is set to a range of $m/2$ to $m/4$, which yields more or less peaked retirement distributions, given m as the estimated average service life. In this paper, s is set to $m/4$. Accordingly, the corresponding survival function $S_\tau = 1 - \int_0^t f_\tau$ is obtained.

Second, because capital goods are subject to physical wear and tear and new technology substitution during their service life, capital goods of different ages have different utilization efficiencies. To obtain the PCS, it is necessary to ensure that capital goods of different service ages have the same utilization efficiency, to treat them as "equivalent", i.e., to sum up, the new fixed asset investment in the whole society through the average age efficiency/retirement function φ_τ of capital goods.

$$PCS = \sum_{\tau=0}^{T-1} d_\tau \times S_\tau \times I_{t-\tau} = \sum_{\tau=0}^{T-1} \varphi_\tau \times I_{t-\tau}, \tag{13}$$

where d_τ represents the age-efficiency function of capital goods. The Australian Bureau of Statistics and the OECD have employed hyperbolic age-efficiency profiles instead of linear and geometric shapes. The form of hyperbolic decline is:

$$d_t = \left(T - t\right) / \left(T - bt\right), \tag{14}$$

where b ≤ 1 represents the slope parameter of the relative efficiency loss of capital goods, which depends on the service life of the capital goods. Referring to Organization for Economic Co-operation and Development (2009) on the setting of the slope parameter and service life, this paper determines the parameters *b* of ICT and non-ICT as 0.6 and 0.7, respectively.

(1) Fixed capital investment series. This paper selects the fixed asset investment amount of ICT in each province as the fixed capital investment series of the current year. The non-ICT fixed asset investment data is then obtained by subtracting the ICT from the whole society's fixed asset investment. (2) Fixed asset investment price index. Due to the lack of provincial data on ICT and non-ICT assets, each province's overall fixed assets investment price index is used as a substitute, and the nominal value calculated based on the current price is converted into the actual value based on the 2003 price. (3) Service life of assets. Limited to data availability, this paper extrapolates the service lives of ICT and non-ICT to 24 and 30 years, respectively, by weighting the average proportion of construction, equipment, and other assets as a component of fixed-asset investment in each industry sector from 2003 to 2020. It is worth noting that, regarding the study of Guo et al. (2023), this paper assumes the service lives of the construction, equipment, and other assets to be 40, 16, and 20 years. (4) Capital stock in the base period. In this paper, the base year is set as 2003, and the capital stock in the base period is obtained by dividing the amount of ICT and non-ICT investment in the base year by the sum of its average depreciation rate and average investment growth rate (Young, 2003). Based on the service lives of ICT and non-ICT investment and assuming a residual value rate of 4%, the average depreciation rates of ICT and non-ICT investment can be estimated to be 12.55% and 10.17%, respectively. The average investment growth rate is obtained using the sum of the average growth rates of ICT and non-ICT investment from 2004 to 2008.

3.2.3. Mediating variables

Marketization degree (*Md*). It is measured using China's marketization index (Fan et al., 2019).

Human capital (*Hc*). It is measured using the actual per capita human capital stock from the China Human Capital Index Report 2022 (China Center for Human Capital and Labor Market Research, 2022).

3.2.4. Control variables

Control variables include: (1) Non-ICT capital stock (*Nict*). Capital stocks other than ICT capital stock, calculated in section 2.2.2 for each province, represent the non-ICT capital stock. (2) R&D investment (*Rdi*). The percentage of R&D expenditures to GDP is used for this measure (Liu et al., 2022). (3) Government size (*Gs*). We use the proportion of general government budget expenditures to GDP (Mollick & Vianna, 2024). (4) Urbanization level (*Ur*). We adopt the ratio of the non-agricultural population to the total population (Ma & Shi, 2023). Descriptive statistics are given in Table 2.

3.3. Estimation method

The benchmark model is Equation (15), where Heg_{it} is the high-quality economic growth of province i in year t; $lnIct_{it}$ represents ICT capital stock; that is, the logarithm of ICT capital stock of province i in year t; X_{ijt} are control variables; u_i and γ_t represent the province and year fixed effect; and ε_{it} denotes the random disturbance term.

Table 2. Descriptive statistics

Variables	Symbol	Interpretation	Obs	Mean	Std. Dev.	Min	Max
Dependent variable	*Heg*	High-quality economic growth index	540	0.267	0.212	0.078	0.909
Independent variable	*lnIct*	Logarithm of ICT capital stock	540	5.723	0.896	2.521	7.624
Control variables	*lnNict*	Logarithm of Non-ICT capital stock	540	9.865	1.143	6.817	12.113
	Rdi	R&D investment	540	0.009	0.006	0.001	0.032
	lnGs	Logarithm of government scale	540	–1.614	0.415	–2.536	–0.442
	lnUr	Logarithm of urbanization rate	540	–0.659	0.266	–1.382	–0.056
Mediating variables	*Md*	Marketization degree	540	6.226	1.85	2.33	11.91
	lnHc	Logarithm of human capital	540	5.518	0.602	4.232	7.065

$$Heg_{it} = \alpha_0 + \alpha_1 \ln Ict_{it} + \sum_j \alpha_j X_{ijt} + u_i + \gamma_t + \varepsilon_{it}. \quad (15)$$

To further examine the heterogeneous effects of ICT capital stocks, we create the dummy variable regression model in Equation (16), where *yh* is the time dummy variable with a value of 1 or 0, 1 for the 2009–2020 period and 0 otherwise. Equation (17) constructs a regional dummy variable *north*, which represents the northern region of China when the value is 1.

$$Heg_{it} = \beta_0 + \beta_1 \ln Ict_{it} + \beta_2 \ln Ict_{it} \times yh + \sum_j \beta_j X_{ijt} + u_i + \gamma_t + \varepsilon_{it}; \quad (16)$$

$$Heg_{it} = \chi_0 + \chi_1 \ln Ict_{it} + \chi_2 \ln Ict_{it} \times north + \sum_j \chi_j X_{ijt} + u_i + \gamma_t + \varepsilon_{it}. \quad (17)$$

This study also investigates if the degree of marketization and human capital have mediating effects. With reference to Baron and Kenny (1986) and Hayes (2009), we use the stepwise regression method to create the following mediating effect model:

$$Mv_{it} = \delta_0 + \delta_1 \ln Ict_{it} + \sum_j \delta_j X_{ijt} + u_i + \gamma_t + \varepsilon_{it}; \quad (18)$$

$$Heg_{it} = \theta_0 + \theta_1 \ln Ict_{it} + \theta_2 Mv_{it} + \sum_j \theta_j X_{ijt} + u_i + \gamma_t + \varepsilon_{it}, \quad (19)$$

where *Mv* denotes the mediating variables, i.e., the marketization degree (*Md*) and the logarithm of human capital (*lnHc*). We first need to test whether α_1 is significant. If α_1 is significant, the following three cases may occur. A complete mediating effect is considered when θ_1 is not significant but δ_1 and θ_2 are significant. A partial mediating effect is considered when δ_1, θ_1 and θ_2 are all significant and $\theta_1 < \alpha_1$. The bootstrap sampling method should be used to test for a mediating effect when either δ_1 or θ_2 is not significant.

4. Results

4.1. Measurement results of ICT capital stock and high-quality economic growth

4.1.1. Measurement results of high-quality economic growth

This paper computes the high-quality economic growth index of 30 provinces in China from 2003 to 2020, as outlined in Section 2.2.1 (see Figure 2). First, the index of the eastern coastal region was significantly higher than that of the central and western areas in 2003, while the high index extends further into the eastern and southern regions in 2020, indicating that the high-quality economic growth is uneven across the country and that there is regional variability. Second, although most provinces' overall high-quality economic growth is improving, the average value during the sample period is between 0.2 and 0.4, indicating that China's high-quality economic growth still has more room for improvement. The reasons are as follows: the better economic base and closer proximity to international markets in the eastern coastal and southern provinces have led to higher economic growth indexes in these regions. In addition, China's economic growth mode had previously been dominated by a crude mode for an extended period, so high-quality economic growth still needs to be further enhanced.

Regarding index rankings (Figure 3), Beijing, Shanghai, and Guangdong are always at the top, while Gansu is often at the bottom. Guangdong ranked first, followed by Shanghai and Beijing, with Gansu, Guizhou, and Yunnan at the bottom in 2003. Shanghai ranked first, followed by Beijing and Guangdong, with Xinjiang, Gansu, and Inner Mongolia at the bottom in 2020. Moreover, Chongqing, Anhui, and Guangxi have the most considerable growth rates, while the fluctuations in the remaining provinces are relatively small and within a reasonable range. The reason is that according to the Economic Growth Convergence Theory, relatively backward regions have higher economic growth rates due to their weaker economic base.

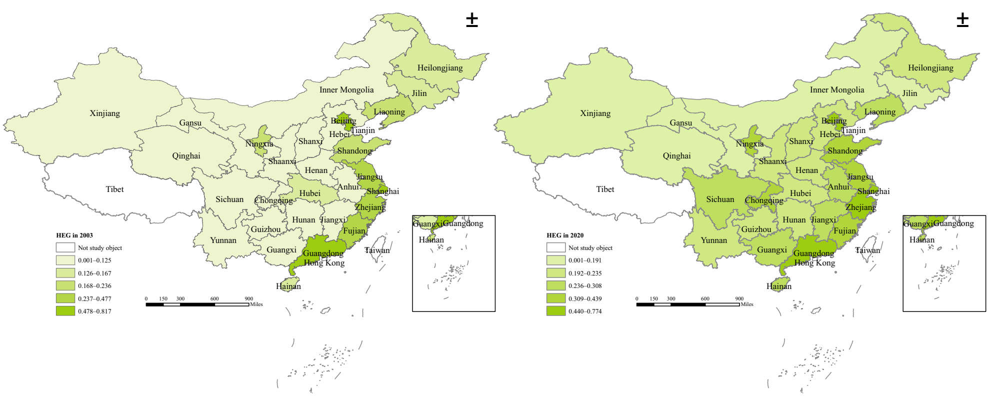

Figure 2. Distribution of high-quality economic growth index of 30 provinces in China in 2003 and 2020

4.1.2. Measurement results of ICT capital stock

According to section 2.2.2, this paper estimates the ICT and non-ICT capital stock data in 30 provinces of China from 2003 to 2020 (Figure 4). It shows that the value of non-ICT capital stock is significantly higher than that of ICT capital stock. After bounding the south and north by the Qinling Mountains and Huaihe River, the capital stock in the south is significantly larger than that in the north.

Regarding the ranking of the average growth rate of ICT capital stock (Figure 5), the growth rate of ICT capital stock in Jilin, Inner Mongolia, and Qinghai is at the top, while that in Jiangxi and Guangdong is at the bottom. It should be noted that although the growth rates of some regions are relatively low, the absolute value of growth is still very high due to the large ICT capital stock base in these regions.

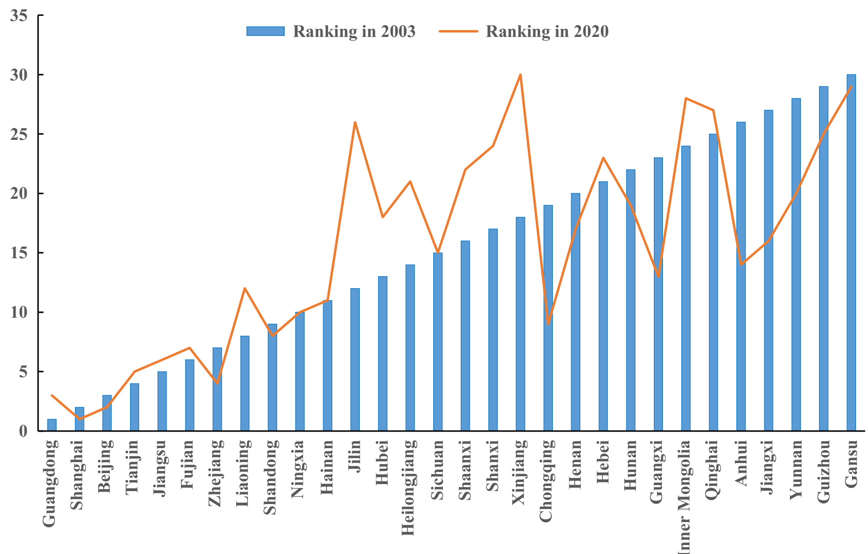

Figure 3. Ranking of high-quality economic growth index of 30 provinces in China in 2003 and 2020

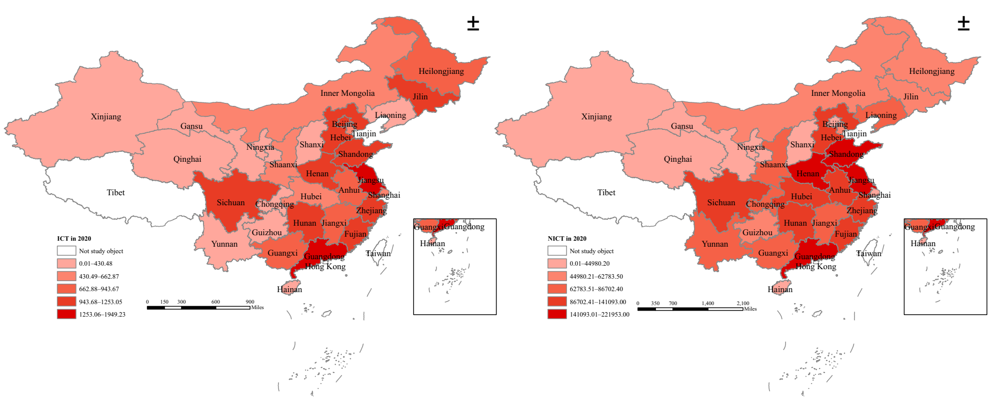

Figure 4. ICT and non-ICT capital stock data in 2020 (Unit: 100 million yuan)

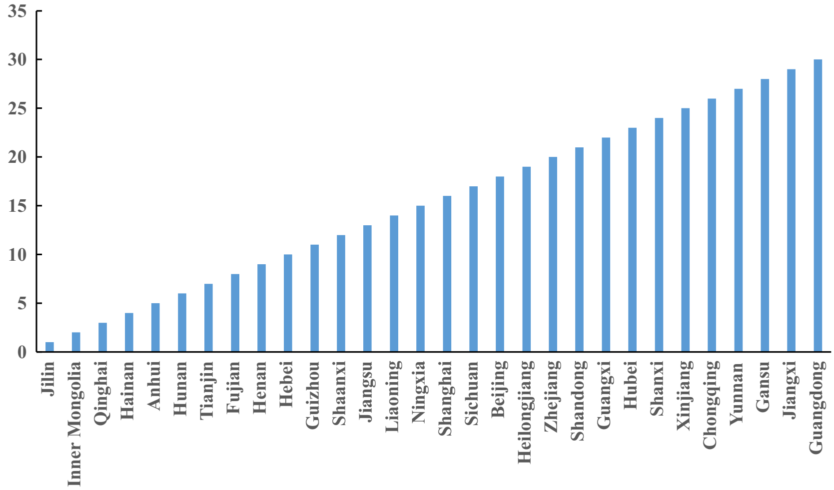

Figure 5. Ranking of the average growth rate of ICT capital stock over the sample period

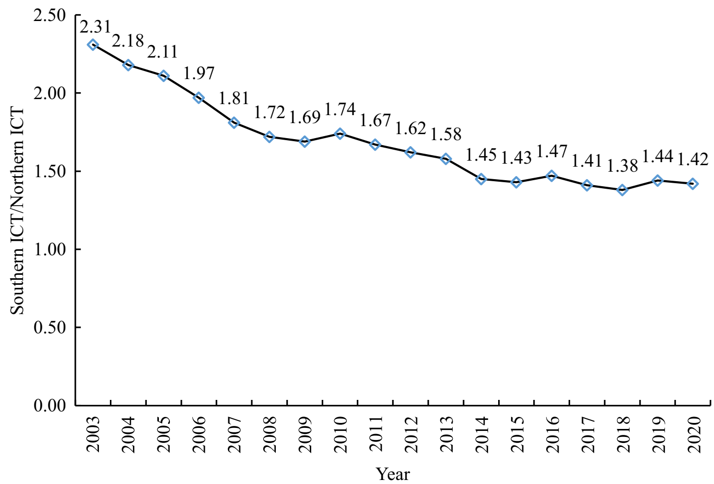

Figure 6. Ratio of ICT capital stock in the south to the north from 2003 to 2020

In terms of the ratio of ICT capital stock in the south to the north (Figure 6), although there is a significant difference in the ICT capital stock between the south and north, the ratio of ICT capital stock in the south to the north shows a decreasing trend over time, indicating that the gap between the south and north is gradually narrowing.

4.2. Direct effects

Table 3 provides the regression results of direct effects. Whether or not control variables are included, the results show that the ICT capital stock significantly positively affects high-quality economic growth. *Hypothesis 1* is supported.

Table 3. Direct effects

Variables	*Heg* (1)	*Heg* (2)	*Heg* (3)	*Heg* (4)
lnIct	0.0964*** (10.32)	0.1101*** (11.24)	0.1116*** (3.22)	0.0176*** (5.17)
lnNict		–0.1194*** (–14.63)	–0.0875*** (–3.63)	–0.0373*** (–7.16)
Rdi		9.4145*** (6.76)	9.6988** (2.27)	1.2563*** (3.68)
lnGs		–0.0322** (–2.15)	0.0471 (0.98)	–0.0212*** (–3.28)
lnUr		0.5622*** (25.26)	0.5899*** (5.14)	0.2295*** (13.78)
Constant	–0.2748*** (–3.66)	1.0544*** (17.99)	21.7664** (2.24)	–4.8784*** (–4.13)
Province FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Woold test				P = 0.0000
Pesaran test				P = 0.0000
Wald test				P = 0.0000
R^2	0.15	0.75	0.78	0.88
Observations	540	540	540	540

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, the numbers in () are robust t-statistics.

Specifically, Column (1) uses *lnIct* to regress *Heg*, showing that the coefficient is positive at a 1% significance level. Columns (2) and (3) further add all control variables and are estimated using the ordinary least square (OLS) estimation and mixed-effect regression, respectively, showing that the effect of *lnIct* on *Heg* remains significantly positive. Column (4) considers the possible existence of intra-group autocorrelation, inter-group contemporaneous correlation, and inter-group heteroskedasticity for the error term ε_{it}, and therefore validates it using the Woold test, the parametric test proposed by Pesaran (2021), and the Wald test, respectively. The results demonstrated that the P-values of the three tests were less than 0.01, rejecting the original hypotheses of the non-existence of intra-group autocorrelation, inter-group contemporaneous correlation, and inter-group heteroskedasticity. Based on this, Column (4) uses the feasible generalized least square (FGLS) to correct the model, showing that the regression coefficient of *lnIct* on *Heg* is 0.0176 at a 1% significance level, which suggests that the ICT capital stock positively impacts high-quality economic growth.

Furthermore, the results of Column (4), including all control variables, show that non-ICT capital stock (*lnNict*) negatively influences high-quality economic growth, suggesting that we should replace other capital with ICT capital to promote high-quality economic growth. R&D investment (*Rdi*) is significantly positive at a 1% significance level, showing that the increase in R&D investment makes technicians accelerate the unlocking of new technologies and promote technological innovation, which is conducive to economic stability and environmental protection. Government scale (*lnGs*) negatively affects high-quality economic growth. Since the market determines resource allocation, excessive government intervention increases market volatility and impedes high-quality economic growth.

Urbanization rate (*lnUr*) positively affects high-quality economic growth. With the increasing level of urbanization in China, many farmers have become urban residents, and changes in their consumption habits and increased demand for products are conducive to population aggregation and industrial structure upgrading, thereby promoting high-quality economic growth.

Referring to Guo et al. (2023), this paper performs robustness tests by replacing the main variables and changing the sample treatment. Regarding the main variable replacement, the NCS of ICT is applied to substitute its PCS for the mechanism test for robustness tests. We construct a new measurement sample using a bilateral 1% and 5% shrinkage of ICT capital stock to eliminate the effects of outliers in the core independent variable on the estimation results. In addition, for the endogeneity discussion, we choose the interaction term between the number of courier stations in each province in the Ming Dynasty and year dummies (*c.mp # year*), and the core independent variable lagged one period as the instrumental variable of the per capita infrastructure capital stock. According to the robustness test and endogeneity discussion, the study concludes that ICT capital stock significantly positively affects high-quality economic growth. The estimation results are not presented due to space limitations.

4.3. Heterogeneous effects

The results of the heterogeneity test are presented in Table 4. Column (1) shows that the estimated coefficient of *lnIct* on *Heg* is 0.0172 at the 1% significance level, and the coefficient of the interaction term of ICT capital stock with the time dummy variable ($lnIct \times yh$) is significantly 0.0015. Therefore, the coefficient of *lnIct* on *Heg* in 2009–2020 is 0.0187 (0.0172 + 0.0015 = 0.0187), a more substantial contribution than in 2003–2008. It implies that ICT capital stock has a significant positive effect on high-quality economic growth, which is greater in the later period, confirming *Hypothesis 2a*. After the official issuance of 3G licenses in early 2009, China's three major mobile communication operators officially put 3G into commercial use. By September of the same year, China's cell phone subscribers exceeded 700 million, further spawning the development of 4G and 5G, thus accelerating high-quality economic growth.

Column (2) shows that the estimated coefficient of *lnIct* on *Heg* is significantly 0.0286. The coefficient of the interaction term of ICT capital stock with the dummy variable for the north ($lnIct \times north$) is significantly –0.0197, indicating that the coefficient of *lnIct* on *Heg* in the north is 0.0089 (0.0286 – 0.0197 = 0.0089), which is smaller than that in the south. Therefore, the positive impact of ICT capital stock on high-quality economic growth is more significant in the south compared to the north, thus testing *Hypothesis 2b*. The original industrial and demand structure makes it difficult for the northern provinces to transform the economic model, resulting in economic disparities between the north and the south. Meanwhile, human capital in the north continues to flow towards the south, and the rate of brain drain is too fast, making the promoting effect of ICT capital stock to high-quality economic growth more robust in the south.

Table 4. Heterogeneous analysis

Variables	Different development periods	Different development regions
	Heg (1)	*Heg* (2)
lnIct	0.0172*** (5.11)	0.0286*** (8.96)
lnIct×yh	0.0015*** (3.78)	
lnIct×north		–0.0197*** (–5.88)
lnNict	–0.0306*** (–8.57)	–0.0336*** (–8.77)
Rdi	1.0166*** (3.14)	1.2011*** (4.68)
lngz	–0.0286*** (–4.67)	–0.0154*** (–2.73)
lnurb	0.2512*** (15.24)	0.2151*** (14.32)
Constant	–4.6946*** (–4.11)	–5.6942*** (–4.96)
Province FE	Yes	Yes
Year FE	Yes	Yes
R^2	0.39	0.60
Observations	540	540

Note: ***p < 0.01, **p < 0.05, *p < 0.1, the numbers in () are robust t-statistics.

4.4. Mediating effects

The results of the mediating effects are shown in Table 5. Column (1) illustrates that the ICT capital stock positively impacts high-quality economic growth. Column (2) reveals the estimated coefficient of ICT capital stock on marketization degree is 0.0797, indicating that it can enhance the marketization degree. Column (3) shows that the degree of marketization also positively impacts high-quality economic growth. Still, the estimated coefficient of ICT capital stock has decreased from 0.0176 to 0.0173, suggesting that the marketization degree presents a partial mediating effect. Moreover, we can obtain the total effect of the ICT capital stock on high-quality economic growth is 0.0176, the direct effect is 0.0173, and the indirect impact is 0.0003 (0.0797 × 0.0036 = 0.0003). In the era of Industry 4.0, ICT with technological advantages reinforces the market's role in resource allocation. This further proves that ICT investment can drive high-quality economic growth by increasing marketization degree, verifying *Hypothesis 3a*.

In Column (4), the impact of ICT capital stock on human capital is significantly positive, suggesting that it can promote human capital. The effect of human capital on high-quality economic growth is significantly positive, but the coefficient of ICT capital stock has also decreased in Column (5), indicating a partial mediating effect. The direct effect is 0.0172, and the indirect effect is 0.0004 (0.0197 × 0.0221 = 0.0004), suggesting that ICT capital goods

Table 5. Mediating effects

Variables		Mediator: Marketization degree		Mediator: Human capital	
	Heg (1)	*Md* (2)	*Heg* (3)	*lnHc* (4)	*Heg* (5)
lnIct	0.0176*** (5.17)	0.0797*** (4.35)	0.0173*** (5.46)	0.0197*** (8.35)	0.0172*** (4.79)
Md			0.0036*** (2.66)		
lnHc					0.0221*** (8.16)
Control variables	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
R^2	0.88	0.59	0.34	0.77	0.66
Observations	540	540	540	540	540

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, the numbers in () are robust t-statistics.

help to promote the accumulation of high-skilled human capital and increase the specialization of R&D activities. The findings suggest that the ICT capital stock can indirectly promote high-quality economic growth by improving human capital. *Hypothesis 3b* is confirmed.

5. Discussion

5.1. Discussion on direct effects

For the direct effects of ICT capital stock on high-quality economic growth in Section 3.2, as shown in the empirical results in Table 3, this study obtains a vital finding that ICT high-quality economic growth is significantly boosted by ICT capital investment, which is in line with the findings of Edquist and Henrekson (2017) and Wang and Guo (2023). It should be mentioned that they measure high-quality economic growth using either total factor productivity or green total factor productivity. However, considering that a single indicator cannot reflect the efficiency of factor allocation, this study builds an indicator system with multiple dimensions to measure high-quality economic growth. Meanwhile, ICT productive capital stock is estimated using the improved PIM in this paper, which improves estimation accuracy compared to the literature that employs actual amount, investment flow, or net capital stock to quantify ICT capital investment.

5.2. Discussion on heterogeneous effects

By analyzing the heterogeneous effects of ICT capital stock on high-quality economic growth in section 3.3, this study concludes that the positive effects of ICT capital stock on high-quality economic growth are more significant after 2009 and in southern China. In terms of time heterogeneity, the impact of ICT capital stock on high-quality economic growth is more significant over time. This finding is related to the time lag of ICT capital investment. Edquist and Henrekson (2017) found that the positive effect of ICT capital investment on total factor productivity is obtained by a lag of seven to eight years in ICT capital investment. Regarding regional heterogeneity, ICT capital investment contributes more to high-quality economic growth in the south of China than in the north, as the southern part of the country is more economically developed than the northern part. Most cross-country studies also suggest that the contribution of ICT to productivity varies considerably among different economies, with the contribution of ICT being more significant for developed countries and emerging Asian economies (Dedrick et al., 2013; Niebel, 2018), which is mainly due to differences in infrastructure, human capital, institutional environment, and organizational management. In addition, unlike many previous studies that divide China into eastern, central, and western regions (Li & Wu, 2022; Wen et al., 2023), this paper tests regional heterogeneity by dividing China into southern and northern regions, which better reflects China's actual economic development in recent years.

5.3. Discussion on mediating effects

The paper further analyzes the mediating effects of the degree of marketization and human capital through section 3.4, which finds that ICT capital stock positively impacts high-quality economic growth through the degree of marketization and human capital accumulation. The latter has a more substantial mediating effect. This result is in accordance with earlier studies that concluded that ICT raises total factor productivity by enhancing the quality and efficiency of traditional production factors like labor and capital (Khan et al., 2017; Kallal et al., 2021). For capital factors, ICT not only realizes the dynamic allocation of capital in the market by processing and monitoring data but also changes the production and organization modes of enterprises and industries, creates plenty of new product markets, and thus optimizes the capital structure and increases the marketization degree. For labor factors, ICT encourages workers to acquire new knowledge and information at the lowest cost and continuously innovate to adapt to the application of new technology, thus enhancing the value of human capital and accelerating the transformation of data factors into real productivity.

5.4. Limitations and future research

Although this study offers a comprehensive examination of the impact of ICT capital stock on high-quality economic growth, there are still limitations. (1) Due to data availability, this paper only analyzes the impact of ICT capital investment on high-quality economic growth at the provincial level. In future research, more samples can be used to test the impact of ICT capital investment on high-quality economic growth at the city or county level. (2) ICT capital investment's nonlinear and spatial impacts on high-quality economic growth must be further explored.

6. Conclusions and policy recommendations

This study thoroughly examines the multidimensional relationship between ICT capital stock and high-quality economic growth using Chinese province panel data. The primary contributions of this study are the measurement of the high-quality economic growth index and ICT capital stock, as well as the development of a comprehensive empirical framework to evaluate the impact of ICT investment on China's high-quality economic growth, which fills the gaps in existing research. The findings indicate that, first, China's high-quality economic growth index is generally favorable, and the indexes of the eastern coastal and southern regions are more extensive compared with those of the inland and northern regions. Even though the south has a more extensive ICT capital stock than the north, the disparity between the two is progressively closing. Second, high-quality economic growth is significantly positively impacted by ICT capital stock. Third, there are apparent heterogeneous effects between different development periods and different development regions. ICT capital stock positively impacted high-quality economic growth more after 2009 than before and more in the south than in the north. Finally, the transmission mechanism tests show that ICT capital stock can indirectly contribute to high-quality economic growth by increasing marketization degree and human capital.

The study makes the following policy recommendations based on the abovementioned conclusions. First, given that ICT capital investment plays a substantial role in promoting high-quality economic growth and has a more significant impact in the southern region, governments should strategically increase ICT investment according to local conditions. On the one hand, ICT investment should be increased. Different regions should vigorously develop ICT-based emerging industries and accelerate the combination of the real economy and ICT. On the other hand, the regional gap in ICT capital should be narrowed. The problem of unbalanced regional development still exists in China. In promoting ICT construction in a coordinated manner, it is necessary for the central government further to increase the policy tilt towards the northern region, optimize the spatial distribution of ICT capital stock, and improve the policy of harmonious regional development. Second, the degree of marketization should be further enhanced. Specifically, policymakers are encouraged to uphold the market's dominant role in allocating resources, transform government functions, and improve administrative efficiency. Meanwhile, optimizing market supervision methods, fighting unfair competition, and creating a fair and transparent market operating environment are necessary. Third, the level of human capital should be constantly improved. All regions, especially the northern provinces, should optimize the relevant human resources policies to avoid the loss of talent. On the one hand, the government should adhere to market demand orientation, focus on cultivating skilled talents, and promote vocational education reform. On the other hand, governments should increase investment in inclusive human capital and facilitate the social security system to raise human capital.

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