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How Population Aging Drives Labor Productivity: Evidence from China

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Abstract: Population aging is a critical demographic trend in China, presenting both challenges and opportunities for advancing sustainable development in alignment with the UN's SDGs, particularly SDG 8, Decent Work and Economic Growth, SDG 9,Industry, Innovation, and Infrastructure,SDG 10,Reduced Inequalities. This study investigates the impact of population aging on labor productivity, with a focus on the mediating role of the capital-labor ratio and heterogeneities across industries, skill levels, and regions. Using data from Chinese listed firms between 2011 and 2018,this paper used fixed effects models and mediation models for econometric regressions to explore the relationship between population aging and labor productivity. The analysis reveals that population aging significantly enhances labor productivity. The capital-labor ratio emerges as a critical mechanism, mediating the relationship between aging and productivity by incentivizing firms to increase capital intensity in response to labor shortages. The findings highlight notable heterogeneities. Labor-intensive firms and low-skilled worker segments experience stronger productivity gains from aging compared to their capital-intensive and high-skilled counterparts. At the regional level, the productivity effects are most pronounced in first- and second-tier cities, while third-tier cities show negligible impacts, reflecting resource and structural constraints. This study underscores the dual role of population aging as a challenge and an opportunity. Policy recommendations include promoting capital investment, automation, workforce upskilling, and regional development to sustain productivity growth amidst demographic transitions. These findings offer valuable insights for policymakers and businesses navigating the complexities of aging economies.

Keywords: sustainable aging economy; population aging; labor productivity; capital-labor ratio; regional heterogeneity; skill level; industry structure

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1. Introduction

Population aging is central to achieving key United Nations Sustainable Development Goals (SDGs), such as SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 10 (Reduced Inequalities).[1] Population aging represents one of the most significant demographic trends in the 21st century, particularly in China, where the rapid decline in fertility rates and increased life expectancy have led to profound societal and economic transformations. China's aging population is already at an upper-middle level in the world. Between 1953 and 2021, China's population aged 65 and above increased from 26.32 million to 200 million, or from 4.4 percent to 14.2 percent. Historically, the degree of aging increased by 0.15, 0.18 and 0.46 percentage points per year respectively from 1990 to 2000, from 2000 to 2010 and from 2010 to 2020, indicating a significant acceleration of aging.[2] This demographic shift poses unique challenges to labor markets, industrial productivity, and economic sustainability, while simultaneously offering opportunities for innovation

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[1] Data are sourced from the Sustainable Development Goals platform (https://sdgs.un.org/goals, accessed on March 31, 2025).
[2] Data are sourced from National Bureau of Statistics of China (http://www.stats.gov.cn, accessed on November 22, 2024).

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and policy intervention[1–3]. Understanding its multifaceted effects is critical for policymakers and businesses alike.

Labor productivity, a cornerstone of economic efficiency, directly influences competitiveness, innovation, and sustainable development[4–6]. Recent research underscores the critical influence of demographic changes on productivity dynamics. Firstly, aging population leads to a shortage of young workers, and firms will replace them with more machinery. Population aging reduces the working-age population, leading to labor shortages[7–9], particularly in sectors reliant on manual and repetitive tasks. Acemoglu and Restrepo [10] find that population aging drives the increased adoption of robots and other automation technologies, as the decline in middle-aged workers engaged in manual production tasks necessitates automation and aging populations correlate with higher adoption rates of robots and automation technologies globally. Fortunately, automation technologies often improve labor productivity by substituting labor with capital Battisti et al. [11].

Further, the effect of population aging on the improvement of labor productivity varies from different countries and regions .Maestas et al. [12] reveals changes in predetermined components of population aging across American states are used to estimate the effect of aging on the slowdown in labor productivity growth from 1980 to 2010. However, in most non-OECD countries, declining fertility rates will cause labour-force-to-population ratios to rise as the shrinking proportion of young people is more than offset by a larger share of working-age adults[13–15] and work experience in global human capital accumulation also matters[16] .

Additionally, China's vast size and uneven distribution of population and resources create major differences across regions, leading to significant regional and industrial variations in labor productivity.Thus, when exploring the relationship between an aging population and labor productivity, it is crucial to consider regional and industrial variability. Chen et al. [17] finds population aging has a significant positive impact on economic growth, which promotes economic growth in more developed regions as well as in rural areas[18]. However, there are few studies on how China's aging population affects corporate labor productivity. This study investigated the impact of population aging on corporate labor productivity using fixed effects models and mediation models for econometric regressions, with a specific focus on the mediating role of the capital-labor ratio. Additionally, heterogeneous effects of population aging on corporate labor productivity are examined in greater detail.

As a result, our work contributes in the following three ways to this increasing knowledge: First, this study employs firm-level data from Chinese listed companies and fixed effect and mediation econometric models to determine the effect of population aging on corporate labor productivity. Second, we also find out the effects of aging vary across regions, industries, and skill levels, underscoring the heterogeneous nature of its economic implications. Finally, we investigate the significant positive impact on labor productivity is primarily mediated through increases in the capital-labor ratio.

The rest of this paper is organized as follows: Section 2 provides a review of relevant literature about population aging, labor productivity and capital-labor raio and then gives the hypothesis. Section 3 summarizes the data, empirical approach and variables. Section 4 discusses the empirical findings and their importance. Section 5 analyzes the robustnesses in further detail.Section 6 performs a mechanism analysis. Section 7 summarizes the findings of this research and makes a number of policy suggestions.

The structure of this paper is as follows: Section 2 provides a review of the relevant literature on labor productivity, and the capital-labor ratio, followed by the development of the research hypotheses. Section 3 outlines the data, empirical methodology, and variable definitions. Section 4 presents the empirical findings and their implications. Section 5 provides a detailed analysis of robustness checks. Section 6 performs the mechanism analysis. Finally, Section 7 summarizes the key findings and offers policy recommendations.

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2. Literature Review

2.1. Labor Productivity

Labor productivity, a key indicator of economic efficiency, has been a central focus in the fields of economics and management.Labor productivity is typically defined as the output per unit of labor input, measured by metrics such as GDP per capita, output per hour worked, or sectoral labor productivity[19,20].

Labor productivity is influenced by a combination of factors, including capital investment, technological progress, human capital, and resource allocation efficiency. Capital investment is a primary factor in enhancing labor productivity[21]. Technological progress is the long-term driver of labor productivity growth[4].The diffusion of technology across industries and regions plays a pivotal role in reducing production costs and enhancing competitiveness. Human capital, including education and vocational training, positively impacts labor productivity [22,23].Investment in human capital not only increases individual productivity but also fosters innovation and knowledge spillovers that benefit the broader economy. Hsieh and Klenow [14] highlight that resource misallocation across sectors significantly hinders aggregate labor productivity. Optimizing resource distribution is particularly effective in emerging markets.

2.2. Capital-Labor Ratio

The capital-labor ratio is defined as the total capital stock divided by the total labor input in terms of hours or the number of employees, which plays a critical role in representing labor productivity[4,24]. It is usually increased by higher capital investments, enabling workers to operate more efficiently and produce greater output per worker. Increases in the capital-labor ratio significantly raise the marginal productivity of labor, particularly in capital-intensive industries[25].

In the aging economies, the substitution of capital for labor is a common response to shifts in labor market dynamics. When labor supply decreases due to demographic changes, such as population aging, or when labor costs rise, firms increasingly rely on capital investment to maintain or enhance efficiency [26–28].This substitution effect is particularly pronounced in aging economies, where the shrinking working-age population creates labor shortages. By increasing the capital-labor ratio, firms mitigate the adverse effects of labor supply constraints, leveraging capital-intensive technologies to sustain production.

The adoption and diffusion of technology significantly influence the impact of the capital-labor ratio on productivity growth. Advanced technologies, such as machine learning and industrial IoT, enhance the efficiency of capital-intensive operations, amplifying the benefits of a higher capital-labor ratio. However, the rate and scope of technology adoption vary widely across regions and industries. Studies [15,29] highlight that disparities in access to and utilization of technology contribute to uneven productivity gains.

2.3. Hypotheses

Population aging, as a significant demographic shift, exerts profound and multifaceted impacts on labor markets and economic structuresMaestas et al. [12], Bloom et al. [13], Jedwab et al. [16] . Its effects are not only direct, through changes in the composition and behavior of the workforce, but also indirect, mediated by firms' strategic responses to demographic challenges. Existing literature highlights two key pathways: first, the direct enhancement of labor productivity through accumulated experience and knowledge of workers, and second, the role of the capital-labor ratio as a critical mechanism enabling firms to adapt to labor shortages. Building on these insights, the following hypotheses are proposed to explore the relationship between population aging and labor productivity in greater depth.

Hypothesis 1: Population aging has a positive impact on labor productivity.

Population aging drives significant structural changes in labor markets, primarily through a reduction in the working-age population. This decline in labor supply incentivizes firms to adopt

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productivity-enhancing technologies and improve operational efficiency. Acemoglu and Restrepo [10] argue that aging economies are more likely to rely on automation and capital substitution to address labor shortages, leading to productivity gains. Additionally, older workers, with their accumulated experience and knowledge, contribute positively to productivity in industries where expertise and decision-making are critical [12,30,31].

Hypothesis 2: The positive impact of population aging on labor productivity is primarily achieved through an increase in the capital-labor ratio.

The capital-labor ratio of a firm is affected by changes in the two major production factors of capital and labor. We believe that population aging promotes enterprises to introduce advanced production equipment and technology, which leads to the increase of capital-labor ratio, and then improves the labor productivity of enterprises.

3. Materials and Methods

3.1. Data Sources

This study is conducted using a sample of Chinese listed companies from 2011 to 2018, a period characterized by significant demographic transitions and structural economic changes in China. The choice of listed companies is appropriate for this analysis as population aging, treated as an exogenous variable, allows for a clearer assessment of its effects on firm-level dynamics.

Firm-level data are sourced from the CSMAR and WIND databases[3], while demographic statistics, including measures of population aging such as the proportion of the elderly population to the working-age population (`Old_depth`), are obtained from the National Bureau of Statistics of China[4]. These regional-level demographic indicators are merged with firm-level data based on the location of corporate headquarters, facilitating the analysis of the spillover effects of aging on firm operations.

To ensure the accuracy and robustness of the analysis,continuous variables are winsorized at the top and bottom 1% percentiles to mitigate the influence of outliers, which could skew regression results and lead to biased estimates. Firms in the financial sector are excluded due to their distinct regulatory and operational frameworks, which differ substantially from non-financial industries.Companies listed on the risk warning board during any sample year are excluded to avoid potential biases arising from financial instability.Delisted firms are removed to ensure data continuity and to focus on active market participants.Observations with missing key variables, such as labor productivity, demographic measures, or financial indicators, are excluded to maintain data integrity.

After applying these exclusions and refinements, the final dataset comprises 3,076 listed companies, resulting in 18,775 firm-year observations. This dataset provides a comprehensive and representative sample for analyzing the relationship between population aging and labor productivity. The firm-year structure enables a robust panel data analysis, accounting for both cross-sectional and temporal variations.

3.2. Econometric Model

To evaluate the relationship between population aging and labor productivity, this study constructs the following baseline econometric model, as specified in Equation (1):

$$Y_{it} = \alpha_1 + \beta_1 X_{ipt} + \gamma_1 X'_{it} + u_t + \sigma_j + \epsilon_{it} \tag{1}$$

In this specification, the dependent variable Y_{it} represents the labor productivity of firm i in year t, measured as output per unit of labor. The key explanatory variable X_{ipt} captures the depth of population aging (`Old_depth`) for firm i located in province p during year t. This variable reflects

[3] Firm-level data are sourced from the CSMAR database (https://data.csmar.com, accessed on November 22, 2024) and WIND database (https://www.wind.com.cn, accessed on November 22, 2024).

[4] Region-level data are sourced from National Bureau of Statistics of China (http://www.stats.gov.cn, accessed on November 22, 2024).

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the degree of demographic aging, defined as the proportion of the elderly population relative to the working-age population in a given region.

The vector X'_{it} includes a set of firm-level control variables and regional macroeconomic factors that may influence labor productivity. These firm-level controls incorporate profitability (ROA), leverage (LEV), firm size (SIZE), capital intensity (PPE), and liquidity (CASH), among others. Regional controls, such as GDP growth (GDP), average wages (AVG_WAGE).By incorporating these covariates, the model mitigates omitted variable bias and isolates the effect of population aging on labor productivity.

The terms u_t and σ_j represent year and industry fixed effects, respectively, to control for time-varying macroeconomic shocks and industry-specific factors that may simultaneously affect labor productivity and the explanatory variables. The error term ϵ_{it} captures unobserved idiosyncratic shocks at the firm level.

To account for potential autocorrelation within firms over time, this study employs robust standard errors clustered at the firm level. This approach ensures reliable statistical inference by addressing heteroskedasticity and within-cluster dependence.

The coefficient β_1 measures the marginal impact of population aging (Old_depth) on labor productivity. If Hypothesis 1 holds true, indicating a positive relationship between population aging and labor productivity, β_1 is expected to be positive. A significant and positive β_1 would suggest that firms in regions with higher levels of population aging tend to exhibit higher productivity.

3.3. Variable Selection

3.3.1. Core Explanatory Variables

The dependent variable, $Labor\_Productivity_{i,t}$, measures the labor productivity of firm i in year t. Following the methodology of Bjuggren [32], it is calculated as the natural logarithm of the firm's per capita operating revenue. This approach provides a consistent and robust measure of labor productivity, capturing variations in firms' operational efficiency across years and regions.

The primary explanatory variable, $Old\_depth_{i,p,t}$, represents the old-age dependency ratio in province p, where firm i is located in year t. The old-age dependency ratio, defined as the proportion of elderly individuals (aged 65 and above) to the working-age population (aged 15–64), serves as a key indicator of population aging. By linking provincial demographic trends to firm-level productivity, $Old\_depth_{i,p,t}$ captures the external pressures of aging on corporate performance.

3.3.2. Mediating Variable

The mediating variable, $clr_{i,t}$, represents the capital-labor ratio of firm i in year t. $clr_{i,t}$ is constructed to reflect the per capita capital holdings within firms[33]. It is calculated as net fixed assets over the number of employees . As a critical mechanism linking population aging to labor productivity, the capital-labor ratio highlights firms' strategic adjustments in response to demographic shifts, such as increased investment in capital to compensate for labor shortages.

3.3.3. Other Control Variables

To ensure robustness and mitigate potential omitted variable bias, this study incorporates a comprehensive set of control variables, capturing both firm-level characteristics and regional macroeconomic conditions.The return on assets (*roa*) is calculated as the ratio of pre-tax profits to total assets at year-end, reflecting the profitability of the firm. The leverage ratio (*lev*) is defined as the ratio of total liabilities to total assets at year-end, capturing the firm's financial structure. Fixed asset intensity (*ppe*) is measured as the net value of fixed assets divided by total assets at year-end, indicating the degree of capital intensity. The cash ratio (*cash*) is calculated as the ratio of total cash to current liabilities at year-end, providing an indication of liquidity. Firm size (*size*) is measured as the natural logarithm of total assets at year-end, representing the scale of the firm. The book-to-market ratio (*bm*) is calculated as the ratio of the firm's total market capitalization to net assets at year-end, reflecting the valuation of the firm. Tobin's Q (*tobinq*) is defined as the ratio of market value to the difference between total assets and the net value of intangible assets and goodwill, serving as a proxy for growth opportunities.

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The independent director ratio (*indratio*) is calculated as the proportion of independent directors on the board, indicating governance quality. Finally, ownership concentration (*top*1) is measured as the proportion of shares held by the largest shareholder relative to total shares outstanding, capturing the degree of control exerted by major shareholders. To account for regional macroeconomic conditions, additional controls include the GDP growth rate (*gdp*) of the city where the firm is registered and the local wage level (*avgwage*), measured as the natural logarithm of the average wage of employees in the firm's province.

4. Empirical Results

4.1. Descriptive Statistics

The results of the descriptive statistics concerning the main variables in this paper are shown in Table 1. The dependent variable, labor productivity (*labprod*), has a mean value of 13.72 and moderate variability, indicating differences in firm-level productivity. The core explanatory variable, the old-age dependency ratio (*old_depth*), averages 14.20, with significant regional variation, reflecting the uneven impact of population aging across provinces. The capital-labor ratio (*clr*) has a mean of 12.49, aligning with the study's focus on the role of capital intensity in mediating the effects of aging on labor productivity. Other firm-level variables, such as firm size (*size*), leverage (*lev*), and return on assets (*roa*), show reasonable variability, providing a robust context for analyzing productivity dynamics. Regional controls, including average wages (*avgwage*) and GDP growth (*gdp*), exhibit substantial differences, capturing the economic diversity of the sampled regions. These statistics highlight the relevance of the dataset for examining the relationship between population aging, capital intensity, and labor productivity. The observed variation across key variables supports the empirical analysis of aging's impact on corporate outcomes.

Table 1. Descriptive statistics.

Variables	Sample Size	Mean	Standard Deviation	Minimum	Maximum
labprod	18,769	13.72	0.868	11.95	16.41
old_depth	19,180	14.20	3.319	8.600	21.10
size	18,775	22.10	1.281	19.89	26.09
clr	18,775	12.49	1.129	9.354	15.58
lev	18,775	0.416	0.209	0.0497	0.886
ppe	18,775	0.217	0.162	0.00226	0.702
cash	18,775	0.959	1.639	0.0285	10.78
bm	18,775	4.166	3.604	0.810	22.72
roa	18,775	4.632	5.581	-16.15	21.41
tq	18,040	2.074	1.342	0.865	8.765
indratio	18,392	0.374	0.0532	0.333	0.571
top1	18,392	35.48	14.70	9.443	74.29
avgwage	18,392	11.09	0.330	10.45	11.89
gdp	18,702	9.959	4.613	-4.890	23.96

4.2. The Effect of Population Aging on Labor Productivity

The regression analysis demonstrates a significant positive relationship between population aging (measured by `old_depth`) and labor productivity (`labprod`). The results support the **Hypothesis 1** that population aging enhances labor productivity . This finding is consistent across all three model specifications, and the statistical significance of the `old_depth` coefficient strengthens as more control variables are introduced. Specifically, in Model (1), the coefficient of `old_depth` is positive and statistically significant at the $p < 0.10$ level. In Models (2) and (3), the significance improves to $p < 0.01$, highlighting a robust relationship between population aging and labor productivity. This result aligns with the hypothesis that aging populations drive structural changes in labor markets, such as increased reliance on automation and other productivity-enhancing adjustments [10,34].

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The inclusion of control variables in Model (3) provides further insights into the factors influencing labor productivity. Profitability (roa) and firm size (size) both exhibit significant positive impacts on labor productivity, suggesting that higher profitability and larger firm size enhance operational efficiency.The significant positive coefficient implies that higher leverage(lev) may improve productivity by optimizing resource allocation and increasing investment efficiency.[35]The negative coefficient of ppe suggests that an excessive reliance on capital-intensive investment may not always translate into productivity gains, potentially due to resource misallocation. [14]The positive coefficient of avgwage indicates that higher wage levels, reflecting either improved worker skills or industry-specific productivity gains, contribute to labor productivity. The negative relationship between GDP growth and productivity suggests that lower growth rates may reflect structural economic adjustments, prompting firms to utilize resources more efficiently [36].

The R-squared values increase significantly across the models, from 0.0103 in Model (1) to 0.3436 in Model (3). This indicates that the inclusion of firm-level controls and industry fixed effects substantially improves the explanatory power of the model. While population aging remains an important determinant of labor productivity, firm-specific characteristics and industry-level factors play critical roles in shaping productivity outcomes.

Table 2. Effect of Population Aging on Labor Productivity.

	(1) labprod	(2) labprod	(3) labprod
old_depth	0.0083*	0.0107***	0.0144***
	(0.0045)	(0.0041)	(0.0038)
roa			0.0133***
			(0.0019)
lev			0.6229***
			(0.0831)
ppe			-0.5281***
			(0.0888)
cash			0.0003
			(0.0063)
size			0.1761***
			(0.0131)
bm			-0.0163***
			(0.0032)
tq			-0.0032
			(0.0040)
indratio			0.1058
			(0.2016)
top1			0.0008
			(0.0008)
avgwage			0.4012***
			(0.0547)
gdp			-0.0093***
			(0.0022)
Constant	13.6019***	13.5675***	5.0712***
	(0.0665)	(0.0597)	(0.6539)
Year-FE	Yes	Yes	Yes
Industry-FE	No	Yes	Yes
Observations	18769	18768	17964
R-squared	0.0103	0.2041	0.3436

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

5. Robust Test

5.1. Robustness Test: Changing the Dependent Variable

To ensure the robustness of the baseline results, this study employs an alternative measure of labor productivity (`labprod_adjust`), defined as the natural logarithm of a firm's operating revenue minus non-operating income, divided by the number of employees. By excluding non-operating income, this adjusted measure better reflects changes in firms' productivity attributable to regular production and operational efficiency. The regression results using `labprod_adjust` as the dependent variable are presented in Table 3.

Across all three model specifications, the coefficient for `old_depth` remains positive and statistically significant. Specifically,in Model (1), the coefficient is significant at the $p < 0.10$ level while in Models (2) and (3), the significance improves to $p < 0.01$, with the coefficients increasing in magnitude from 0.0112 to 0.0147. The R^2 values increase significantly from Model (1) (0.0116) to Model (3) (0.3453), indicating that the inclusion of firm-level controls and fixed effects substantially improves the explanatory power of the model. This highlights the importance of firm-specific and industry-level characteristics in explaining labor productivity variations.

These results confirm that population aging, proxied by the old-age dependency ratio, consistently enhances firm-level labor productivity, even when using a refined productivity measure.

Table 3. Robustness Test Results: Changing the Dependent Variable.

	(1) labprod_adjust	(2) labprod_adjust	(3) labprod_adjust
old_depth	0.0087*	0.0112***	0.0147***
	(0.0045)	(0.0041)	(0.0038)
roa			0.0139***
			(0.0019)
lev			0.6249***
			(0.0837)
ppe			-0.5240***
			(0.0896)
cash			-0.0013
			(0.0065)
size			0.1776***
			(0.0131)
bm			-0.0165***
			(0.0032)
tq			-0.0034
			(0.0040)
indratio			0.0986
			(0.2029)
top1			0.0008
			(0.0008)
gdp			-0.0096***
			(0.0022)
avgwage			0.3983***
			(0.0551)
Constant	13.5799***	13.5454***	5.0515***
	(0.0670)	(0.0601)	(0.6585)
Year-FE	Yes	Yes	Yes
Industry-FE	No	Yes	Yes
Observations	18755	18754	17952
R-squared	0.0116	0.2063	0.3453

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

5.2. Robustness Test: Changing the Independent Variable

To further validate the relationship between population aging and labor productivity, the primary explanatory variable `old_depth` is replaced with `old_ratio`, defined as the proportion of the elderly population (aged 65 and above) to the total population. This alternative measure provides a broader perspective on population aging, allowing for a more comprehensive assessment of its impact. The regression results, presented in Table 4, confirm the robustness of the findings across this alternative specification.

The coefficient for `old_ratio` is consistently positive and statistically significant at the $p < 0.01$ level across all three models, indicating a positive relationship between the proportion of the elderly population and labor productivity.These results verify the relationship between population aging and labor productivity when changing the independent variable.

Table 4. Robustness Test Results: Changing the Independent Variable.

	(1) labprod	(2) labprod	(3) labprod
old_ratio	0.0254***	0.0257***	0.0218***
	(0.0067)	(0.0060)	(0.0056)
roa			0.0133***
			(0.0019)
lev			0.6241***
			(0.0830)
ppe			-0.5269***
			(0.0888)
cash			0.0006
			(0.0063)
size			0.1761***
			(0.0131)
bm			-0.0163***
			(0.0032)
tq			-0.0032
			(0.0040)
indratio			0.1092
			(0.2016)
top1			0.0008
			(0.0008)
gdp			-0.0088***
			(0.0021)
avgwage			0.3768***
			(0.0542)
Constant	13.4520***	13.4486***	5.3091***
	(0.0724)	(0.0650)	(0.6429)
Year-FE	Yes	Yes	Yes
Industry-FE	Yes	Yes	Yes
Observations	18769	18768	17964
R-squared	0.0129	0.2063	0.3438

Standard errors in parentheses
*$p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

5.3. Robustness Test: Capital-Intensive vs. Labor-Intensive Firms

To examine the heterogeneity of firms in the impact of population aging on labor productivity, firms are classified into capital-intensive and labor-intensive groups[5]. The separate regressions are run for each group using both `labprod` and `labprod_adjust` as dependent variables.

[5] Capital intensity = total assets / operating revenue; labor intensity =the number of employees /operating revenue.

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Table 5 shows the coefficient for `old_depth` is negative but statistically insignificant in both the `labprod` (Model 1) and `labprod_adjust` (Model 3) regressions, which suggests that for capital-intensive firms, population aging does not significantly impact labor productivity. In contrast, for labor-intensive firms, the coefficient for `old_depth` is positive and highly significant ($p < 0.01$) in both the `labprod` (Model 2) and `labprod_adjust` (Model 4) regressions, indicating that as population aging intensifies, labor-intensive firms experience significant productivity gains.Table 5 shows that population aging has a more direct impact on labor-intensive firms; therefore, under the pressure brought by population aging, labor-intensive firms can invest more capital and then improve labor productivity.

Table 5. Robustness Test Results: Capital-Intensive vs. Labor-Intensive Samples.

	(1) labprod	(2) labprod	(3) labprod_adjust	(4) labprod_adjust
	capital-intensive	labour-intensive	capital-intensive	labour-intensive
old_depth	-0.0004	0.0067***	-0.0001	0.0069***
	(0.0043)	(0.0025)	(0.0043)	(0.0025)
roa	-0.0007	0.0080***	-0.0006	0.0087***
	(0.0022)	(0.0013)	(0.0022)	(0.0013)
lev	0.2763***	0.1298**	0.2748***	0.1289**
	(0.0927)	(0.0550)	(0.0932)	(0.0560)
ppe	-0.4339***	-0.0872	-0.4347***	-0.0764
	(0.0965)	(0.0584)	(0.0971)	(0.0585)
cash	-0.0077	-0.0027	-0.0085	-0.0044
	(0.0070)	(0.0042)	(0.0071)	(0.0043)
size	0.0764***	0.0420***	0.0772***	0.0432***
	(0.0148)	(0.0099)	(0.0148)	(0.0101)
bm	0.0009	-0.0113***	0.0005	-0.0114***
	(0.0041)	(0.0022)	(0.0042)	(0.0022)
tq	-0.0041	0.0013	-0.0042	0.0012
	(0.0047)	(0.0030)	(0.0047)	(0.0030)
indratio	0.1208	-0.0183	0.1196	-0.0332
	(0.2289)	(0.1338)	(0.2296)	(0.1349)
top1	0.0011	0.0007	0.0011	0.0007
	(0.0009)	(0.0006)	(0.0009)	(0.0006)
gdp	-0.0075***	-0.0013	-0.0078***	-0.0013
	(0.0023)	(0.0015)	(0.0024)	(0.0015)
avgwage	0.2112***	0.1046***	0.2092***	0.0976**
	(0.0566)	(0.0384)	(0.0569)	(0.0388)
Constant	10.2847***	10.8831***	10.2781***	10.9104***
	(0.6746)	(0.4920)	(0.6772)	(0.4980)
Year-FE	Yes	Yes	Yes	Yes
Industry-FE	Yes	Yes	Yes	Yes
Observations	8936	8980	8935	8969
R-squared	0.2612	0.1618	0.2620	0.1715

Standard errors in parentheses
*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$

5.4. Robustness Test: Distinguishing Skilled Workers

To examine the heterogeneous effects of population aging on labor productivity across different worker skill levels, firms are categorized into groups based on the proportion of high-skilled workers[6]. Firms with a higher proportion of such employees are classified as employing high-skilled workers,

[6] High-skilled worker proportion is defined as the ratio of employees with a bachelor's degree or higher to the total number of employees.

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while others are categorized as employing low-skilled workers. Table 6 presents the regression results for these two subsamples using `labprod` and `labprod_adjust` as dependent variables.

As for low-skilled workers group,the coefficient of `old_depth` is positive and statistically significant in both `labprod` (Model 1, $p < 0.05$) and `labprod_adjust` (Model 3, $p < 0.01$) regressions. Specifically, the coefficients are 0.0084 in Model 1 and 0.0211 in Model 3, indicating that population aging has a strong positive effect on the productivity of firms with a higher proportion of low-skilled workers. This suggests that population aging compels firms with low-skilled labor to enhance labor productivity .

For firms with a higher proportion of high-skilled workers, the coefficient for `old_depth` is statistically insignificant in both `labprod` (Model 2) and `labprod_adjust` (Model 4). The coefficients are -0.0024 in Model 2 and 0.0059 in Model 4, suggesting that population aging has a negligible direct impact on the productivity of high-skilled workers, which implies that firms with a high proportion of skilled employees are less affected by aging-related labor market dynamics, potentially due to their reliance on advanced skills and knowledge rather than manual labor.

Table 6. Robustness Test: Distinguishing Skilled Workers.

	(1) labprod	(2) labprod	(3) labprod_adjust	(4) labprod_adjust
	low-skilled	high-skilled	low-skilled	high-skilled
old_depth	0.0084**	-0.0024	0.0211***	0.0059
	(0.0038)	(0.0046)	(0.0048)	(0.0051)
clr	0.5992***	0.3466***		
	(0.0181)	(0.0224)		
roa	0.0150***	0.0263***	0.0101***	0.0199***
	(0.0020)	(0.0025)	(0.0025)	(0.0028)
lev	0.6653***	0.9917***	0.4691***	0.8335***
	(0.0882)	(0.1041)	(0.1105)	(0.1138)
ppe	-2.5796***	-2.1275***	-0.2649**	-0.4482***
	(0.1131)	(0.1658)	(0.1130)	(0.1343)
cash	-0.0050	-0.0146**	0.0181	-0.0140*
	(0.0094)	(0.0063)	(0.0112)	(0.0075)
size	0.0610***	0.0583***	0.2023***	0.1211***
	(0.0153)	(0.0155)	(0.0192)	(0.0166)
bm	-0.0086**	-0.0222***	-0.0114**	-0.0259***
	(0.0041)	(0.0039)	(0.0045)	(0.0044)
tq	-0.0049	-0.0001	-0.0068	-0.0018
	(0.0042)	(0.0050)	(0.0054)	(0.0054)
indratio	-0.0801	-0.0746	0.2336	-0.1112
	(0.1994)	(0.2432)	(0.2566)	(0.2636)
top1	0.0038***	0.0002	0.0018	0.0002
	(0.0009)	(0.0010)	(0.0011)	(0.0011)
gdp	-0.0031	-0.0059**	-0.0086***	-0.0113***
	(0.0022)	(0.0028)	(0.0029)	(0.0030)
avgwage	0.2624***	0.2891***	0.3508***	0.3459***
	(0.0675)	(0.0577)	(0.0885)	(0.0629)
Constant	1.9727**	5.1322***	4.7100***	7.1744***
	(0.8139)	(0.7049)	(1.0768)	(0.7564)
Year-FE	Yes	Yes	Yes	Yes
Industry-FE	Yes	Yes	Yes	Yes
Observations	8886	9030	8881	9023
R-squared	0.5122	0.5198	0.2441	0.4414

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

5.5. Robustness Test: City-Level Heterogeneity in Population Aging Effects

To examine the heterogeneous effects of population aging (`old_depth`) on labor productivity (`labprod`) across different city tiers, as defined by the "City Business Attractiveness Ranking" published by Yicai's New First-Tier Cities Research Institute. Cities are classified into first-tier (including new first-tier cities), second-tier, and third-tier cities. To account for unobserved city-specific factors, city fixed effects are included in all regressions. Table 7 presents the results for the full sample and each city tier.

For all samples (Column 1),The coefficient for `old_depth` is positive and statistically significant ($p < 0.01$), suggesting that population aging has an overall positive impact on labor productivity across all city tiers, reflecting the broader structural adjustments and technological advancements triggered by demographic shifts in urban economies.

For first-tier cities (Column 2),the coefficient for `old_depth` remains positive and significant ($p < 0.01$) and is slightly larger than that for the full sample,indicating that first-tier cities, with their advanced economic infrastructure and access to resources, benefit more from aging-related productivity enhancements. These cities are likely to leverage better technology adoption, skilled labor, and institutional frameworks to mitigate the challenges of an aging workforce. Further, the coefficient for `old_depth` for first-tier cities (Column 2) is even larger and remains highly significant ($p < 0.01$), which suggests that second-tier cities may experience the most pronounced productivity gains from population aging. As transitional economies, these cities are increasingly adopting automation and other efficiency-enhancing technologies to address labor shortages, resulting in substantial productivity improvements.

In contrast, for the third-Tier Cities (Column 4), the coefficient for `old_depth` is statistically insignificant, indicating no measurable effect of aging on labor productivity in third-tier cities. This result may reflect the limited economic diversification, inadequate resources, and slower adoption of advanced technologies in these cities. The constrained ability to invest in education, infrastructure, and industrial upgrades hampers their capacity to transform demographic challenges into productivity gains.

The findings reveal substantial heterogeneity in the impact of population aging on labor productivity across city tiers.These insights underscore the importance of tailored policy interventions that consider the unique economic and demographic dynamics of each city tier.

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Table 7. Robustness Test: City-Level Heterogeneity in Population Aging Effects.

	(1) all samples	(2) first-tier	(3) second-tier	(4) third-tier
old_depth	0.0147***	0.0159***	0.0236***	0.0006
	(0.0038)	(0.0049)	(0.0086)	(0.0080)
roa	0.0132***	0.0106***	0.0139***	0.0152***
	(0.0019)	(0.0028)	(0.0037)	(0.0035)
lev	0.6241***	0.6904***	0.6759***	0.4733***
	(0.0831)	(0.1194)	(0.1699)	(0.1542)
ppe	-0.5293***	-0.7178***	-0.6539***	-0.1751
	(0.0899)	(0.1397)	(0.1808)	(0.1514)
cash	0.0006	0.0006	0.0009	0.0064
	(0.0063)	(0.0086)	(0.0131)	(0.0129)
size	0.1763***	0.1584***	0.1969***	0.2013***
	(0.0131)	(0.0183)	(0.0279)	(0.0259)
bm	-0.0161***	-0.0128***	-0.0223***	-0.0166***
	(0.0032)	(0.0046)	(0.0063)	(0.0061)
tq	-0.0033	-0.0044	0.0020	-0.0076
	(0.0040)	(0.0055)	(0.0076)	(0.0077)
indratio	0.1068	0.0521	0.3305	0.0167
	(0.2014)	(0.2888)	(0.3847)	(0.3756)
top1	0.0008	0.0010	0.0016	0.0002
	(0.0008)	(0.0012)	(0.0017)	(0.0016)
gdp	-0.0092***	-0.0222***	-0.0057	-0.0050
	(0.0022)	(0.0041)	(0.0041)	(0.0032)
avgwage	0.4195***	0.3626***	0.0519	0.6828***
	(0.0610)	(0.0681)	(0.2074)	(0.2149)
Constant	4.8563***	6.0447***	8.2039***	1.5716
	(0.7153)	(0.8101)	(2.4197)	(2.4362)
Year-FE	Yes	Yes	Yes	Yes
Industry-FE	Yes	Yes	Yes	Yes
City-FE	Yes	Yes	Yes	Yes
Observations	17964	8966	4398	4599
R-squared	0.3438	0.3986	0.3360	0.2402

Standard errors in parentheses
$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

6. Additional Discussion

6.1. Mediating Effect of Capital-Labor Ratio

6.1.1. Mediating Econometric Model

The relationship between population aging and labor productivity is deeply rooted in the structural changes brought about by demographic shifts. A declining labor force, driven by aging populations, results in an increase in the capital available per unit of labor, thereby enhancing firm-level productivity.

To examine the mediating mechanism , the mediation model is constructed in Equations(2)and (3):

$$Y_{it} = \alpha_2 + \beta_2 X_{it} + \psi M_{it} + \gamma_2 X'_{it} + u_t + \sigma_j + \epsilon_{it}, \tag{2}$$

$$M_{it} = \alpha_3 + \beta_3 X_{it} + \gamma_3 X'_{it} + u_t + \sigma_j + \epsilon_{it}. \tag{3}$$

In the specificaitons, M_{it} is operationalized as the per capita capital holdings (`clr`), a key indicator capturing the relationship between capital and labor within firms, while the other variables and fixed effects are consistent with the baseline model(Equation(2)).

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By integrating Equations (5), (6), and (7), this study constructs a robust framework to analyze the pathways through which population aging influences corporate labor productivity via changes in the capital-labor ratio.

If **Hypothesis 2** holds true, the following should be observed:

- A significant positive β_3, indicating that population aging increases the capital-labor ratio.
- A significant positive ψ, confirming that an increased capital-labor ratio enhances labor productivity.

6.1.2. Results: Mediating Effect of Capital-Labor Ratio

Table 8 presents the analysis of the mediating role of the capital-labor ratio (clr) in the relationship between population aging (old_depth) and labor productivity ($labprod$ and $labprod\_adjust$). The findings provide robust evidence that the capital-labor ratio serves as a significant channel through which aging impacts productivity.

Model (1) demonstrates that old_depth has a positive and statistically significant effect on clr ($\beta = 0.0221, p < 0.01$). This indicates that population aging leads to an increase in the capital-labor ratio. The result aligns with the hypothesis that firms respond to labor shortages caused by aging populations by increasing capital investments relative to labor inputs, thereby raising capital intensity. The inclusion of clr in models (2) and (3) significantly reduces the explanatory power of old_depth, providing strong evidence for its mediating role. In Models (2) and (3), the inclusion of clr as a mediating variable substantially alters the relationship between old_depth and labor productivity: The direct effect of old_depth on both $labprod$ and $labprod\_adjust$ becomes statistically insignificant ($p > 0.10$), indicating that the impact of aging on productivity is fully mediated by the capital-labor ratio. clr itself exhibits a strong positive and significant effect on both $labprod$ ($\psi = 0.4698, p < 0.01$) and $labprod\_adjust$ ($\psi = 0.4674, p < 0.01$). This confirms that a higher capital-labor ratio enhances labor productivity, acting as the primary mechanism through which aging influences productivity outcomes.

These results confirm the centrality of the capital-labor ratio as a mediating variable in **Hypothesis 2**. Population aging prompts firms to increase capital investment relative to labor, mitigating the adverse effects of labor shortages.The increased capital-labor ratio directly improves labor productivity, emphasizing the importance of structural adjustments in aging economies.

This finding underscores the need for policies that encourage capital investment and technological advancements to support productivity in aging societies. Investments in automation, infrastructure, and workforce development can help sustain productivity growth amid demographic transitions.

Table 8. The Mediating Effect of the Capital-Labor Ratio (CLR).

	(1) clr	(2) labprod	(3) labprod_adjust
old_depth	0.0221***	0.0040	0.0044
	(0.0042)	(0.0033)	(0.0033)
roa	-0.0155***	0.0206***	0.0211***
	(0.0021)	(0.0017)	(0.0017)
lev	-0.4554***	0.8351***	0.8350***
	(0.0878)	(0.0723)	(0.0733)
ppe	4.0936***	-2.4511***	-2.4364***
	(0.0936)	(0.0974)	(0.0985)
cash	0.0229***	-0.0107**	-0.0122**
	(0.0070)	(0.0053)	(0.0054)
size	0.2261***	0.0700***	0.0721***
	(0.0134)	(0.0116)	(0.0118)
bm	-0.0046	-0.0141***	-0.0142***
	(0.0033)	(0.0028)	(0.0029)
tq	-0.0018	-0.0023	-0.0024
	(0.0041)	(0.0035)	(0.0035)
indratio	0.3330	-0.0489	-0.0550
	(0.2160)	(0.1748)	(0.1768)
top1	-0.0017*	0.0016**	0.0016**
	(0.0009)	(0.0007)	(0.0007)
avgwage	0.2141***	0.2998***	0.2970***
	(0.0549)	(0.0467)	(0.0472)
gdp	-0.0105***	-0.0043**	-0.0046**
	(0.0023)	(0.0019)	(0.0019)
clr		0.4698***	0.4674***
		(0.0163)	(0.0165)
Constant	4.2271***	3.0921***	3.0849***
	(0.6605)	(0.5592)	(0.5655)
Year-FE	Yes	Yes	Yes
Industry-FE	Yes	Yes	Yes
Observations	17970	17964	17952
R-squared	0.5694	0.5038	0.5010

Standard errors in parentheses
*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$

7. Conclusions and Policy Implications

The following are the study's primary findings:

(1)Positive Impact of Population Aging on Labor Productivity. Population aging, as measured by *old_depth*, has a significant positive effect on labor productivity (*labprod* and *labprod_adjust*). This finding highlights how demographic shifts drive firms to adjust production practices and adopt innovations to sustain efficiency. However, the impact varies significantly across different contexts.

(2)Mediating Role of the Capital-Labor Ratio. The capital-labor ratio (*clr*) serves as a critical mechanism linking population aging and labor productivity. Aging populations lead to an increase in capital intensity, which, in turn, significantly boosts productivity. This mediating effect is evidenced by the insignificance of the direct relationship between aging and productivity when *clr* is included in the regression models. The results emphasize the structural adjustments firms make in response to demographic changes.

(3)The effects of aging differ between capital-intensive and labor-intensive firms.- In labor-intensive firms, *old_depth* positively and significantly impacts productivity, as these firms face labor shortages and adopt strategies to enhance workforce efficiency. In capital-intensive firms, the relationship is insignificant, possibly due to their already high reliance on capital and less sensitivity to labor dynamics.

(4)Heterogeneous Impacts Across Skill Levels Population aging has a stronger effect on the productivity of firms employing low-skilled workers than those with high-skilled workers. For low-skilled workers, aging prompts firms to adopt automation and optimize labor use. In contrast, the productivity of high-skilled workers appears less directly influenced by demographic changes, possibly due to their reliance on expertise and human capital.

(5)City-Level Variations. Population aging has a stronger effect on the productivity of firms employing low-skilled workers than those with high-skilled workers. For low-skilled workers, aging prompts firms to adopt automation and optimize labor use. In contrast, the productivity of high-skilled workers appears less directly influenced by demographic changes, possibly due to their reliance on expertise and human capital.

Based on these findings, the following policy recommendations are proposed:

(1)Encourage Capital Investment and Automation. Governments and firms should incentivize investments in capital-intensive technologies through more subsidies and lower taxes, such as automation and robotics, to address labor shortages and sustain productivity growth.

(2)Support Workforce Adaptation. Governments can help workers adapt to changing labor market demands by retraining and upskilling programs, particularly in third-tier cities and labor-intensive sectors.

(3)Promote Regional and Industrial Diversification. Investments in infrastructure, education, and industry diversification are critical for third-tier cities. Such measures can unlock productivity potential by enabling these cities to transition toward more efficient economic structures.

(4)Foster Technological Innovation in Aging Economies.Governments should actively support research and development (R&D) in technologies tailored to aging societies, such as intelligent elderly care systems, healthcare innovations, and labor-saving devices. Public-private partnerships can accelerate the adoption of these innovations.

(5)Tailored Policies for Different City Tiers. First-tier cities should focus on sustaining innovation-driven productivity growth, while second-tier cities should leverage their transitional advantages to enhance automation and capital investments. Third-tier cities require foundational investments to address structural weaknesses and unlock productivity gains.

While this study provides robust evidence on the positive relationship between population aging and labor productivity, mediated through the capital-labor ratio, several avenues warrant further exploration to deepen our understanding of this complex phenomenon.

1. Technological Innovation as a Complementary Mechanism.The analysis highlights the capital-labor ratio as a critical pathway through which aging impacts productivity. However, the role of technological innovation, particularly automation and artificial intelligence, deserves more attention. Aging populations incentivize firms to adopt advanced technologies to mitigate labor shortages, yet the interplay between technology adoption and firm-level productivity remains underexplored. Future studies could investigate how specific technologies influence productivity across industries and regions with varying aging dynamics.

2. Sectoral and Regional Heterogeneity. The results reveal notable differences in the impact of aging on productivity across sectors and cities, with capital-intensive industries and first- and second-tier cities benefiting more than their counterparts. These findings suggest that regional and industrial policies play a critical role in shaping productivity outcomes. Further research could focus on the role of local governance, infrastructure investment, and education systems in amplifying or mitigating the productivity effects of aging.

3. Labor Market Adaptations. This study underscores the differential impacts of aging on high- and low-skilled workers. While low-skilled labor experiences more pronounced productivity improvements, high-skilled labor appears less directly affected. Future research could delve into how firms adapt their human resource strategies, including training programs, workforce restructuring, and recruitment practices, to optimize productivity in response to demographic changes.

In conclusion, while this study provides valuable insights into the mechanisms linking population aging and labor productivity, it also opens the door for further exploration of complementary mechanisms, which will be crucial for navigating the economic and social challenges of aging populations and ensuring sustainable development in the decades to come.

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