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Research Article

A Study on the Multiple Mechanisms of Population Aging Affecting Regional Economic Growth: Empirical Evidence from Chinese Provinces

Danfeng Sun1,Yuyao Wang[1],Xuanyu Hu[2*],Jingdan Ran[3],Yao Wang[4]
Southwest University, Chongqing, China.
Corresponding author. E-mail: hxy291002965@proton.me

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ABSTRACT

The demographic shifts triggered by population aging profoundly influence the regional economic development patterns worldwide. Investigating the mechanisms through which aging affects regional economic growth helps clarify the economic development trajectory under new trends. Based on provincial panel data from China spanning 2010 to 2020, this study employs a bidirectional fixed-effects threshold model and a Spatial Durbin Model (SDM) to explore the impact and mechanisms of population aging on economic growth. The analysis reveals that population aging suppresses regional economic development. However, its effect on economic growth is non-linear: before the elderly dependency ratio reaches the threshold of 18%, aging has a positive impact on economic growth, but beyond this threshold, its effect becomes significantly negative. The primary channels through which aging hinders economic growth are the reduction in labor supply and the increased burden on social security systems. Nevertheless, technological advancement and infrastructure development can partially mitigate these negative impacts. Furthermore, the impact of aging on regional economic development varies across regions, depending on spatial factors and local development conditions. Aging not only affects economic growth within a region but also exerts negative spillover effects on neighboring regions through spatial interactions.

Based on these findings, this study suggests that the government should optimize population structure, actively foster the "silver economy," strengthen human capital development, and enhance regional coordination to mitigate the spatial spillover risks of aging.

Keywords: Population Aging; Economic Growth; Threshold Effect; Spatial Durbin Model; Spatial Spillover Effect.

INTRODUCTION

Population aging profoundly influences the economic growth patterns and social structures of countries worldwide. Addressing the economic structural shocks induced by aging has become one of the most pressing issues in global economic and social development. Generally, a country is considered to be experiencing mild aging When individuals aged 65 and above account for over 7% of the total population, a society is considered aging, and when this figure reaches 14%, it is classified as moderately aged. As the world's second most populous nation, China has experienced notable demographic shifts in recent years

According to the results of the Seventh National Population Census, while China's total population grew by only 5.38% over the past decade, the number of people aged 65 and above increased by 60.3%, reaching 190.64 million, accounting for 13.5% of the total population. By the end of 2022, the elderly population had risen to 209.78 million, making up 14.9% of the total, officially marking China’s transition into a moderately aged society. This rapid aging trend has led to profound transformations in the labor supply structure and social security system. The rising elderly population and increasing elderly dependency ratio have resulted in a relative decline in the working-age population. A growing number of retirees have placed additional pressure on pension funds, while the impact of aging on household savings and investment behavior has further reshaped economic growth patterns and the functioning of capital markets.

The challenge of "aging before affluence" raises a critical question: how can China sustain long-term economic growth amid rapid demographic shifts? This issue demands urgent academic investigation and policy responses.

A report by United Nations, Haver Analytics, and DB Global Markets Research provides a graphical projection of China’s worker-to-retiree ratio from 2000 to 2050, illustrating the impact of an aging population. As shown in the figure, the ratio has been steadily declining, from 10 in 2000 to a projected 2 by 2040, meaning only two workers will support each retiree. This demographic shift will strain economic growth, increase fiscal pressure on social security, and challenge labor market stability. Therefore, understanding how aging affects economic sustainability and formulating adaptive policy measures are critical for addressing these challenges.

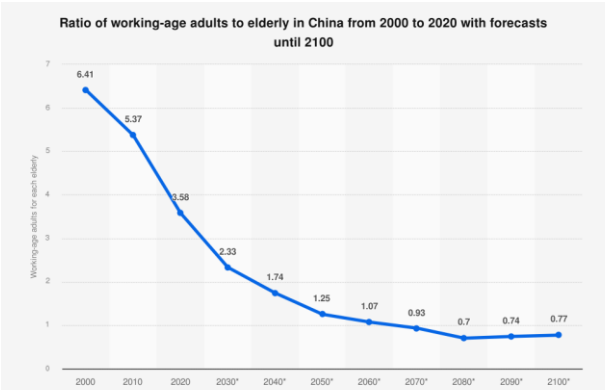


Figure 1. China's Worker-to-Retiree Ratio Projection (2000–2050)

2. LITERATURE REVIEW AND RESEARCH HYPOTHESES

In recent years, academia has conducted extensive research on the question of "how population aging affects economic growth," focusing primarily on two aspects: the specific impacts and the theoretical mechanisms. However, existing studies have yielded diverse and sometimes conflicting conclusions.

2.1 The Specific Impact of Population Aging on the Economy

Currently, academia presents distinctly different conclusions regarding this issue. On one hand, the majority of scholars argue that population aging negatively affects economic growth. At the macroeconomic level, Hu Qian et al. (2020), utilizing panel data from 172 countries between 1960 and 2019, empirically concluded that aging significantly reduces economic growth rates[1]. Similarly, Maity et al. (2020) conducted an empirical analysis of India's economy and demonstrated a significant negative correlation between aging and economic growth, suggesting serious detrimental effects of aging on India's economic development[2]. At the microeconomic level, Liu Yue et al. (2023) employed China's provincial panel data from 2000 to 2019 to show empirically that aging significantly inhibits economic growth[3].

On the other hand, some researchers contend that population aging may promote regional or overall economic growth. At the macroeconomic level, Chen et al. (2022) applied the entropy-weighted method to comprehensively measure aging and developed a mediation model using entropy as the key explanatory variable, finding a significant positive impact of population aging on economic growth[5]. Additionally, Bawazir et al. (2020) analyzed Middle Eastern countries and found through empirical study that the elderly dependency ratio positively influences economic growth[6]. At the microeconomic level, Zhao et al. (2018), employing a dynamic panel system GMM estimation, concluded that population aging contributes to economic growth from the perspective of total marginal effects, provided the level of financial deepening is below a certain threshold[7].

Furthermore, some scholars suggest that the relationship between population aging and economic growth may exhibit nonlinear characteristics, varying in direction and magnitude depending on the stage of development and economic structure. For example, Lee et al. (2019) indicated that at lower aging levels, aging might not significantly affect economic growth, but it tends to establish a negative relationship once the proportion of elderly population reaches a sufficiently high threshold[8].

Synthesizing prior studies, this study puts forward the following research hypotheses:

Hypothesis 1: Overall, the negative impact of population aging on economic growth is more significant.

Hypothesis 2: The impact of population aging on economic growth exhibits nonlinear characteristics.

2.2 Mechanism Analysis

Currently, scholars have extensively explored the mechanisms by which population aging influences economic growth. Existing studies primarily focus on the following dimensions:

1. Labor Factor Mechanism

Population aging first influences labor supply, a core factor in economic growth. An increasing elderly population share reduces the proportion of working-age individuals, thus lowering total labor supply and weakening economic growth potential. Chen (2014) found that a decline in labor participation rates significantly reduces urban residents' income in the long term[9]. Furthermore, population aging may decrease labor productivity: on the one hand, individual cognitive ability and physical conditions deteriorate with age, affecting labor efficiency and thereby reducing technical efficiency. On the other hand, the retirement of experienced older workers and their replacement by relatively inexperienced younger workers may reduce overall production efficiency, leading to decreased scale efficiency[10].

However, some scholars argue that the reduced labor supply due to aging could be partially offset by technological progress and enhanced human capital. For example, Li and Gao (2020) argue that population aging can positively affect labor productivity through technological advancements[11].

2. Capital Factor Mechanism

Population aging significantly impacts capital accumulation by affecting saving rates and investment patterns. According to the life-cycle theory, younger populations tend to save more, whereas older populations tend to consume savings. Consequently, as aging intensifies, the overall social saving rate tends to decline[12]. Horioka et al. (2012) discovered that countries experiencing rapid aging witness significantly declining private savings rates, leading to insufficient investment capital supply, thereby negatively impacting capital formation and economic growth [13].

Moreover, aging might alter capital market structures, influencing the efficiency of capital allocation. Wang et al. (2024) indicate that intensified population aging forces firms to frequently adjust capital structures in response to rising labor costs and dynamic market demands, potentially increasing capital market volatility and adversely affecting long-term economic stability [14].

3. Industrial Structure Mechanism

Population aging influences economic growth by altering the consumption demand structure and reallocating production factors, driving changes in industrial structures. With intensifying aging, industries related to medical care, elderly care, and health technologies experience increased demand, while traditional labor-intensive sectors, such as manufacturing and construction, may face suppression. Fang (2021) empirically demonstrates that population aging significantly promotes the servitization of industrial structures [15].

Simultaneously,agin gcould accelerate automation and intelligent transformation in the manufacturing sector. Wang and Wang (2020) discovered that aging pressures enterprises to adopt artificial intelligence solutions as substitutes for labor, thereby driving industrial upgrading [16].

Drawing from these insights and existing literature, this study puts forward the following hypotheses:

Hypothesis 3:Population aging affects regional economic development by influencing labor factors.

Hypothesis 4:Population aging affects regional economic development by influencing capital factors.

Hypothesis 5:Population aging affects regional economic development by influencing industrial structure.

3.VARIABLE DEFINITION AND MEASUREMENT

3.1 Data Sources

This study selects provincial-level data from 2010 to 2020, covering a total of 31 provincial-level cities. The data are sourced from the China Urban Statistical Yearbook for the corresponding years. After data cleaning of key variables, a balanced panel dataset for 31 Chinese provinces from 2000 to 2020 is obtained. The effective sample size available for the baseline regression analysis is 341.

3.2 Variable Definition and Measurement

1. Dependent Variable—Urban Economic Development

Following Yang et al. (2023)[17], this study measures urban economic development using regional Gross Domestic Product (regional GDP). To ensure consistency and reduce heteroscedasticity in data analysis, the regional GDP is transformed by taking its natural logarithm.

2. Core Independent Variable—Population Aging

Given that in rural China, certain individuals over the age of 65 may remain in employment, whereas some working-age individuals are unemployed, combined with China's unique characteristic of "growing old before getting rich," a more precise definition of elderly population should reflect those genuinely incapable of labor participation. Therefore, following Zhao et al. (2023)[18], this paper adopts the elderly dependency ratio as the proxy for population aging at the regional level.

3. Control Variables

Based on existing literature (Yu et al., 2022; Zhou, 2023; Han et al., 2025) [19][20][21], this study selects the following control variables to mitigate potential omitted-variable bias:Regional Technological Level, measured by the natural logarithm of the number of high-tech enterprises.Local Fiscal Capacity, measured by the natural logarithm of local fiscal revenue.Infrastructure Development, measured by the natural logarithm of total regional highway mileage.Social Security Level, measured by the number of participants in the regional basic pension insurance system.Consumption Capacity, measured by the natural logarithm of urban residents' per capita household income.Labor Force Level, measured by the natural logarithm of the total number of employed urban residents.

Table 1. Descriptive Statistics of Variables

Variable Name	Variable Symbol	Observations	Mean	Std. Dev.	Min	Max
Regional Gross Domestic Product	$\ln GDP$	341	9.651	1.013	6.229	11.619
Elderly Dependency Ratio	adr	341	14.111	3.809	6.710	25.480
Number of High-Tech Enterprises	$\ln hti$	341	5.952	1.541	1.609	9.275
Local Fiscal Revenue	$\ln lfr$	341	16.697	0.962	12.959	18.677
Total Highway Mileage	$\ln road$	341	11.631	0.840	9.390	12.884
Number of Participants in Basic Pension Insurance	$\ln pen$	341	7.538	0.936	4.504	8.979
Urban Household Per Capita Income	$\ln inc$	341	10.254	0.180	9.898	10.495
Number of Urban Employed Persons	$\ln emp$	341	7.181	0.122	6.901	7.319

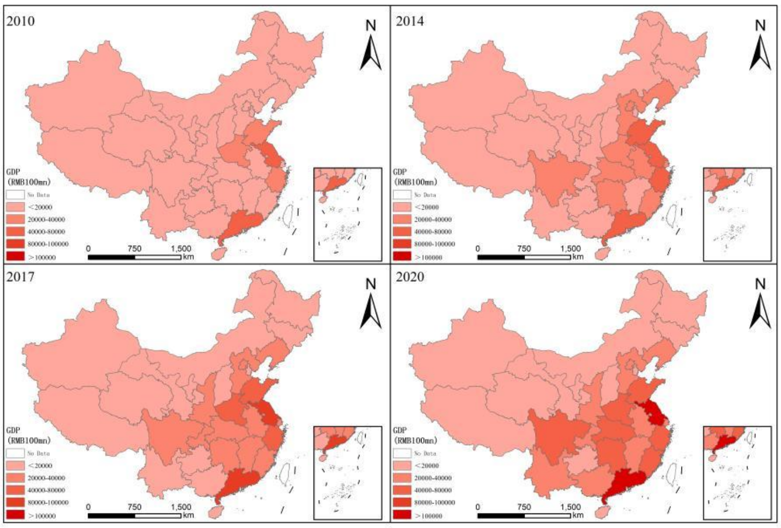
3.3 Overall Situation

To examine how aging levels correlate with economic development in various regions of China, this study applies ArcGIS software to map the elderly dependency ratio and GDP of each province for the years 2010, 2014, 2017, and 2020.This visualization aims to reveal the spatial-temporal evolution characteristics and examine the intrinsic relationship between these two variables.

First, regarding the spatial-temporal changes in the elderly dependency ratio, the degree of aging in Chinese provinces has shown a continuous upward trend, with significant regional disparities. In 2010, most regions in China exhibited a relatively low elderly dependency ratio (5%-15%), with only a few provinces, such as Sichuan, reaching higher levels (15%-20%). By 2020, the elderly dependency ratio had exceeded 20% in multiple regions, particularly in the eastern coastal areas (e.g., Jiangsu, Shanghai), central and western regions (e.g., Sichuan, Chongqing), and the northeastern provinces, indicating an intensification of population aging and an increasing burden on the working population. Additionally, the northeastern and certain western provinces have experienced a faster rise in aging levels, likely influenced by population outflows.

Second, in terms of the spatial-temporal evolution of GDP, China’s economic growth pattern has generally followed the trend of eastern coastal leadership, central region rise, and western region slow development. In 2010, GDP was primarily concentrated in coastal provinces such as Guangdong, Jiangsu, Zhejiang, and Shandong, with some central provinces (e.g., Henan, Hubei) also experiencing economic growth. By 2020, Guangdong's GDP surpassed 10 trillion yuan, with Jiangsu and Zhejiang demonstrating significant growth, whereas most central and western provinces, despite economic expansion, still lagged behind the coastal regions. Furthermore, economic growth in the northeastern region remained relatively slow, aligning with challenges such as population outflows and industrial restructuring.

Overall, there appears to be a certain correlation between the rising elderly dependency ratio and economic development levels in China, though this relationship is nonlinear and requires further empirical examination. The eastern coastal areas, despite being economically developed, exhibit more severe aging issues; the central region is experiencing rapid economic growth with a relatively stable demographic structure, while the western and northeastern regions face the dual challenge of economic stagnation and accelerating aging. This suggests that economic growth does not necessarily alleviate aging pressures; on the contrary, in certain developed areas, factors such as high living costs, declining fertility rates, and demographic shifts make aging issues even more pronounced.



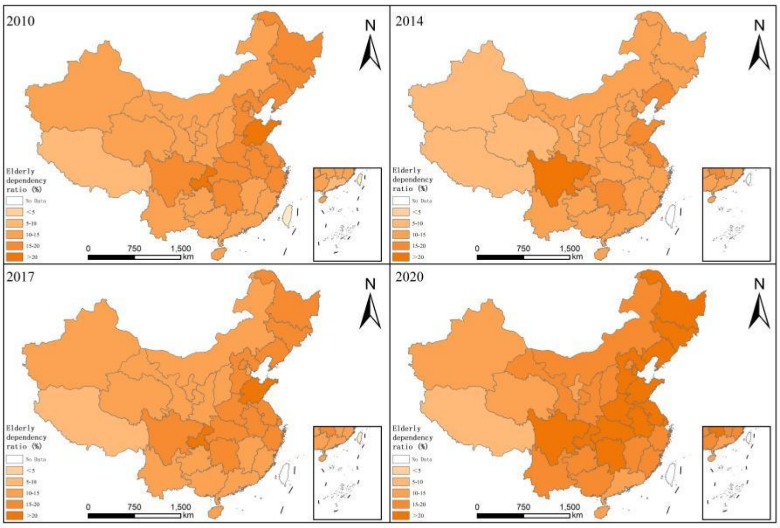


Figure 2. Overall Distribution of GDP and Elderly Dependency Ratio

4.EMPIRICAL ANALYSIS

4.1 Correlation Analysis

Considering the exploratory nature of this research, a correlation analysis is first conducted to preliminarily examine linear relationships among variables and validate theoretical expectations. Additionally, this analysis serves to identify potential risks of multicollinearity among independent variables. The detailed results are presented in Table 2.

Table 2. Correlation Analysis

	adr	ln_gdp	ln_hti	ln_lfr	ln_road	ln_pen	ln_inc	ln_emp
adr	1.000	-0.358	0.515	0.527	0.274	0.568	0.538	0.499
ln_gdp	-0.358	1.000	0.922	0.952	0.340	0.930	0.267	0.267
ln_hti	0.515	0.922	1.000	0.884	0.191	0.827	0.092	0.085
ln_lfr	0.527	0.952	0.884	1.000	0.164	0.848	0.269	0.280
ln_road	0.274	0.340	0.191	0.164	1.000	0.557	0.095	0.093
ln_pen	0.568	0.930	0.827	0.848	0.557	1.000	0.266	0.280
ln_inc	0.538	0.267	0.092	0.269	0.095	0.266	1.000	0.946
ln_emp	0.499	0.267	0.085	0.280	0.093	0.280	0.946	1.000

As presented in Table 2, the correlation coefficient between the elderly dependency ratio and regional GDP is -0.358, indicating an initial negative relationship between these two variables. Additionally, the regional GDP exhibits relatively strong correlations with most of the control variables, preliminarily suggesting that the selected control variables may significantly influence the dependent variable. Meanwhile, the correlation coefficients among the control variables themselves are mostly low, implying a low risk of multicollinearity in subsequent empirical analyses. However, further verification is necessary.

4.2 **Multicollinearity Identification**

To enhance the robustness and accuracy of the regression model, this study conducted a multicollinearity diagnostic test on the explanatory variables. The variance inflation factor (VIF) was computed using the baseline regression model (Ordinary Least Squares, OLS) to assess linear correlations among variables (see Table 3). Given the necessity to directly reflect the original correlations among all explanatory variables and reduce potential interference from unobserved heterogeneity associated with fixed-effects models, the baseline regression was selected for this diagnostic process, enabling a more accurate identification of multicollinearity risks.

The results show that the VIF for the number of participants in basic pension insurance (ln_pen) is 6.55; the VIF for urban residents' per capita household income (ln_inc) is 5.42; for the number of urban employees (ln_emp), it is 4.25; for local fiscal revenue (ln_lfr), 8.39; for the number of high-tech industry enterprises (ln_hti), 7.33; for road mileage (ln_road), 3.19; and for the elderly dependency ratio (adr), 2.13. All variables have VIF values significantly below the common threshold of 10, with an average VIF of 5.322. This indicates the absence of serious multicollinearity within the model, confirming that the estimated regression coefficients are stable and reliable, and thus suitable for subsequent fixed-effects panel regression analysis.

Table 3. Multicollinearity Diagnostics

Variables	VIF	1/VIF
ln_pen	6.550	0.153
ln_inc	5.420	0.185
ln_emp	4.250	0.235
ln_lfr	8.390	0.119
ln_hti	7.330	0.136
ln_road	3.190	0.313
adr	2.130	0.469
Mean VIF	5.322	

4.3 Baseline Regression

To examine whether population aging significantly influences economic development, this study first applies Ordinary Least Squares (OLS) regression and Fixed-Effects (FE) models to examine how population aging influences China's economic growth. Province-level and time fixed effects are incorporated into the FE model to control for regional and temporal heterogeneity. The model specification is as follows:

where i denotes the province, t denotes the year, and X_{it} represents control variables. Furthermore, α_0 is the intercept term, β_1 and γ_j are corresponding regression coefficients, ε_i denotes the province-specific fixed effects, λ_t denotes the time-specific fixed effects, and ω_{it} represents the random error term.

The baseline OLS regression results show that the coefficient for the elderly dependency ratio (adr) is positive but statistically insignificant, contradicting the theoretical expectation that aging inhibits economic growth. This discrepancy might arise from the inability of OLS regression to control for unobserved heterogeneity across provinces and years. For example, eastern provinces typically exhibit higher levels of aging but also possess stronger economic foundations, potentially masking the negative impact of aging. In contrast, the Fixed-Effects (FE) model, by controlling for inherent provincial differences and temporal trends, reveals a significantly negative coefficient for adr, indicating that population aging substantially suppresses economic growth by reducing labor supply and increasing social security burdens. Moreover, the FE model demonstrates superior explanatory power, as indicated by its higher R^2 value compared to the OLS regression. Thus, Hypothesis 1 is supported by empirical evidence.

Table 4. Regression Analysis

Variables	(1) OLS Regression	(2) Fixed Effects
adr	0.0010	-0.0138***
	(0.2908)	(-3.7379)
ln *hti*	0.1851***	0.1776***
	(11.6499)	(7.3726)
ln*lfr*	0.4814***	0.0885***
	(17.6870)	(3.8249)
ln*road*	0.0704***	0.1012***
	(3.6619)	(2.7700)
ln*pen*	0.2871***	-0.0545
	(8.3896)	(-1.5546)
ln*inc*	0.4655***	0.5152***
	(2.8926)	(5.9183)
ln*emp*	-0.3764	1.1316***
	(-1.5917)	(8.3919)
Province Fixed Effects	NO	YES
Year Fixed Effects	NO	YES
Intercept	-4.5551***	7.0952***
	(-6.1045)	(11.8856)
Observations	341	341
R^2	0.973	0.996

t-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

4.4 Robustness Test

To verify the robustness of the empirical findings, this study conducts three conventional robustness checks within the fixed effects model framework: alternative variable definitions, sample adjustments, and omitted-variable assessments, to further evaluate the impact of population aging on economic development.

1. Exclusion of provinces with extreme characteristics.

Considering that certain provinces may display extreme heterogeneity in terms of population aging or economic performance—such as Beijing and Shanghai with significantly lower elderly dependency ratios but strong economies, or Guizhou and other provinces with relatively higher elderly ratios and weaker economic bases—such outliers might mask the true effects of the elderly dependency ratio (adr). To address this concern, provinces whose adr values lie beyond two standard deviations from the mean (adr > 25% or adr < 12%) are excluded. After removing these outliers, the fixed effects model is re-estimated. The findings show that the negative association between ADR and economic growth persists, supporting the robustness of the original results.

2. Exclusion of special years.

To further validate robustness, the year 2020 is excluded due to potential disturbances associated with the COVID-19 pandemic, including significant economic fluctuations and policy adjustments that could impact regional economic performance and elderly dependency ratios. Re-estimating the fixed effects model without the 2020 data, results again confirm the significant negative effect of population aging on regional economic growth, thus ensuring the reliability and stability of the research findings.

3. Alternative Measurement of the Core Explanatory Variable.

To conduct a more in-depth robustness check on the effects of population aging on economic growth, we replaced the core explanatory variable (adr, elderly dependency ratio) with an alternative measure—the proportion of the elderly population (the ratio of the population aged 65 and above). Results, as shown in column (3), indicate that the coefficient for this alternative measure is significantly negative (-2.5102, p < 0.01), highly consistent with the original estimation using adr. This consistency demonstrates that changing the measurement method of the core variable does not affect the core conclusions, thereby further confirming the robustness of the findings that population aging significantly suppresses regional economic growth.

Table 5. Robustness Checks

Variables	(1)	(2)	(3)
Core Explanatory Variable	-0.0066***	-0.0106***	-2.5102***
	(-1.3248)	(-2.6047)	(-4.2551)
Control Variables	YES	YES	YES
Intercept Term	6.5823***	7.0344***	7.2527***
	(4.0487)	(11.5497)	(12.1375)
Two-Way Fixed Effects	YES	YES	YES
Observations	223	310	341
R^2	0.991	0.996	0.996

t-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

4.Assessing the Impact of Omitted Variables

In the baseline regression, province-specific and time-fixed effects were considered to minimize estimation bias caused by omitted variables. However, it is still not possible to completely rule out the influence of other omitted variables on the baseline results. Therefore, following the approach of Wang Wei et al. (2019)[22], the following index is constructed:

The calculation results are shown in the table below:

Table 6. Ratio Test Results

Limited Set of Control Variables	Full Set of Control Variables	Values of $Ratio_{r,f}$
Controlling Only for Province and Time Fixed Effects	Partial Control Variables	524.65725
Controlling Only for Province and Time Fixed Effects	All Control Variables	28.755568

According to the results presented in the table, the two $Ratio_{r,f}$ values range from 28.755 to 524.657, with an average value of 276.706. These findings indicate that for omitted variables to significantly affect the baseline estimation results, their explanatory power would need to be at least 28.755 times that of all included control variables, with an average requirement exceeding 276.706 times. Given that the baseline regression has already accounted for as many micro-level factors influencing regional economic development as possible, the potential impact of omitted variables on the estimation results is minimal. Thus, the baseline estimation remains robust and credible.

In conclusion, the empirical analysis reaffirms the robustness of the estimated effects of population aging on economic development, indicating that aging, to a certain extent, constrains regional economic growth.

4.5 Threshold Effect Test

Considering the potential nonlinear relationship between population aging and regional economic development, this study sets the elderly dependency ratio (adr) as the threshold variable and constructs a threshold effect model using regional GDP as the dependent variable. The model is specified as follows:

where $I()$ is the indicator function, and θ represents the threshold value.

This study employs a threshold regression model to examine whether adr exhibits a threshold effect and evaluates its significance using the F-test. As shown in Table 7, the estimated single-threshold value for adr is 18% (F = 5.31, p = 0.0294), leading to the rejection of the null hypothesis of no threshold effect. This finding suggests that the impact of aging on regional economic growth differs significantly above and below this threshold.

The detailed regression results are presented in Table 8. When adr ≤ 18%, the coefficient of adr is 0.0029 ($p < 0.01$), indicating a significant positive effect of aging on economic growth. This result suggests that at lower levels of aging, the economy may benefit from the “silver economy”, where increased elderly consumption boosts regional economic activity. However, when adr > 18%, the coefficient of adr turns significantly negative (-0.0071, $p < 0.05$), suggesting that at higher aging levels, the economic burden increases due to declining labor supply and rising social security costs, thereby hindering economic growth.

These findings confirm Hypothesis 2, demonstrating the presence of a nonlinear threshold effect in the relationship between aging and regional economic development.

Table 7. Threshold Effect Test Results

Dependent Variable	Threshold Type	F Statistic	Threshold Variable	θ Threshold Value
$\ln GDP$	Single	5.31**	adr	18

Table 8. Threshold Regression Results

Variables	$\ln GDP$
$adr(adr \leq \theta)$	0.0029***
	(0.0659)
$adr(adr > \theta)$	-0.0071**
	(-2.3051)
Control Variables	YES
Intercept Term	-14.9125***
	(-14.1166)
Two-Way Fixed Effects	YES
Observations	341
R^2	0.995

t-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

4.6 Mechanism Test

To examine the mechanisms through which population aging influences economic growth, this study utilizes a fixed-effects model to analyze factors such as labor supply, social security burden, technological progress, and infrastructure support, with empirical results presented in Table 9.

1. Labor Supply Channel

Theoretically, aging affects economic growth negatively by reducing labor supply. To empirically verify this mechanism, an interaction term between elderly dependency ratio (adr) and employment (ln_emp) is introduced into the fixed-effects model. Results (column 1 in Table 9) indicate that when adr ≤ 18%, the coefficient of the interaction term (adr × ln_emp) is significantly positive (0.0029, $p < 0.01$), suggesting that a lower elderly dependency ratio enhances economic growth via increased labor supply. Conversely, when adr > 18%, the interaction coefficient turns significantly negative, suggesting that at higher aging levels, the positive contribution from employment is substantially weakened (or reversed). Thus, Hypothesis 1 regarding labor supply mechanism is confirmed.

2. Social Security Burden Channel

Population aging theoretically suppresses economic growth by increasing the financial burden from expanding pension coverage (ln_pen). To test this mechanism, an interaction term between pension coverage and adr is incorporated. Column 2 of Table 9 shows that when adr ≤ 18%, the interaction term coefficient is -0.0018 ($p < 0.01$), significantly negative, indicating even moderate levels of aging impose notable fiscal constraints. When adr > 18%, the coefficient is -0.0008 ($p < 0.01$), also significantly negative, further suggesting intensified fiscal stress under higher levels of aging. Thus, Hypothesis 4 regarding the social security mechanism is confirmed.

3. Technological Progress Adjustment Channel

High-tech industries (ln_hti) theoretically can mitigate the negative impact of aging on economic growth through productivity enhancement. This paper investigates this moderating effect by including the interaction term (adr × ln_hti). According to column 3 in Table 9, the coefficients of the interaction terms are -0.0006 (adr ≤ 18%) and -0.0002 (adr > 18%), both statistically insignificant ($p > 0.1$). This insignificance implies limited moderating effects from technological progress at both aging levels in the current sample.

4. Infrastructure Support Channel

The infrastructure (ln_infrastructure) is hypothesized to mitigate aging-induced economic downturn. Introducing an interaction term (adr × ln_infra) into the fixed-effects model (column 4, Table 9), results show a significantly negative coefficient (-0.0014, $p < 0.01$) when adr ≤ 18%, indicating that infrastructure improvements have a limited buffering effect at lower levels of aging. When adr > 18.0%, the coefficient is slightly negative (-0.0005), but insignificant, suggesting a potential yet weaker supportive effect from infrastructure at higher aging levels.

Overall Conclusion:

Overall, the empirical findings confirm that population aging exerts a significant constraint on regional economic growth, primarily by reducing labor supply and escalating social security costs. Meanwhile, technological advancement and improved infrastructure potentially mitigate the negative impacts of aging on economic growth, though such mitigating effects were not statistically significant in this analysis and thus require further exploration.

Table 9. Mechanism Test

Variables	(1)	(2)	(3)	(4)
$X_{it} * adr(adr \le \theta)$	0.0029***	-0.0018***	-0.0006	-0.0014***
	(0.0659)	(-2.8991)	(-0.7990)	(-3.2826)
$X_{it} * adr(adr > \theta)$	-0.0071**	-0.0008**	-0.0002	-0.0003
	(-2.3051)	(-2.2695)	(-0.3346)	(-0.9760)
Control Variables	YES	YES	YES	YES
Intercept Term$(adr \le \theta)$	7.1977***	7.1353***	6.2090***	7.3851***

	(11.6569)	(12.9215)	(9.9038)	(15.5718)
Two-Way Fixed Effects	YES	YES	YES	YES
Observations	341	341	341	341
R^2	0.995	0.996	0.995	0.996

t-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

4.7 Regional Heterogeneity and Spatial Spillover Effects

Due to differences in economic development, industrial structure, and labor market dynamics, the effect of population aging on economic growth varies significantly across regions. Economically developed areas, characterized by abundant capital, strong technological innovation capabilities, and optimized industrial structures, generally experience weaker negative impacts of aging on economic growth. In fact, these regions may even benefit from aging through labor-substituting technologies and industrial upgrading. Conversely, less economically developed areas often face greater economic pressures due to aging, including intensified labor shortages, slower capital accumulation, and increased social security burdens. Consistent with this viewpoint, Gao and Rong (2024), employing provincial-level panel data, found that the direct impact of aging on economic growth in China's eastern coastal provinces is weaker than that in the central and western regions, displaying a spatial pattern that is more pronounced in northern provinces compared to southern ones[23].

Moreover, the impact of population aging extends beyond local regions through spatial spillover effects, primarily via population migration. Regions severely affected by aging tend to experience an outward migration of younger labor forces, consequently benefiting labor-importing areas while diminishing economic vitality in exporting regions. To comprehensively explore these dynamics, this study further investigates regional heterogeneity and spatial spillover effects.

4.7.1 Regional Differences Analysis

Given the substantial regional differences, such as the developed high-tech industries in eastern provinces and comparatively weaker infrastructure in central and western provinces, the economic consequences of aging pressures may significantly vary. Thus, to reveal the structural and regional disparities comprehensively, this paper conducts a heterogeneity analysis.

Building upon prior studies that differentiate regions spatially (based on the "Hu Line"), this study further categorizes regions according to their economic performance, dividing provinces into economically developed and less-developed groups (using regional GDP mean as the threshold). Comparative analysis is then performed, with results presented in Table 10.

Eastern vs. Western Regions:

The results indicate that the coefficient of the elderly dependency ratio (adr) in eastern regions is significantly negative (-0.0102, $p < 0.05$), though relatively smaller in magnitude. This weaker effect may stem from positive contributions of high-tech industries and infrastructure, partially offsetting the adverse impact of aging on labor supply. Conversely, the western regions exhibit a stronger negative coefficient (-0.0115, $p < 0.05$). The larger magnitude likely results from insufficient technological progress and limited local fiscal resources in these areas, unable to adequately counterbalance the negative effects of aging through reduced labor supply and increased social security burdens. These findings underscore significant structural differences in regional impacts of population aging on economic development.

Economically Developed vs. Less-developed Regions:

Similarly, economically developed provinces display a negative yet relatively small coefficient (-0.0115, $p < 0.1$) for adr, indicating partial mitigation of aging-induced pressures through advanced technology and infrastructure. In contrast, economically less-developed provinces demonstrate the most substantial negative coefficient (-0.0195, $p < 0.01$), likely reflecting inadequacies in technological advancement and limited local fiscal capacities that amplify the adverse effects associated with aging.

In conclusion, the results highlight significant regional differences in how population aging affects economic development, which are closely linked to geographic location and regional economic performance.

Table 10. Heterogeneity Analysis

Variables	Eastern Region	Western Region	Developed Region	Moderately Developed Region
adr	-0.0102** (-2.2080)	-0.0148** (-2.2813)	-0.0115* (-1.7962)	-0.0195*** (-3.7235)
Control Variables	YES	YES	YES	YES
Constant Term$(adr \leq \theta)$	7.7219*** (9.4806)	2.5604* (1.7863)	8.6228*** (4.6801)	1.8119 (1.5628)
Two-Way Fixed Effects	YES	YES	YES	YES
Observations	242	99	124	216
R^2	0.991	0.998	0.981	0.995

t-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

4.7.2 Spatial Spillover Effect

Considering that the influence of population aging on economic development is not limited to a single region but generates spatial spillover effects across regions through mechanisms such as population migration, capital allocation, consumption demand shifts, technological diffusion, and fiscal pressures, traditional econometric methods alone may inadequately capture such cross-regional impacts. For instance, economically developed coastal regions with abundant medical resources often attract elderly populations from surrounding areas, stimulating local pension and healthcare industries but simultaneously intensifying pressures on public finances. Conversely, central and western regions might experience economic slowdowns due to outward migration of the working-age population. This interconnected regional dynamic implies that the impacts of aging are not isolated occurrences but exhibit significant spatial interdependencies.

To more comprehensively capture both the direct and spillover effects of population aging on economic growth, this study introduces a spatial econometric model. Integrating spatial autocorrelation characteristics, the model analyzes how population aging transmits through various channels across regions, examining its aggregate impact on economic development.

When studying spatial effects of regional economic variables, it is essential first to verify the presence of spatial autocorrelation among variables, ensuring an appropriate model specification. Therefore, prior to constructing the spatial spillover model, this study employs Moran's I statistic to conduct a spatial autocorrelation test on key variables. The results are presented in Table 11.

Table 11. Spatial Autocorrelation Test

Elderly Dependency Ratio	Moran's Index	Z	p-Value
2010	0.4332	5.9585	0.00
2011	0.4202	5.7081	0.00
2012	0.4353	5.9411	0.00
2013	0.4391	5.9939	0.00
2014	0.4021	5.5131	0.00
2015	0.4366	5.9822	0.00
2016	0.4628	6.2578	0.00
2017	0.4768	6.4342	0.00
2018	0.449	6.0409	0.00
2019	0.4644	6.234	0.00
2020	0.5138	6.8623	0.00

According to the Moran's I test results, the elderly dependency ratio exhibited significant spatial autocorrelation from 2010 to 2020 (Moran's I increasing from 0.4332 to 0.5138, with p-values < 0.01). This indicates that aging levels display a spatial clustering effect, and the strength of this spatial dependence has intensified over time. Such findings suggest that the aging level in one region may influence adjacent regions, thereby confirming the presence of spatial spillover effects. As a result, the test is validated, supporting the necessity of constructing a spatial econometric model.

Following this, a binary contiguity matrix is employed to construct the spatial econometric model, where:

To comprehensively account for spatial influences on regional economic development, this study adopts the approach of Yan Fen et al. (2023)[24]and systematically compares three spatial econometric models:

1. Spatial Autoregressive Model (SAR)

2. Spatial Error Model (SEM)

3. Spatial Durbin Model (SDM)

A model selection test is conducted to determine the **optimal model** for capturing the spatial effects, with the model specifications detailed as follows:

$$\ln GDP_{it} = \alpha_0 + \beta_1 W \ln GDP_{it} + \beta_2 adr_{it} + \gamma_j X_{it} + \beta_3 W adr_{it} + \gamma_k WX_{it} + \varepsilon_i + \lambda_t + \omega_{it} + v_t$$

From top to bottom, the models include the Spatial Autoregressive Model (SAR), the Spatial Error Model (SEM), and the Spatial Durbin

Model (SDM), where W represents the spatial matrix and v_t denotes the spatial effect.

The LR test is conducted as follows:

Table 12. Model Selection Test

Methodology	F-Statistic	p-Value
LR Test for SAR and SDM	36.54	0.000
LR Test for SEM and SDM	32.14	0.000

All results are statistically significant at the 1% level, confirming that the Spatial Durbin Model (SDM) does not simplify into either the Spatial Lag Model (SLM) or the Spatial Error Model (SEM). Hence, the SDM is selected for further analysis.

Table 13. Spatial Durbin Model Regression Results and Effect Decomposition

Variables	X	W*X	Direct Effect	Indirect Effect	Total Effect
adr	-0.005*** (0.00)	-0.011*** (0.00)	-0.005*** (0.00)	-0.013*** (0.00)	-0.006*** (0.00)
Control Variables	YES	YES	YES	YES	YES
Two-Way Fixed Effects	YES	YES	YES	YES	YES
rho	0.062***(0.00)				
sigma2_e	0.020***(0.00)				
Observations	341	341	341	341	341
R^2	0.875	0.875	0.875	0.875	0.875
Number of Provinces	31	31	31	31	31

t-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

According to the regression results and effect decomposition of the Spatial Durbin Model (SDM) in Table 13, the core variable adr (aging level) exhibits negative and statistically significant direct, indirect, and total effects at the 1% significance level. This indicates that aging significantly suppresses economic growth within a given region while simultaneously exerting negative spatial spillover effects on neighboring regions, thereby constraining overall economic growth.

Specifically:

The direct effect coefficient is -0.005, indicating that a one-unit rise in the aging level results in an average reduction of 0.005 units in economic growth within the same region.

The indirect effect coefficient is -0.013, suggesting that aging in neighboring regions exerts a notable negative spillover effect on local economic growth.

The total effect coefficient is -0.006, reinforcing the overall inhibitory influence of aging on economic growth.

Additionally, the spatial lag coefficient rho (0.062, $p < 0.01$) is significantly positive, indicating the presence of spatial dependence in economic growth—meaning that economic growth in one region is influenced by the growth levels of neighboring regions. The model's R^2value of 0.875 suggests a high overall goodness of fit, reinforcing the reliability of the regression results.

Overall Implications:

These findings highlight that aging not only directly restricts local economic growth but also generates negative spatial spillover effects, thereby influencing the economic development of surrounding regions. This interregional linkage and diffusion effect suggests several possible underlying mechanisms:

1.Labor Force Reduction and Migration Effects:

Aging leads to a decline in the working-age population, exacerbating labor outflows and reducing local economic vitality, which in turn affects adjacent regions through population mobility dynamics.

2.Consumption Contraction and Market Impact:

Since elderly individuals typically have a lower marginal propensity to consume, aging may suppress aggregate demand, weakening market activity and causing regional economic interdependencies to amplify these effects.

3.Fiscal Burden and Investment Crowding-out:

Increased expenditures on pensions and healthcare impose significant fiscal pressures, potentially diverting public resources away from infrastructure and industrial development, thereby restraining economic growth and spilling over into neighboring regions.

4.Labor Shortages and Innovation Constraints:

A shrinking workforce may hinder technological innovation and industrial upgrading, while adjustments in capital markets could dampen investment dynamism, leading to a broader regional economic downturn.

In summary, these results underscore the interregional and systemic nature of aging's economic consequences. Addressing these challenges requires coordinated regional policy responses that mitigate aging-related economic risks while fostering sustainable development across interconnected economies.

5. Conclusions and Implications

Based on panel data covering 31 provinces in China from 2010 to 2020, this paper employs a fixed-effects model to investigate the impact of population aging on regional economic development. The findings are as follows: firstly, in general, the negative effects of population aging on regional economic growth outweigh the positive impacts, indicating that population aging is more likely to hinder regional economic growth. Secondly, this relationship exhibits a non-linear characteristic; at lower levels of aging or in regions with relatively low aging rates, population aging can to some extent stimulate economic growth—commonly known as the "silver economy"—yet beyond a certain threshold, it significantly suppresses local economic growth. Thirdly, in terms of mechanisms, population aging negatively affects economic growth primarily by reducing labor supply and increasing fiscal burdens. However, technological advancements and improved infrastructure can mitigate these negative effects. Finally, from differentiated and dynamic perspectives, the impact of population aging on economic development varies significantly depending on spatial location and regional development status. Moreover, population aging not only inhibits local economic growth but also generates negative spillover effects on neighboring regions through spatial interactions.

Building on the above findings, this study presents the following policy implications:

Firstly, optimizing the population structure is essential for coordinated economic and social development. Institutional improvements and pension reforms should be implemented to facilitate the adoption of delayed retirement policies. Concurrently, enterprises should proactively adjust their human resource strategies to enhance employment opportunities and labor participation among older workers. Individuals should foster lifelong learning awareness, actively improve their vocational skills, and maintain competitiveness in the labor market.

Secondly, actively cultivating and expanding the "silver economy" can drive industrial upgrading and innovation. By providing policy support and financial guidance, enterprises should be encouraged to develop products and services targeted at the elderly, such as smart elderly care and healthcare industries. Enterprises should accelerate technological innovation, enhance digitalization and intelligence levels, and reduce reliance on traditional labor-intensive models. Accurate insights into elderly consumption demand will facilitate new market growth opportunities.

Thirdly, strengthening human capital construction will enhance technological adaptability and productivity. Enterprises should establish multi-level lifelong vocational training systems to improve employability and skill levels, particularly for older workers. Governments can promote increased investment in human capital through fiscal incentives, training subsidies, and optimized public services. Additionally, individuals should actively engage in vocational education and training to improve their skill reserves and economic contributions.

Finally, enhancing society's comprehensive ability to adapt to population aging is vital for improving overall welfare. Accelerating age-friendly renovations in public facilities and constructing long-term care systems, especially integrated medical and elderly care models, can alleviate public fiscal burdens. Developing elderly-friendly products and services will enhance individuals' quality of life. Furthermore, individuals should strengthen awareness of wealth and health management, reasonably allocate financial assets, and adopt healthy lifestyles to maintain economic independence and quality of life during old age. Addressing aging challenges through multi-stakeholder collaboration is crucial for achieving sustained and healthy economic growth.

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