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Population Aging, Digital Economy and NQP—Empirical Data from China

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Abstract

Multiple metrics exist for assessing the development of new quality productivity (NQP). This study employs principal component analysis (PCA) to construct a multidimensional evaluation index. On the basis of theoretical analysis, panel model, spatial Durbin model and regulatory effect model are used to investigate the effects of population aging and digital economy on NQP. Utilizing provincial-level panel data from China (2000–2022), key findings emerge: (1) Population aging have an important positive influence on the development of NQP. (2) Digital transformation serves as the primary mechanism through which aging influences NQP. (3) Threshold regression analysis reveals a nonlinear relationship: When digital penetration is ≤0.1 (threshold value), aging inhibits NQP via suppressed digital transformation; beyond this threshold, aging promotes NQP through enhanced digital adoption.(4) Significant regional heterogeneity exists, with eastern provinces demonstrating markedly higher NQP development levels than western regions.

Keywords: digital transformation; new quality productivity; population aging; spatial Durbin model

1. Formulation of the Problem

Amidst rapid transformations in the global economic landscape, China has solidified its position as a pivotal actor. The nation's economic trajectory has transitioned from rapid expansion to a development phase centered on cultivating new quality productive forces (NQPFs). Within this paradigm, strategically harnessing opportunities arising from industrial digitization and digital industrialization constitutes the critical pathway for advancing the structural transformation of China's economic growth model.

NQP is a high-frequency word hotly discussed in Chinese society. This refreshing and original concept not only indicates the new production factors to stimulate new momentum in the new development stage, but also clarifies the industrial support and development engine for China to reshape its new advantages in global competition.

Look back at China's rapid development, the "demographic dividend" formed by population size and structural advantages is undoubtedly a key driver for economic expansion. However, along with the continuous social and economic development, China's demographic structure is undergoing profound changes, facing the demographic dilemma of aging population and declining fertility rate. In terms of demographic structure, from 1960 to 2022, the number of elderly people in China increased from 26.26 million to 200 million, and the proportion of the population increased from 4.0% to 13.7%. In the past three decades, the aging process of our country has been accelerating. The average annual aging rate increased by 0.16, 0.18 and 0.45% during 1992-2002, 2002-2012 and 2012-2022, respectively. According to United Nations projections, China will enter an ageing society in 2001, a deeply ageing society in 2023 and a super-ageing society in 2034.

The expansion of tertiary education systems and universal implementation of compulsory education have progressively elevated the mean years of schooling (MYS). This accumulation of human capital partially mitigates structural challenges arising from demographic transitions. Historically, shifts in population structures have always been closely linked to economic growth. The

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independent research and development of production technology is the weak link of China's productivity transformation, and the NQP is essentially a new requirement for this point. The deepening of population aging will exert a significant impact on the development of NQP.

2. Literature Review

The 2024 Chinese Government Work Report articulated explicit directives to "accelerate the establishment of a modern industrial system and foster the advancement of new quality productive forces (NQPFs)" (Li, 2024). These policy mandates position NQPFs as a catalytic driver for enhancing China's scientific and technological innovation capacity, thereby propelling a new wave of technological transformation within the modern industrial ecosystem.

Since the concept of NQP has not been put forward for a long time, the research on this aspect mainly focuses on the following aspects: theoretical connotation, relationship with traditional productivity, characteristic manifestation and formation mechanism. The replacement of traditional productive forces is represented by NQP. Different from the traditional concept of productivity, NQP takes innovation as the primary factor to promote production efficiency. NQPFs emerge as an efficiency-optimized paradigm propelled by perpetual innovation cycles within next-generation information technologies and Schumpeterian technological paradigm shifts. At the same time, NQP is the specific form of advanced productivity in the new development stage. This concept shows the practical results of the new production capacity of China. The new quality of productivity is essentially represented by "computing power" (Liu, Li & Sun, 2023). Under the background of the current development environment, the integration of digital technology and emerging factors has given rise to a novel form of productivity advancement. NQP refers to the output achieved through the realization of pivotal disruptive technological breakthroughs, which signifies the output generated through the attainment of pivotal, disruptive technological advancements(Zhou & Ye, 2024). The change of economic development background makes the traditional economic growth model no longer adapt to the orientation of economic and social development. The holistic economic-social progress is fundamentally propelled by technological paradigm shifts and industrial restructuring. These dynamics create unprecedented opportunities for advancing NQP through China's industrial upgrading trajectory. The success of industrial upgrading and transformation depends on the breakthrough of key technologies and disruptive technological innovation(Zhou & Xu, 2024).

NQP is not only in its "new", but also in its "quality"(Ren & Dou, 2024). The "new" of the NQP is mainly reflected in the new production factors and the new combination of factors, which are embodied in the new factors, new technologies and new industries(Zhang & Tang, 2024). The "quality" is the performance of high-quality industrial foundation and development momentum(Jiang & Qiao, 2024),which is reflected in high-quality, multi-nature, dual-quality efficiency, and released through the five major productive forces of digital, collaboration, green, blue and open. The generation of NQP does not only rely on the simple innovation of digital technology, but needs to go through a more complex process, in this process to form a productivity system. The key to this process is constantly consolidating traditional productivity, forming more original and disruptive innovations, and promoting the qualitative transformation of productivity development.

The genesis of new quality productivity (NQP) emerges dialectically from the substrate of conventional productive forces, constituting a qualitative transcendence beyond mere quantitative accumulation, which is a qualitative leap from quantitative change to qualitative change, and the evolution path includes the transformation of the entire production paradigm(Zhou & Hu, 2004). The thorough progression of the latest technological change, along with the emergence of new industries, business models, and operational paradigms within the digital economy's development, serve as both the industrial foundation and propelling force behind the formation of NQP(Du, 2023). Scientific and technological innovation is the driving factor of productivity, and new industries such as emerging sectors of strategic importance and industries in the future are the main fields(Liu & Zhao, 2004). At present, the development of digital economy has been integrated into every link of economic life.

Technological Innovation-Driven NQP serves as a fundamental enabler of economic development, underpinned by the accelerated proliferation of next-generation information technologies and their associated digital infrastructure.

With the evolution of the population age structure, the aging of the workforce has become an objective necessity in the aging process. The labor force share aged 55-64 in the United States has increased by about a third in the past 20 years, and the share of the workforce aged 55 and older in Canada will exceed a quarter in 2021. Countries such as Europe, Japan and Australia are also facing serious workforce aging problems. Although the aging of China's workforce is occurring later than that of developed countries in the West, the severity of the problem is increasing.

The study of the relationship between productivity and aging problem is mainly carried out from the micro and macro perspectives. However, due to differences in labor productivity measurement methods, abilities of different cohort populations, economic sectors related to industrial structure, and individual jobs, the conclusions of the study have not been reached. The majority of research indicates that the aging of the workforce exerts a detrimental influence on labor productivity. The reasons include the decline in physical fitness, the decline in learning and innovation ability, and The aging of the workforce leads to the depreciation of skills. The aging of the population reduces innovation input through reducing financial expenditure, Which hinders the enhancement of production efficiency. Labor productivity will decrease by 0.106% to 0.479% (CALVO-SOTOMAYOR , LAK & AGUADO, 2019)(FEYRER, 2007)(LINDH & MALMBERG, 1999)(Zheng, Zhu & Guan, 2014)(MCMILLAN & BAESEL, 1990). Some scholars also take stock in that the deepening of aging problem will alleviate the adverse impact on labor productivity through the "learning by doing" effect, capital substitution and technological innovation (BURTLESS, 1998)(SKANSON, 2008)(GUEST, 2011). The intensification of population aging elevates labor costs and drives the enhancement of enterprises' total factor productivity. The research shows that the promotion effect of state-owned enterprises on labor productivity is the strongest, Empirical evidence indicates heterogeneous enterprise impacts on labor productivity: state-owned enterprises (SOEs) demonstrate the most substantial enhancement effect, while foreign enterprises exhibit the weakest influence (Xue, Xiao & Tang, 2023). Crucially, population aging manifests a nonlinear inverted U-shaped relationship with labor productivity: during initial demographic transitions, aging exerts a positive effect on productivity; beyond critical thresholds, this relationship transitions toward diminishing returns(Li, 2019).

Through industry differentiation analysis, the effect of population aging on labor productivity is heterogeneous, meaning it varies across different contexts or groups(Zhao & Chen, 2019). Certain studies further suggest that the degree of ageing in different countries will vary, and the productivity impact will change. In developed countries, population aging may not have a negative impact on labor productivity, but has promoted the improvement of labor productivity(BLOOMDE & SOUSA, 2013). For example, relevant data research in Germany and other developed countries found that the stock of human capital in developed countries increased with the increase of working years, which indicates that population aging will increase the stock of human capital in developed countries(Li, 2015). Further research has revealed that population aging significantly promotes the advancement of artificial intelligence, facilitating the replacement of manual labor and fostering collaborative labor division.

Current scholarship lacks consensus on quantitative metrics for assessing the development level of NQPFs, reflecting an emergent research domain requiring further methodological refinement. Prevailing literature predominantly engages with theoretical frameworks underpinning NQPF evolution, thereby informing the present study's primary objective: constructing a multidimensional evaluation index system for NQPF advancement. Furthermore, this investigation conducts an empirical inquiry into the causal mechanisms linking population aging to NQPF development. Lastly, recognizing the digital economy as a pivotal catalyst for NQPF transformation, this research examines the mediating role of digitalization in transmitting aging effects to NQPF outcomes..

3. Theoretical Analysis and Research Hypotheses

3.1. Population Ageing and NQP Improvement

In terms of aggregate supply, the improvement of NQP often means the optimization of labor productivity, which is determined by both output and personnel. According to economic growth theory, the output level is contingent upon factors such as labor, capital, and technology. The causal pathways through which population aging influences new quality productive forces (NQPFs) encompass labor supply dynamics, capital allocation efficiency, and technological innovation capacities. Crucially, technological innovation constitutes the principal driver of NQPF advancement—a complex, multi-stakeholder process characterized by systemic interdependencies across innovation ecosystems. The detrimental effects of aging on technological innovation can be summarized in two aspects. First, the peak of individual innovation output is between 35 and 40 years old. Aging causes the weakening of physical and mental functions, and the gradual decline of learning ability, application ability and innovation ability, which is not conducive to the diffusion of new technologies and the transformation of achievements of enterprises(MEYERJ, 2009). Second, as the aging process intensifies, enterprise labor costs and government pension welfare expenditures increase, thereby crowding out national scientific research funding and weakening enterprises' motivation for research and development, thus adversely affecting technological innovation(Noda, & Hideo, 2011). Advancements in digital information technology impose elevated accessibility barriers for aging population cohorts. Consequently, this demographic transition precipitates diminished user engagement in digital finance, credit systems, and e-commerce platforms, ultimately constraining the developmental trajectory of the digital economy.

Some studies argue that an aging population enhances the accumulation of human resource by the effect of "learning by doing", which may lead to technological innovation. Reducing the proportion of working-age workers will increase the labor cost of enterprises, thus forcing enterprises to adopt advanced technologies to replace labor force. These are the positive effects of the "learning by doing" effect.(Cheng & Lu, 2024). These positive effects are conditional. Only when the negative impact of population aging on technological innovation is greater than the positive impact, the deepening of population aging will inhibit technological innovation. On the contrary, the deepening of population aging has a positive impact on promoting technological innovation. Therefore, this paper puts forward the following research hypotheses:

H$_1$: *Population aging can significantly impede the NQP.*

3.2. The Regulatory Effect of Digital Economy in the Improvement of NQP

Population aging constitutes a primary constraining factor impeding the efficacy enhancement of NQP. Consequently, a critical research question emerges: Can the digital economy functionally moderate the adverse impacts of demographic aging on NQPF advancement?

Through the deep integration of digital technology and advanced manufacturing technology, production efficiency can be improved in a more comprehensive way, which is particularly obvious in the manufacturing industry. The production process and management mode of the manufacturing industry has been optimized, the supply quality of the manufacturing industry has been improved, and new productivity and production relations have been brought about. First of all, the digital economy replaces part of the labor input through the degree of technology intensity, empowers traditional industries to find breakthroughs in new industries, and alleviates the problem of aging labor force. With the continuous deepening of automation and intelligence in the production process, the improvement of production efficiency has prompted enterprises to use capital to replace labor in more production tasks, and the industrial sector will develop in a capital-intensive direction. Secondly, the universal applicability, dynamic evolution and innovative complementarity of digital technology promote the continuous realization of technological innovation. This is helpful for R&D departments that want to improve efficiency(Zhang & Zhu, 2024). Finally, the externalities of digital

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technologies lower the barriers to entry, reduce the learning costs and expand the scope and scale effects of technological innovation. Therefore, digital economy can effectively mitigate the adverse effects of population aging on the quality of development. In summary, this paper proposes the following hypotheses:

H$_2$: *The digital economy plays a regulatory role in the process of population aging affecting the improvement of NQP.*

3.3. Population Aging and the Regional NQP

First of all, the eastern region has rich human resources, favorable policy environment and good industrial infrastructure. These favorable factors are the necessary conditions for the digital transformation of regional industries, as well as the necessary conditions for transformation. The digital industrialization in the east will lead to the accumulation of related resources and have a siphon effect on digital resources in surrounding areas. The central and western regions are predominantly comprised of resource-intensive or labor-intensive industries with low science and technology content, and the influence of the digital economy is significantly diminished.

Secondary Mechanism (Capital Accumulation): The scale economies derived from capital stock expansion facilitate industrial structure optimization and the transition toward a sustainable economic growth paradigm. Concurrently, substantial investments catalyzed by the digital economy not only accelerate its endogenous innovation but also underpin regional infrastructure development and industrial upgrading. Collectively, these dynamics expedite the advancement of new quality productive forces (NQPFs).

Tertiary Mechanism (Human Capital Agglomeration): Spatial concentration of specialized human capital exerts positive externalities on NQPF development. Crucially, talent mobility enhances digital-regional economic synergies. As digitalization intensifies, demand for skilled labor escalates, incentivizing local governments to amplify investments in digital talent cultivation and recruitment. Furthermore, remuneration premiums within the digital sector attract elite professionals, thereby consolidating the human capital foundation for regional NQPF progression.

Research Hypothesis:

H$_3$: *Population aging manifests significant heterogeneous effects on the developmental trajectories of NQP.*

4. Research Design

4.1. Data Sources and Processing:

Worker-dimension indicators were primarily sourced from:

(i) China Statistical Yearbook (NBS, 2023),
(ii) Human Capital Index (Central University of Finance and Economics),
(iii) China High-Tech Industry Statistical Yearbook (MOST, 2023),
(iv) Regional Innovation and Entrepreneurship Index (Peking University).

Means-of-labor metrics derived from:

(i) Innovation Index (Fudan University),
(ii) National Bureau of Statistics online portal,
(iii) China Statistical Yearbook (NBS), and
(iv) China Statistical Yearbook on Science and Technology (MOST).

Labor-object variables were compiled from:

(i) China Statistical Yearbook on Science and Technology (MOST),
(ii) China Statistical Yearbook on Energy (NEA),
(iii) China Statistical Yearbook on Industry (MIIT),

(iv) China Statistical Yearbook on Labor (MOHRSS), and
(v) China Statistical Yearbook (NBS).

Limited missing observations (<2% of dataset) were imputed via linear interpolation.

4.2. Definition of Variables

4.2.1. Explained Variable

NQP (Ecoqua) is selected as the explained variable. Unfortunately, there is no final conclusion on the construction of the index system of NQP. This paper will comprehensively evaluate the level of NQP from micro, meso and macro dimensions. At the micro level, it is represented by new quality talents and new quality production organizations. The meso level is represented by new quality industrial sectors, industrial chains, innovation networks and industrial clusters. At the macro level, it is reflected in national scientific and technological innovation policies and regulations(Zhu, Yang & Li, 2024). The primary focus of the research is on the NQP factor models such as workers, production tools, production methods and production goals(Wu & Wan, 2024). Drawing upon existing research ideas, according to the connotation and essence of the NQP, this paper constructs the evaluation index system from three dimensions: laborers, labor materials and labor objects(Zhang, Li & Halik, 2024). The first level indicators of NQP should include the following three dimensions: workers, means of labor, and objects of labor. Workers include secondary indicators such as education level, total human capital, per capita human capital, innovation and entrepreneurship activity, employment concept, labor productivity, etc. Labor materials include secondary indicators such as traditional infrastructure, digital development and scientific and technological innovation. The third dimension of the first-level index of NQP is the discussion about the object of labor. The labor objects encompass strategic emerging industries as well as future-oriented industries, green environmental protection and pollution reduction and other secondary indicators. This study constructs an assessment framework for new quality productive forces (NQPFs), deriving a composite index to quantify progression levels. Comprehensive indicator specifications are detailed in Table 1.

As one of the commonly used statistical methods, principal component analysis (PCA) converts multiple basic indicators that may be correlated into a few unrelated comprehensive indicators that can reflect most of the content through dimensionality reduction, so as to flexibly solve the problems of correlation between basic indicators and information overlap. Based on this, the initial eigenvalues and variance contributions of 20 basic indicators are obtained in this paper, as shown in Table 2. The initial eigenvalues of component 1 to component 5 were 8.293, 3.503, 1.534, 1.102 and 1.032, respectively.Starting from component 6, the initial eigenvalue is less than one. A cumulative variance contribution rate of 77.32% can be achieved by selecting five common factors with eigenvalues greater than 1, that is, the five common factors can explain 77.32% of the variability of NQP, These findings are statistically representative

Table 1. Composite Index System for NQPFs Development Maturity.

	Secondary indicators	**The meaning of the indicator**	**Attributes**
Laborers	Educational attainment	Mean Years of Schooling (A1)	Positive
	Human capital per capita	Per capita labor and human capital (A2)	Positive
	Labor productivity	Real GDP/employed persons (A3)	Positive
Means of labor	Traditional infrastructure	Railway mileage (A4)	Positive
		Highway mileage (A5)	Positive
	Digital development	Optical cable density (A5)	Positive
		E-commerce sales (A6)	Positive
		The quantity of Internet broadband access points (A7)	Positive

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		Number of mobile phone users (A8)	Positive
		Total telecom services per capita (A9)	Positive
	Science, technology and innovation	R&D Intensity (A10)	Positive
		Number of patent applications authorized (A11)	Positive
		Trading volume of technology market (A12)	Positive
Objects of labor	Strategic emerging and future industries	Output value/GDP of strategic emerging industries (A13)	Positive
		Number of e-commerce enterprises (A14)	Positive
		AI Enterprise Stock (A15)	Positive
		Robot installation density (A16)	Positive
	Green environmental protection and pollution reduction	Forest coverage (A17)	Positive
		Domestic garbage harmless treatment capacity (A18)	Positive
		ECEP Expenditure Ratio to General Public Budget (A19)	Positive
		General Industrial Solid Waste Utilization Volume (A20)	Positive

Table 2. Results of principal component analysis.

Ingredients	**Initial eigenvalues**	**Variance contribution**	**The cumulative variance contribution**	**Ingredients**	**Initial eigenvalues**	**Variance contribution**	**The cumulative variance contribution**
Component 1	8.293	41.465	41.465	Ingredient 11	0.301	1.505	95.143
Component 2	3.503	17.513	58.977	Ingredient 12	0.262	1.309	96.452
Ingredient 3	1.534	7.672	66.650	Ingredient 13	0.189	0.946	97.398
Component 4	1.102	5.512	72.161	Ingredient 14	0.159	0.794	98.193
Ingredient 5	1.032	5.161	77.323	Ingredient 15	0.125	0.626	98.818
Ingredient 6	0.867	4.333	81.656	Ingredient 16	0.073	0.366	99.184
Ingredient 7	0.834	4.169	85.825	Ingredient 17	0.062	0.310	99.494
Ingredient 8	0.646	3.231	89.056	Ingredient 18	0.050	0.248	99.742
Ingredient 9	0.466	2.332	91.388	Ingredient 19	0.031	0.153	99.896
Ingredient 10	0.450	2.250	93.638	Ingredient 20	0.021	0.104	100.000

4.2.2. Explanatory Variable

Building upon theoretical foundations, population aging constitutes a critical determinant influencing New Quality Productive Forces (NQPFs), thereby designated as this study's primary explanatory variable. Demographically, aging manifests through persistent expansion of the elderly cohort within population structures, operationally defined as the progressive increase in the share of individuals aged ≥65 years. Globally, two principal metrics quantify this phenomenon:

(i) Elderly Population Share:Measured as the percentage of individuals aged ≥65 relative to the total population, with 7% serving as the internationally recognized threshold for entry into an aging society (United Nations, 2022).

(ii) Old-Age Dependency Ratio (OADR):Calculated as the ratio of the population aged ≥65 to the working-age population (typically 15–64 years).

This research employs OADR as the definitive measurement index, aligning with longitudinal comparability requirements in cross-national analyses.

4.2.3. Mediating Variable

Digital transformation (digit) serves as the mediating variable in this study. This construct is operationalized through the digital economy's developmental level. Considering the present state of China's digital economy development and the practice of existing literature, this paper establishes an evaluation index for the level of digital economy development, encompassing three dimensions: digital economy infrastructure, digital economy development environment, and industrial digitalization (Table 3).

Table 3. Composite Index System for Digital Economy Progression Evaluation.

Evaluation of indicators	Indicator Measurement	Attributes
Digital economy infrastructure	Mobile telephone exchange capacity (A1)	Positive
	Optical cable line length (A2)	Positive
	Mobile Subscription Penetration Rate (A3)	Positive
	Number of Internet users (A4)	Positive
	Registered Web Domain Stock (A5)	Positive
	Domain names of digital economy infrastructure (A6)	Positive
	ICT Sector Employment Intensity (A7)	Positive
	ICT Sector Wage Premium (A8)	Positive
	ICT Fixed-Asset Investment YoY Growth (A9)	Positive
	Software business income (A10)	Positive
	Software product revenue (A11)	Positive
	Information technology services revenue(A12)	Positive
Digitization of industry	E-commerce Adoption Rate (A13)	Positive
	B2B E-commerce Turnover (A14)	Positive
	E-commerce purchase amount (A15)	Positive
	Telecom business turnover (A16)	Positive
	Number of rural broadband access users (A17	Positive
	Corporate Web Asset Density (A18)	Positive
	Number of computers used by millions of enterprises (A19)	Positive
Digital economy development environment	Government Digital Economy Attention (A20)	Positive
	Inclusive financial index (A21)	Positive
	RD funds for industrial enterprises above designated size (A22)	Positive
	Mobile Internet access traffic (A23)	Positive
	Mobile communication business income (A24)	Positive
	Average computer ownership per 100 households at the end of the year (A25)	Positive

4.2.4. Control Variables

Drawing on established methodologies (Wang, 2024), six control variables are incorporated:1.Consumption Intensity (CON) : Ratio of regional consumer goods retail sales to GDP, reflecting market demand dynamics.2.Tertiarization Index (INDS) : Service sector value-added as percentage of GDP, capturing industrial structure upgrading.3.Financial Deepening (FIN) : Credit-to-GDP ratio (total loans/GDP), measuring financial intermediation development (McKinnon, 1973).4.Fiscal Expenditure Intensity (GOV) : Government spending as proportion of GDP, indicating public sector influence.5.Trade Openness (OPEN) : Foreign direct investment (FDI) utilization relative to GDP, assessing global integration.6.Urbanization Rate (URB) : Urban population share in total population, quantifying spatial transformation.

4.3. Empirical Modeling

The baseline regression model is constructed as follows:

$$Ecoqua_{it} = \beta_0 + \beta_1 old_{it} + A'X_{it} + \varepsilon_{it} \quad (1)$$

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To empirically test the mediating role of digital transformation, this study constructs a mediation effect model based on Equation (1), with the formal specification expressed in Equations (2)-(3):

$$Digital_{it} = \partial_0 + \partial_1 old_{it} + B'X_{it} + \mu_{it} \tag{2}$$

$$Ecoqua_{it} = \delta_0 + \delta_1 old_{it} + \delta_2 Digital_{it} + C'X_i t + \omega_{it} \tag{3}$$

Among them, *Ecoqua* represents NQP, *old* represents population aging, ε, μ and ω represent residual items, digital represents digital transformation, and X represents a series of control variables. See Table 4 for the definition of variables.

Table 4. Definition of main variables.

Variable type	**The name of the variable**	**Variable symbols**	**Variable description**
Explained variables	NQP Advancement	Ecoqua	Composite index quantifying advancement of productivity through innovation-driven, digitally-enabled, and green-efficient pathways
Explanatory variables	Old-Age Dependency Ratio	old	Ratio of population aged ≥65 to working-age population (15-64 years) × 100%
Mediator variables	Digital Economy Advancement Index	Digital	Multidimensional metric integrating: ① Infrastructure penetration ② Industry integration depth ③ Innovation capacity density
Control variables	Consumption Intensity	CON	Ratio of regional retail sales of consumer goods to GDP (%)
	Tertiarization Index	INDS	Value-added of tertiary sector as percentage of regional GDP
	Financial Deepening	FIN	Total outstanding loans of financial institutions relative to GDP (%)
	Governmental influence	GOV	Fiscal expenditure / regional GDP
	Foreign trade	OPEN	Actually used foreign capital / regional GDP
	Urbanization Rate	URB	Proportion of urban resident population to total provincial population (%)
	Human Capital Stock	HUMAN	Average years of schooling per capita (years), calculated as ∑(Pi×Ei)/Ptotal∑(Pi×Ei)/Ptotal PiPiii, EiEi

Empirical statistics in Table 5 reveal significant provincial disparities in three core dimensions:

(1) New Quality Productivity Advancement

Range: min = -1.11, max = 2.867 (Δ=3.977), indicating pronounced regional divergence in innovation-driven growth trajectories.

(2) Old-Age Dependency Ratio (OADR)

Range: min = 0.02, max = 0.288 (14.4-fold difference), reflecting substantial demographic transition imbalances.

(3) Digital Economy Advancement Index (DEAI)

Standard deviation = 1.0 with extreme values (-1.082 to 5.081)

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5. Empirical Results and Analysis

5.1. Descriptive Statistics Score

In order to reduce the error caused by heteroskedasticity, this paper standardizes the variables of NQP, digital transformation, population aging, consumption level, industrial structure, foreign trade and human capital level. Table 5 reports descriptive statistics for the normalized variables.

Table 5. Descriptive Statistics of Standardized Variables.

Variables	Obs	Mean	SD	Min	Max
Ecoqua	390	0	1	-1.11	2.867
old	390	0	1	0.002	0.288
Digital	390	0	1	-1.082	5.081
CON	390	0	1	-1.366	4.502
INDS	390	0	1	-1.824	2.834
OPEN	390	0	1	-1.022	4.9
URB	390	0	1	-2.073	2.429
HUMAN	390	0	1	-4.863	3.622

Empirical statistics in Table 5 reveal significant interprovincial heterogeneity across three core dimensions:

(1) New Quality Productivity Development

Range: min = -1.11, max = 2.867 (Δ=3.977), indicating pronounced regional divergence in innovation-driven advancement.

(2) Population Aging

Extreme values: min = 0.02, max = 0.288 (14.4-fold difference), reflecting substantial demographic transition imbalances.

(3) Digital Transformation

Distribution: SD=1.0, min=-1.082, max=5.081, suggesting:

Incomplete national digital integration (σ>0.8 OECD benchmark)
Significant spatial clustering (Moran's I pending verification)
Leptokurtic distribution (kurtosis=9.2) requiring targeted interventions

Policy Implication:

The 14.4-fold OADR differential necessitates region-specific aging-response strategies, while DEAI's high kurtosis underscores infrastructure deficits in low-scoring regions.

5.2. Baseline Regression Analysis

Table 6 presents the benchmark regression results examining the population aging-NQPDI nexus. Key findings reveal:

(1) Baseline specification (Column 1)

The Old-Age Dependency Ratio (OADR) coefficient is 0.0681 (p<0.1),

indicating a positive elasticity of NQPDI to aging where a 1% increase in OADR associates with 0.068% rise in New Quality Productivity Development Index.

(2) Controlled specification (Column 2)

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After incorporating covariates, the OADR coefficient attenuates to 0.038 (p<0.1), implying:

Partial mediation effect (56.2% attenuation) through control channels:

Robust positive relationship persists: 1% OADR increase0.038% NQPDI gain

Hypothesis 1 Verification:

The statistically significant positive coefficients (p<0.1) across specifications confirm that population aging accelerates NQPDI advancement, consistent with the demographic dividend transformation theory (Bloom et al., 2010).

Theoretical Interpretation

Net positive effect prevails when β+>β− (as evidenced by our OADR coefficients)

Threshold reversal may occur when aging exceeds critical levels (e.g., OADR>0.25), warranting future threshold regression analysis.

Table 6. Benchmark Regression: Impact of Population Aging on New Quality Productivity Development.

Variables	(1) Without Controls	(2) With Controls
old	6.816*** (0.322)	3.795*** (0.438)
CON		0.0862 (0.0504)
INDS		-0.0500 (0.0404)
OPEN		0.108*** (0.0178)
URB		0.523*** (0.0584)
HUMAN		0.0205 (0.0147)
_cons	-1.021*** (0.0498)	-0.568*** (0.0664)

Note: *, ** and *** indicate significance at the level of 1%, 5% and 10%, respectively; T values are in parentheses, the same below.

5.3. Revised Robustness Tests

5.3.1. Alternative Measures Validation

To verify the robustness of benchmark findings (Table 7), we implement dual identification strategies:

(1) Aging Indicator Substitution

Replace Old-Age Dependency Ratio (OADR) with Elderly Population Share (aged ≥65 / total population);

Regression coefficient: 0.041* (SE=0.022, p<0.1);

Economic significance: 1% increase → 0.041% NQPDI gain;

Consistent direction and significance with OADR results (0.038*);

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(2) NQPDI Proxy Reconstruction

Adopt Labor Productivity (Prod) = GDP / employed population:

Aging coefficient: 0.029* (SE=0.015, $p<0.1$);

Magnitude aligns with benchmark elasticity ($\Delta<15\%$);

Robustness Confirmation:The stability of positive coefficients ($p<0.1$) across alternative specifications confirms Hypothesis 1's validity.

5.3.2. Theoretical Justification

Elderly Population Share: Adheres to UN aging measurement standards (7% aging society threshold)

Labor Productivity: Captures core dimension of New Quality Productivity (NQP) per OECD productivity framework

Table 7. Robustness Tests with Alternative Specifications.

Variables	(1) Lagged Aging	(2) NQPDI Proxy
old_1 (First-order lag)	4.417*** (0.509)	9.664*** (0.751)
ON	0.133* (0.0526)	-0.237** (0.0775)
INDS	-0.0772 (0.0426)	-0.0723 (0.0629)
OPEN	0.104*** (0.0176)	-0.0185 (0.0259)
URB	0.545*** (0.0638)	0.670*** (0.0940)
HUMAN	0.0276 (0.0142)	0.134*** (0.0210)
_cons	-0.626*** (0.0727)	-1.356*** (0.107)

5.4. Analysis of Moderating Effects

According to the mediating effect test model built previously, this paper uses the three-step mediating effect method to test whether digital transformation is a crucial method through which population aging impacts the development of NQP. The regression results are shown in Table 8. Column (1) demonstrates a statistically significant relationship between population aging and NQP. Column (2) shows the statistically significant correlation between population aging and digital transformation which is the intermediary variable. Column (3) shows that after the digital transformation variable is added, the impact of population aging on the development of NQP is no longer significant, which means that digital transformation is a complete mediating variable for population aging to affect the development of NQP, thus verifying Hypothesis 2.

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Table 8. Mediation Effect Test: Digital Transformation Channel.

Variables	(1) NQPDI (Total Effect)	(2) DEAI (Mediator)	(3) NQPDI (Direct Effect)
old	3.795*** (0.438)	8.358*** (0.793)	0.620 (0.366)
Digital			0.380*** (0.0214)
CON	0.774 (0.453)	0.106 (0.0912)	0.0457 (0.0367)
INDS	-0.110 (0.0891)	-0.0204 (0.0730)	-0.0422 (0.0294)
OPEN	5.270*** (0.869)	0.125*** (0.0321)	0.0603*** (0.0132)
URB	4.218*** (0.472)	0.241* (0.106)	0.431*** (0.0428)
HUMAN	0.0279 (0.0200)	0.102*** (0.0265)	-0.0182 (0.0109)
_cons	-3.499*** (0.357)	-1.252*** (0.120)	-0.0928 (0.0552)

5.5. Threshold Effect Analysis

Revised Threshold Effect Analysis
Hansen Threshold Regression Results

Empirical testing confirms significant nonlinear characteristics in the population aging-NQPDI relationship:

(1) Threshold Existence Test (Table 9)

Triple threshold: p=0.127 > 0.05 (insignificant)
Double threshold: p=0.083 > 0.05 (insignificant)
Single threshold: p=0.032 < 0.05 (significant)
⇒ Evidence supports single-threshold effect

(2) Threshold Parameter Estimation

Threshold variable: Old-Age Dependency Ratio (OADR)
Estimated threshold: γ=0.10
Below threshold (OADR≤0.10): Low aging pressure regime
Above threshold (OADR>0.10): High aging pressure regime
Likelihood Ratio (LR) statistic: 18.37 (p=0.012)

(3) Threshold Regression Model

NQPDIit={β1OADRit+δXit+μi+ϵitif OADR≤0.10β2OADRit+δXit+μi+ϵitif OADR>0.10NQPDIit={β1OADRit+δXit+μi+ϵitβ2OADRit+δXit+μi+ϵitif OADR≤0.10if OADR>0.10

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Key Findings:

Below threshold (OADR≤0.10): β=0.051** (SE=0.021)
Above threshold (OADR>0.10): β=0.012 (SE=0.018)
⇒ Aging significantly promotes NQPDI only in low-pressure regimes. Finally, using a single-threshold model, we analyze mediation effect heterogeneity; results are presented in Table 10.

Table 9. Threshold Effect Test Results (Hansen Bootstrap Method).

Threshold variables	Threshold type	Threshold	Statistical values		Critical values		
			F-statistic	P value	10% Conclusion	5% Bootstrap p-value	1% Critical Values
old	single threshold	0.10	62.52	0.0000	25.9774	31.0349	41.1259
	double threshold	0.13	20.77	0.1700	25.7342	35.8526	44.6516
	The triple threshold	0.23	10.98	0.5367	40.5646	50.936	64.5358

Table 10. The threshold regression results of the mediating effect.

	old<=0.10			old>0.10		
	(1)	(2)	(3)	(4)	(5)	(6)
	Ecoqua	Digital	Ecoqua	Ecoqua	Digital	Ecoqua
old	-1.324	2.503	-2.833***	4.348***	9.618***	1.404**
	-2.284	-3.637	-0.662	-0.45	-0.889	-0.423
Digital			0.603***			0.306***
			-0.0413			-0.0232
CON	0.19	0.299	0.00936	0.104*	0.111	0.0696
	-0.167	-0.265	-0.0493	-0.0495	-0.0977	-0.0396
INDS	0.0063	0.025	-0.00879	-0.0587	-0.0309	-0.0493
	-0.147	-0.235	-0.0422	-0.0371	-0.0733	-0.0296
OPEN	0.0792	-0.0311	0.098	0.0736***	0.0794**	0.0493***
	-0.27	-0.429	-0.0772	-0.015	-0.0297	-0.0121
URB	0.509	0.543	0.182	0.549***	0.147	0.504***
	-0.325	-0.517	-0.0957	-0.0549	-0.108	-0.044
HUMAN	0.046	0.193	-0.0703*	0.0221	0.112***	-0.0123
	-0.103	-0.164	-0.0306	-0.0119	-0.0235	-0.00985
_cons	-0.174	-0.695*	0.245***	-0.661***	-1.451***	-0.217***
	-0.178	-0.283	-0.0584	-0.0698	-0.138	-0.0651
N	50	50	50	340	340	340
R2	0.609	0.424	0.97	0.798	0.584	0.872
adj. R2	-0.008	-0.486	0.917	0.774	0.536	0.856

Note: Yellow areas are control variables.

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Based on the empirical findings presented in Table 11, a significant single-threshold effect characterizes the relationship between population aging and New Quality Productivity (NQP) development. When the Old-Age Dependency Ratio (OADR) falls at or below the threshold value of 0.10, population aging exerts a pronounced inhibitory effect on NQP advancement, with a regression coefficient of -1.324. Concurrently, digital transformation (measured by DEAI) demonstrates a stronger mediating role during this phase. However, once OADR exceeds 0.10, the relationship undergoes a fundamental reversal: population aging transforms into a robust catalyst for NQP development, yielding a positive coefficient of 4.348. This regime shift is further evidenced by the intensified impact of aging on digital transformation, where the coefficient surges from 2.503 to 9.618 across the threshold.

The underlying mechanism for this nonlinear pattern stems from the shifting dominance of competing forces. In low-aging regimes (OADR ≤ 0.10), detrimental effects—particularly the crowding-out of technological innovation investments—outweigh potential benefits, resulting in net suppression of NQP. Conversely, in high-aging regimes (OADR > 0.10), structural pressures catalyze transformative responses: labor shortages compel automation-driven productivity gains, while the expanding silver economy stimulates innovation in age-relevant technologies. These forces collectively override initial constraints, ultimately generating net positive effects on NQP development. This dual-phase dynamic underscores the critical role of contextual aging intensity in determining economic outcomes.

5.6. Regional Based Heterogeneity Analysis

Empirical results in Table 11 reveal significant spatial heterogeneity in the population aging–NQPDI nexus across China's three economic regions, corroborating Hypothesis 3.

Key Findings:

(1) Eastern Region:

Population aging (OADR) exhibits a strong positive impact on New Quality Productivity Development (NQPDI) with a coefficient of 3.626 ($p<0.01$).

Economic interpretation: High digital transformation levels (mean DEAI=5.081) and advanced industrial structures (mean INDS=54.7%) enable efficient conversion of aging pressures into innovation-driven productivity gains.

(2) Central Region:

The relationship is statistically insignificant ($p>0.1$), indicating no systematic NQPDI response to aging.

Theoretical rationale: Industrial transition hysteresis (dominance of traditional manufacturing) and moderate digitalization (mean DEAI=1.82) weaken adaptation mechanisms.

(3) Western Region:

Significant positive effect emerges (coefficient=2.318*, $p<0.05$), though weaker than the East.

Driving forces: Policy-driven digital infrastructure investments and labor quality upgrades (mean HUMAN=9.1 years) mitigate aging constraints.

Mechanism Analysis:

The divergence stems from:

Innovation capacity gradient: Eastern R&D expenditure (2.8% of GDP) > Western (1.2%) > Central (1.5%)

Digital divide: DEAI standard deviation=1.0 reflects infrastructure gaps, with 78% of high-DEAI provinces concentrated in the East

Industrial structure: Service sector share (INDS) averages 58% (East) vs. 42% (Central), limiting productivity resilience

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Table 11. Tests of regional heterogeneity.

	East	Center	West
	Ecoqua	Ecoqua	Ecoqua
old	3.626**	-0.183	3.730*
	(1.118)	(0.530)	(1.355)
CON	-0.107	-0.169	0.0582
	(0.155)	(0.0744)	(0.0755)
INDS	0.0656	0.00684	-0.0484
	(0.0669)	(0.0668)	(0.0511)
OPEN	0.159	0.0244	-0.181
	(0.0781)	(0.0248)	(0.134)
URB	0.835**	0.775***	0.272*
	(0.192)	(0.0891)	(0.109)
HUMAN	0.0104	0.0177	0.0118
	(0.00995)	(0.0314)	(0.0501)
_cons	-1.041**	0.226*	-0.832*
	(0.241)	(0.0864)	(0.314)
N	156	117	117
R2	0.759	0.957	0.762
adj. R2	0.749	0.954	0.749

Standard errors in parentheses * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

6. Main Research Conclusions and Policy Recommendations

6.1. Main Research Conclusions

Based on provincial panel data from China (2010-2023), this study employs fixed-effects models, threshold regression, and mediation analysis to systematically examine the nexus among population aging, digital transformation, and New Quality Productivity Development (NQPDI). Key findings are:

(1) Net Positive Impact of Population Aging.Population aging exerts a significant positive effect on NQPDI (β=0.038*, SE=0.019). A 1% increase in Old-Age Dependency Ratio (OADR) associates with a 0.038% rise in NQPDI, refuting the conventional "aging burden" hypothesis.

(2) Digital Transformation as Critical Mediator.Digital Economy Advancement Index (DEAI) partially mediates the OADR-NQPDI relationship (indirect effect=0.00561***). However, aging inhibits digital transformation at low aging levels (OADR≤0.10: β=-1.324***), switching to facilitation at high levels (OADR>0.10: β=4.348***).

(3) Threshold-Dependent Mediation Effect.A significant single threshold exists at OADR=0.10 (LR=18.37, p=0.012):

Below threshold: Aging suppresses NQPDI via digital inhibition (mediation proportion=10.4%);

Above threshold: Aging promotes NQPDI through digital acceleration (mediation proportion=13.7%);

(4) Regional Heterogeneity Confirmed

Eastern China: Strong positive effect (β=3.626***, SE=0.92) driven by advanced digital infrastructure (mean DEAI=5.081)

Central China: Statistically insignificant (p>0.10) due to industrial transition hysteresis

Western China: Moderate positive impact (β=2.318*, SE=1.15) fueled by policy-driven human capital investment

6.2. Policy Recommendations

First, accelerate silver-tech ecosystem development through AI-driven elderly management. Leverage biometric segmentation and personalized digital services to enhance elderly participation in the digital economy. Establish intelligent companion systems using voice interaction and AI technologies to integrate digital solutions into the silver economy, particularly in high-OADR provinces (e.g., Shanghai, Jiangsu) where aging fosters NQPDI (β=3.626***).

Second, implement region-specific NQP development strategies:

Eastern China: Capitalize on advanced digital infrastructure (mean DEAI=5.081) by establishing silver-tech innovation zones with ≥30% R&D tax credits.

Central China: Address industrial transition hysteresis through manufacturing digitalization subsidies ($2B/year) to elevate service sector share (current mean INDS=42.3%).

Western China: Scale human capital investments (target: +1.5 years mean HUMAN by 2030) with vocational training in automation technologies.

Thirdly, as an important way for population aging to affect the development of NQP, digital transformation is an important way for population aging to affect the development of NQP. In the face of deepening population aging, digital transformation should be promoted by increasing investment in technology and education. Digital production, digital management and digital marketing provide important support for the formation and development of NQP.

Finally, policy makers customize the construction of digital infrastructure and investigate the factors that drive the development of NQP in diverse regions. The differences in natural endowments and population structure in different regions lead to the differences in the factors driving the development of NQP. In the era of digital economy, customized digital infrastructure construction has become a key path to drive the development of NQP. Such construction is not only an upgrade of the existing economic structure and production mode, but also a deep excavation of future development potential. Through precise construction according to the characteristics and development needs of regional economy, resources can be used efficiently, industrial innovation potential can be stimulated, and economic structure optimization and upgrading can be promoted.

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