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Turning Silver into Green: How Rural Population Aging Drives Agricultural Green Development

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Article

Keywords: Rural population aging, Agricultural green development, Agricultural socialized services, Bartik (shift–share) IV

Posted Date: November 13th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11351319/v1

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Additional Declarations: No competing interests reported.

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Evidence from Chinese Provinces

Abstract

Amid the global transition toward greener agriculture and rapid demographic restructuring in rural China, the role of rural population aging in agricultural green development remains contested. Using provincial panel data for 30 Chinese provinces from 2011–2024, this study develops an entropy-weighted composite index to quantify agricultural green development. To mitigate endogeneity concerns, we construct a Bartik (shift–share) instrumental variable based on historical ethnic composition from the 1982 Population Census, which allows us to causally estimate the impact of rural aging. The results indicate that rural population aging significantly enhances agricultural green development. Mechanism analysis shows that agricultural socialized services play a central mediating role by facilitating the adoption and diffusion of greener production practices. Heterogeneity tests further reveal that the positive effect is concentrated in the dimensions of output efficiency and green supply, and is stronger in regions with lower economic development and weaker socialized service capacity. These findings clarify how demographic pressure can be transformed into a source of green momentum, and they underscore the policy value of cultivating socialized service markets and designing differentiated regional interventions.

Keywords

Rural population aging; Agricultural green development; Agricultural socialized services; Bartik (shift–share) IV

1. Introduction

In the pursuit of sustainable development, the agricultural sector faces dual pressures: ensuring food security while reducing the accumulated environmental burden caused by long-standing extensive production practices. As the world's largest developing country, China has vigorously advanced an agricultural green development strategy in recent years, aiming to curb environmental degradation by reducing agrochemical inputs and promoting eco-friendly technologies. However, this green transition coincides with profound demographic change in rural China. Rural areas are experiencing a historically rapid acceleration of population aging, where a shrinking labor supply interacts with shifts in farmers' capabilities, generating new constraints and uncertainties for agricultural green development. Population aging is often associated with declining physical capacity in agricultural labor and the outflow of human capital. This raises a central question: how will an increasingly aging countryside shape an agricultural green transition that depends on new technologies and new production paradigms?

The literature on the relationship between rural population aging and agricultural green development has largely converged on two competing views: an "inhibiting" perspective and a "promoting" perspective. The divergence hinges on how farmers adjust production practices under aging pressure and whether such adjustments ultimately lead to greener outcomes. Proponents of the inhibiting view argue that rural aging reduces both the stock and quality of agricultural human capital, thereby directly constraining the adoption of green technologies and improvements in production efficiency. This argument draws primarily on Schultz's human capital theory and technology acceptance models, emphasizing the adverse effects of declining physical capacity, reduced cognitive ability, and heightened risk aversion on green agricultural production. Human-capital depreciation induced by aging limits the use of complex green technologies. Agricultural green development often relies on knowledge-intensive practices—such as precision fertilization, ecological restoration, and biological pest control—which impose higher demands on producers' information-processing and learning capacities. Ren et al. (2023) report that aging among China's smallholders poses a serious threat to agricultural sustainability. They argue that older farmers—often with lower educational attainment and declining managerial capacity—struggle to implement complex field management, leading to reduced land productivity and greater resource waste. Using evidence from Jiangsu Province, Yu et al. (2023) further show that aging significantly reduces farmers' adoption of cropland ecological restoration technologies, attributing this pattern to older farmers' limited access to new knowledge and their difficulty in undertaking the additional physical labor required for green production. This pattern appears globally. In their review of precision agriculture adoption in developed countries, Tey and Brindal (2012) find that older farmers are significantly less receptive to computerized management systems than younger farmers. A meta-analysis of technology adoption in developing countries by Ruzzante et al. (2021) reaches a similar conclusion: age is significantly negatively associated with the uptake of new technologies, partly because older farmers tend to occupy peripheral positions in information networks and are thus less exposed to green innovations. As farmers age, risk aversion typically intensifies, making them more likely to maintain traditional high-input practices to hedge against yield risk. Focusing on maize growers, Mao et al. (2025) find that aging

significantly discourages the adoption of improved crop varieties by increasing both subjective and objective risk avoidance. To avoid the short-term yield losses or uncertainties that may accompany new technologies, older farmers often treat excessive fertilizer and pesticide use as a low-cost form of "yield insurance." Studying labor-intensive agriculture, Liu et al. (2023) also show that aging weakens farmers' incentives for long-term investment; as a result, farmers may shift toward short-term extractive operations or extensive management, which hinders upgrading toward higher value-added and greener production. Consistent with this view, Guo et al. (2015) argue that aging farmers are more inclined to maintain the status quo and lack incentives to alter their existing production function. Moreover, Zeng et al. (2025) note that aging may reduce certain highly polluting inputs because older farmers are less able to perform labor-intensive operations. However, such reductions often come at the cost of lower yields and do not constitute genuine intensive green development. This "low-level greening" is unlikely to be sustainable and may even threaten food security if output falls short.

In contrast, the promoting view argues that labor shortages induced by aging do not necessarily lead to more extensive production. Instead, by altering relative factor prices, aging may generate economic incentives that accelerate the green transformation of agriculture. A classic proposition by Hayami and Ruttan (1985) holds that changes in relative factor prices induce the direction of technological progress. When labor becomes relatively more expensive, technological change tends to be biased toward labor-saving innovations. Using provincial panel data from China, Lu et al. (2024) provide strong evidence for this mechanism, showing that agricultural mechanization significantly raises green total factor productivity by improving managerial practices, enhancing factor-use efficiency, and fostering industrial diversification. Comparative evidence on Asian agricultural development from Otsuka et al. (2013) also suggests that rising wages spur mechanization: mechanization not only addresses the question of "who will farm" but also reduces waste of fertilizers and pesticides through more standardized operations. Evidence from Nepal by Paudel et al. (2020) similarly indicates that labor shortages encourage farmers to adopt more efficient cultivation technologies and resource-management strategies. Agricultural socialized services have become a prominent research focus in recent years. As aging deepens, older farmers may be unable to complete all production tasks on their own, creating substantial demand for service outsourcing. Luo (2017) argues that well-functioning agricultural service markets can substitute for missing household labor, enabling aging farmers to achieve productivity levels comparable to those of younger farmers. Drawing on the social–ecological systems (SES) framework, Wang and Huan (2023) find that agricultural socialized services can facilitate collective action in irrigation commons by strengthening village leadership, increasing dependence on shared resources, and reducing economic heterogeneity among households, thereby mitigating the adverse governance effects of labor outmigration. Li et al. (2023) develop an analytical framework linking labor migration, service demand, and fertilizer use, showing that labor outmigration induces farmers to purchase socialized services and that professional service providers—leveraging technological advantages and economies of scale—can enable more precise and reduced fertilizer application. Zhang et al. (2023) further find that outsourcing fertilization and pesticide-application services may entail initial cost barriers due to principal–agent problems; however, as service scale expands and contiguous farming increases, such outsourcing can significantly improve the technical efficiency of wheat production, generating both environmental and economic gains. Focusing on biopesticide adoption, Han et al. (2024) show that professional

pest-management services significantly increase the likelihood that farmers adopt green inputs, attributing this effect to service organizations' cost advantages in adopting new technologies relative to individual farmers.

Despite these competing perspectives, existing evidence remains inconclusive for two main reasons. First, rural population aging is likely endogenous to agricultural green development: greener and more profitable regions may retain (or attract) different age groups through migration and employment opportunities, while local policy packages and unobserved ecological conditions can simultaneously shape demographic structure and green outcomes. Second, much of the literature emphasizes reduced-form correlations and provides limited causal evidence on the channels through which aging affects green development, particularly the role of agricultural socialized services in reallocating labor and facilitating the diffusion of green practices. To address these gaps, we compile panel data for 30 Chinese provinces from 2011–2024 and construct an entropy-weighted composite index of agricultural green development. We then develop a Bartik (shift–share) instrumental variable based on historical ethnic composition from the 1982 Population Census to obtain causal estimates of the impact of rural aging. Finally, we test the mediating role of agricultural socialized services and examine heterogeneity across sub-dimensions and regional contexts, thereby clarifying when and how demographic pressure can be transformed into green momentum.

The marginal contributions of this study are threefold. First, this study extends the scope of application of induced technological change theory. Using macro-level evidence from China, we show that demographic restructuring can green agricultural production practices by inducing the development of agricultural service markets. Second, we provide more rigorous causal identification in the empirical design. By constructing a historical instrumental variable, we address potential endogeneity bias in prior studies and clarify why ordinary least squares (OLS) estimates may fail to detect the positive effect of aging. Third, the study offers a new policy perspective. Our findings suggest that the key to addressing population aging lies not in reversing demographic trends, but in cultivating well-functioning agricultural socialized service markets. By leveraging service-based substitution for labor, policymakers can transform demographic pressure into a driver of green development.

The remainder of the paper is organized as follows. Section 2 presents the theoretical analysis and develops hypotheses. Section 3 describes the model, variables, and identification strategy. Section 4 reports and discusses the empirical results. The final section concludes and draws policy implications.

2. Theoretical Analysis and Research Hypotheses

This paper is based on the theory of induced technological change and the theory of division of labor to explore how rural population aging, in the context of fundamental changes in labor endowments, promotes agricultural green development through factor substitution and production socialization.

2.1 Rural Population Aging and Agricultural Green Development

Traditional views often hold that rural population aging leads to a reduction in both the quantity and quality of agricultural labor, resulting in more extensive and even stagnant agricultural production. However, when placed within the framework of dynamic factor market adjustments, aging actually serves as an endogenous driver that breaks the traditional inefficient equilibrium

and induces technological upgrading. On the one hand, aging alters relative factor prices, inducing the adoption of labor-saving technologies, which in turn increases agricultural productivity. As young and middle-aged laborers continue to migrate out of rural areas, agricultural labor shifts from relative surplus to relative scarcity, significantly increasing its opportunity cost. As rational economic agents, farmers, in order to maintain agricultural output and household income, inevitably seek to substitute increasingly expensive labor with capital or technological factors. This substitution not only fills the labor gap but also leads to an increase in the organic composition of capital, such as replacing manual labor with mechanized operations and using efficient plant protection technologies to replace manual spraying. This process of capital deepening induced by the scarcity of labor factors directly enhances agricultural output efficiency. On the other hand, the physiological constraints imposed by aging force agricultural production to move away from extensive practices and promote the greening of agricultural production. Older farmers, limited by physical decline and reduced energy, struggle to perform the high-intensity labor required in traditional agriculture. In the absence of alternative technologies, farmers tend to over-fertilize or misuse pesticides to mitigate yield risks or compensate for management deficiencies, treating these inputs as cheap "yield insurance." However, as aging deepens, this reliance on increased chemical inputs to compensate for labor shortages becomes unsustainable. At this point, the modern agricultural machinery and technologies adopted by farmers typically embed standardized operational parameters, enabling precise fertilizer and pesticide application. While farmers adopt these technologies to save labor, they also reduce chemical input use and improve input-use efficiency. Therefore, aging accelerates the transition of agriculture from a high-labor, high-chemical input extensive model to a technology-intensive, resource-saving intensive model, promoting the greening of agricultural production.

Based on this, we propose the following hypothesis:

H1: Rural population aging promotes agricultural green development by inducing factor substitution and upgrading.

2.2 Rural Population Aging, Agricultural Socialized Services, and Agricultural Green Development

If factor substitution explains the driving force behind aging's promotion of green development, the development of agricultural socialized services explains the specific pathway through which this occurs. Due to limited capital and scale, smallholders, especially older farmers, find it difficult to independently purchase and use large modern equipment. Purchasing agricultural socialized services, or outsourcing production, becomes the optimal solution for achieving factor substitution. Aging creates a strong demand for socialized services, which in turn drives the deepening of agricultural division of labor. As farmers age, tasks that require higher physical strength and skills (such as pest control and mechanized planting and harvesting) gradually exceed the capabilities of older farmers. To avoid leaving land idle and to maintain income, older farmers are forced to outsource these production tasks to professional service providers. This process of dividing and transferring operational rights effectively shifts the control of agricultural production from scattered, under-equipped farmers to service providers with professional equipment and technology. Agricultural socialized service providers, under the dual constraints of cost control and technical standards, are more likely to engage in green production practices. Unlike farmers who view pesticides and fertilizers as insurance for yield protection, for service providers offering full-service management or contracted labor and materials, chemical inputs are a significant part

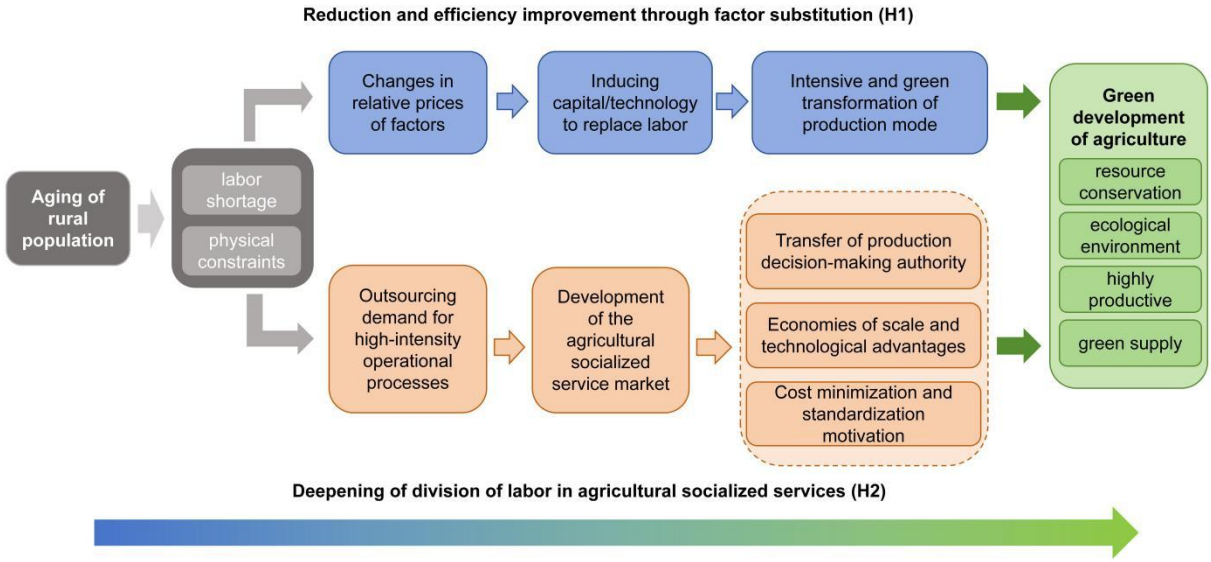
of their production costs. While ensuring output effectiveness, service providers, as profit-maximizing market actors, have a strong economic incentive to precisely control input usage to minimize costs, which incentivizes them to reduce chemical input use and improve input efficiency. Service providers commonly use advanced equipment such as drones and large multifunctional machines, which have strict standardized requirements for liquid concentration and fertilization rates, thereby objectively reducing human error and excessive input. Additionally, service providers conduct large-scale operations, such as integrated pest management, effectively overcoming the defensive spraying tendency of scattered farmers who worry about pest spread between neighboring plots. This collective governance reduces the overall chemical input intensity in the region. In conclusion, aging forces farmers to transfer production decision-making authority, which is then taken up by service providers who, driven by profit maximization and technological advantages, introduce green production methods throughout the agricultural production process.

Based on this, we propose the following hypothesis:

H2: Agricultural socialized services are a key mechanism through which rural population aging promotes agricultural green development. Aging promotes green development by fostering the growth of agricultural socialized service markets.

The theoretical mechanism underlying the relationship among rural population aging, agricultural socialized services, and agricultural green development is summarized in Figure 1.

Figure 1: Theoretical Mechanism Framework of Rural Population Aging Promoting Agricultural Green Development



3. Model Specification, Variable Selection, and Data Description

3.1 Model Specification

(1) Baseline Regression Model: To explore the relationship between rural population aging and agricultural green development, we construct the following baseline regression model:

$$AGD_{it}=\beta_0+\beta_1 Agi_{it}+\sum \beta_2 Control_{it}+\mu_i+\lambda_t+\varepsilon_{it}$$

In this equation, the dependent variable AGD_{it} represents the level of agricultural green development in province i in year t, the key explanatory variable Agi_{it} represents the degree of rural population aging in province i in year t, and $Control_{it}$ includes various control variables such as industry, economy, and society. μ_i represents the individual effect, λ_t represents the time effect, and ε_{it} is the random disturbance term. β_0 is the intercept term, and β_1 and β_2 are the coefficients representing the impact of rural population aging and the control variables, respectively.

(2) Mechanism Model: To examine the mediating role of agricultural socialized services in the effect of rural population aging on agricultural green development, we construct the following mediation effect regression model:

$$SerG_{it}=\alpha_0+\alpha_1 Agi_{it}+\sum \alpha_2 Control_{it}+\mu_i+\lambda_t+\varepsilon_{it}$$

In this equation, the dependent variable $SerG_{it}$ represents the level of agricultural socialized services in province i in year t, with the remaining variables explained as above. α_0 is the intercept term, and α_1 and α_2 are the coefficients representing the impact of rural population aging and the control variables, respectively.

3.2 Variable Selection

(1) Dependent Variable: Agricultural Green Development Level (Score). Based on data availability and applicability, we aim to select indicators that scientifically, objectively, and accurately reflect the actual status of agricultural green development. Drawing from the approaches of Liu et al. (2020) and Zhou et al. (2022), this study selects 22 specific indicators from four dimensions—resource conservation, ecological environment, output efficiency, and green supply—to construct an agricultural green development index system. The entropy-weighted method is used to calculate the agricultural green development level, with the relevant indicators and weights shown in Table 1. Data related to resource conservation, ecological environment, and output efficiency come from the China Rural Statistical Yearbook (2011–2024), China Population and Employment Statistical Yearbook, provincial statistical yearbooks, and the National Bureau of Statistics website. Data on green supply come from the China Green Food Statistical Yearbook (2011–2024).

Table 1: Agricultural Green Development Index System

Dimension	Indicator	Weight	Calculation Method and Unit	Attribute
resource conservation	Crop Rotation Index	0.0285	Total sown area of crops / Arable land area	-
	Proportion of Irrigated Area	0.0546	Effective irrigated area / Arable land area	+
	Water Consumption per Unit of Agricultural Output	0.0078	Total agricultural water consumption / Primary industry added value (ton/ten thousand yuan)	-
	Total Power of Agricultural Machinery per Unit of Arable Land	0.0664	Total power of agricultural machinery / Arable land area (kW/hectare)	+
	Agricultural Financial Support Intensity	0.0389	Agricultural, forestry, and water affairs expenditure / Total fiscal expenditure	+
	Land Productivity	0.1164	Primary industry added value / Arable	+

			land area (ten thousand yuan/hectare)	
	Labor Productivity	0.0702	Primary industry added value / Primary industry employment (ten thousand yuan/person)	+
	Fertilizer Usage Intensity	0.0069	Fertilizer usage / Cropping area (ton/hectare)	-
	Pesticide Usage Intensity	0.0150	Pesticide usage / Cropping area (ton/hectare)	-
	Plastic Film Usage Intensity	0.0092	Plastic film usage / Cropping area (ton/hectare)	-
ecological environment	Diesel Usage Intensity	0.0083	Diesel usage / Cropping area (ton/hectare)	-
	Forest Coverage Rate	0.0594	Forest area / Total land area * 100 (%)	+
	Soil and Water Conservation Area Proportion	0.0774	Soil erosion control area / Total land area * 100 (%)	+
	Disaster Resistance Index	0.0020	(Disaster-affected area - Disaster-prone area) / Disaster-affected area	+
	Per Capita Agricultural GDP	0.0796	Primary industry added value / Rural total population (ten thousand yuan/person)	+
output efficiency	Agricultural Output per Unit Area	0.0975	Primary industry added value / Cropping area (ten thousand yuan/hectare)	+
	Per Capita Disposable Income of Rural Residents	0.0642	Direct data (ten thousand yuan/person)	+
	Agricultural Economic Contribution Level	0.0631	Primary industry added value / Regional GDP (%)	+
	Number of Green Food Enterprises Certified (annual certification count)	0.0168	Logarithm of the number of certified green food enterprises	+
	Number of Green Food Products Certified (annual certification count)	0.0121	Logarithm of the number of certified green food products	+
green supply	Number of Organic Products Certified (annual certification count)	0.0125	Logarithm of the number of certified organic products	+
	Number of Geographical Indication Products Certified (annual certification count)	0.0929	Logarithm of the number of certified geographical indication products	+

(2) Key Explanatory Variable: Rural Population Aging (Agi). This paper measures rural population aging by the proportion of individuals aged 65 and above in the total rural population. Additionally, the rural elderly dependency ratio (Dep) is selected as a substitute variable for robustness checks. Data are sourced from the China Population and Employment Statistical Yearbook (2011–2024).

(3) Instrumental Variable: $Minority_{1982} \times CAgi$. To address potential bidirectional causality (e.g., regions with higher agricultural green development levels may attract or repel specific age structures of labor) and the potential issue of omitted variables, this study follows the approach of Bartik (1991) and constructs an instrumental variable in the form of an interaction term. Specifically, we use the proportion of minority populations in each province from the 1982 Third National Population Census as the cross-sectional share (Share) and the national rural elderly population ratio during the study period as the time shift (Shift). The product of these two variables is used as the instrumental variable for rural population aging in each province during the period.

The validity of this instrumental variable is primarily based on two identification assumptions. First, the instrument must satisfy the relevance condition, meaning that the historical share must be strongly correlated with the current level of population aging. This correlation stems from the specific historical population policies in China and the inertia of its demographic structure. 1982 was a key historical turning point for China's population policy. In that year, family planning was officially incorporated into the Constitution of the People's Republic of China as a fundamental national policy, marking the beginning of the nationwide implementation of the "one-child policy." However, the policy exhibited significant ethnic differences in its design and implementation. Generally, the policy imposed stricter birth quotas and constraints on the Han population, while more lenient arrangements were made for minority groups (Li et al. 2011; Li and Shi, 2025). This means that provinces with a higher proportion of minority populations in 1982 were less constrained by subsequent family planning policies, leading to relatively higher birth rates, which in turn delayed the aging process of the population in these regions several decades later. In other words, the ethnic composition in 1982 had a significant negative predictive effect on the current age structure of the population by influencing fertility rates over the following three decades. Additionally, by introducing the national rural population aging rate as a time trend variable, we can capture the common macro-level trends in demographic transformation, which aligns with the construction standards of Bartik's instrumental variable (Goldsmith-Pinkham et al. 2020).

Second, the instrument must satisfy the exclusion restriction, meaning that the ethnic composition in 1982 should not affect current agricultural green development through any channel other than influencing the current labor force age structure. On the one hand, the 1982 data are historical and predetermined relative to the study period, meaning that current agricultural technological progress or environmental policy shocks cannot retroactively affect the population distribution in 1982. On the other hand, the initial distribution of minority populations across provinces is primarily determined by long-term historical migration and geographic conditions, with no direct connection to current agricultural production. After controlling for provincial fixed effects in the model, the geographical endowments and cultural differences associated with the proportion of minority populations, which remain largely unchanged during the sample period, are absorbed by the fixed effects. Therefore, this instrumental variable can largely isolate the exogenous component of population aging driven by historical inertia, thus meeting the causal identification requirements. The proportion of minority populations from the Third National Population Census and the national rural elderly population ratio data are sourced from the corresponding years of the China Population Yearbook and the China Population and Employment Statistical Yearbook.

(4) Mechanism Variable: Agricultural Socialized Service Level (SerG). Following Xu et al. (2024),

we proxy the output value of agricultural producer services by the output value of the agriculture–forestry–animal husbandry–fishery service sector, and measure the development level of agricultural socialized services as its ratio to employment in the primary industry. The agriculture–forestry–animal husbandry–fishery service sector refers to a range of supportive services for agricultural production activities. Although it does not include scientific and professional technical services, it is conceptually and substantively close to agricultural producer services and can thus capture the development of agricultural socialized services. Data are drawn from the China Statistical Yearbook (2011–2024).

(5) Control Variables. Drawing on prior studies, we include the following controls to mitigate confounding influences on agricultural green development: an extreme climate index (Cri), constructed following Guo et al. (2024), to account for shocks from extreme weather; green innovation (Pat), measured by the number of authorized green patents; financial development (Fin), measured as the ratio of outstanding loans by financial institutions to GDP; agricultural fixed investment (Pro), proxied by agricultural fixed-asset investment; rural informatization (Inf), measured by the number of rural households with internet access; government intervention (Gov), measured as the ratio of general public fiscal expenditure to GDP; economic development (Gdp), measured by regional GDP per capita; agricultural labor (Lab), measured by employment in the primary industry; and the urbanization rate (Urb), measured as the share of urban population in the total regional population. These factors capture climate shocks, technological progress, financing conditions, capital input, information diffusion, policy support, economic fundamentals, labor input, and structural transformation that may jointly shape green outcomes.

3.3 Descriptive Statistical Analysis of Variables

The descriptive statistics of the main variables in the model are reported in Table 2. To reduce data volatility and address heteroskedasticity, the following empirical analysis applies logarithmic transformation to absolute-value variables, including agricultural socialized services, green patents, agricultural fixed investment, rural informatization level, economic development level, and agricultural labor. Missing observations are partially imputed using interpolation.

Table 2: Descriptive Statistics

	VARIABLES	N	Mean	SD	Min	Max
Dependent variable	Score	420	0.3487	0.0707	0.1716	0.6271
Core explanatory variable	Agi	420	0.1419	0.0510	0.0502	0.2957
Mechanism Variable	SerG	420	0.0436	0.0199	0.0124	0.1058
	Cri	420	46.3679	8.6021	25.8066	84.3409
	Pat	420	4759.9369	6875.7428	18.0000	45359.0000
	Fin	420	1.5119	0.4436	0.0789	2.6906
	Pro	420	925.4797	951.2668	1.6046	6120.2291
Control variables	Inf	420	357.9728	372.8353	0.5000	1,560.7000
	Gov	420	0.2549	0.1097	0.1042	0.7583
	Gdp	420	6.5302	3.3957	1.6413	22.8000
	Lab	420	722.2254	513.1085	20.0000	2209.8627
	Urb	420	0.6114	0.1193	0.3504	0.8985

4. Empirical Analysis

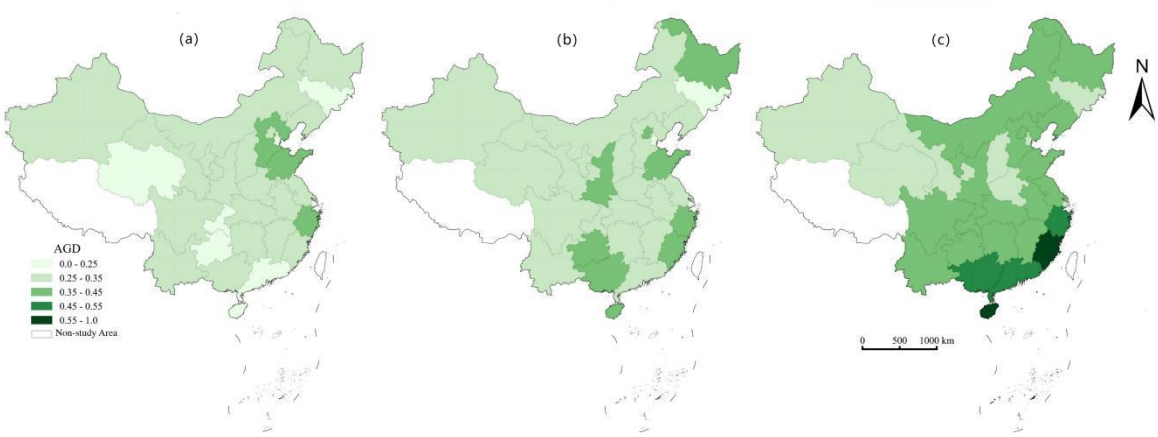
4.1 Spatiotemporal Evolution of Agricultural Green Development

Based on a provincial panel dataset for 30 provinces from 2011–2024 (excluding Hong Kong, Macao, Taiwan, and the Tibet Autonomous Region), we measure agricultural green development across provinces using the entropy-weighting method and analyze its evolution from both temporal and spatial perspectives.

From a temporal perspective, China's agricultural green development exhibits a steady upward trend over the sample period. The estimates indicate that the national mean of the agricultural green development index increased from 0.2876 in 2011 to 0.4088 in 2024, with an average annual growth rate of approximately 3.0104%. This upward trajectory is highly consistent with China's recent policy orientation, including the "zero growth" initiative for chemical fertilizers and pesticides, non-point source pollution control, and supply-side structural reform in agriculture. More specifically, the growth of agricultural green development accelerated after 2015, which is plausibly related to the sustained emphasis on the green development agenda in the annual No. 1 Central Document since 2015 and the strengthened intensity of environmental inspections. Notably, despite the overall improvement, by 2024 the green development index remains below 0.6 in most provinces, suggesting that China's agricultural green development is still at a critical stage of transition and that substantial room remains for a comprehensive green transformation.

From a spatial perspective, pronounced regional disparities are evident, forming a clear east–west gradient characterized by higher levels in the east and lower levels in the west. Using GIS-based visualization, Figure 2 maps the provincial distribution of agricultural green development at three key time points: 2011, 2017, and 2024. The eastern coastal region has consistently remained in the leading group, supported by a strong economic base, advanced agricultural technologies, and well-developed socialized service markets. Taking 2024 as an example, Fujian, Zhejiang, and Guangdong record index values markedly above the national mean. These provinces feature a high degree of agricultural intensification, leading in output efficiency while also performing strongly in resource conservation and environmental friendliness. Central provinces such as Hubei, Hunan, and Anhui—major grain-producing areas—have in recent years explored eco-friendly cropping models while maintaining output. Their index values mostly fall within a mid-range of 0.35–0.45, indicating solid catch-up momentum. Western provinces such as Qinghai, Gansu, and Ningxia lag behind, constrained by ecological fragility, slower technology diffusion, and relatively low levels of economic development. For instance, although Qinghai's index rose from 0.172 in 2011 to 0.314 in 2024—reflecting notable growth—its absolute level remains among the lowest nationwide.

Figure 2: Status of Agricultural Green Development in 2011, 2017, and 2024



4.2 Analysis of Empirical Test Results

Table 3 reports the baseline regression results on the impact of rural population aging on agricultural green development. To address potential endogeneity, we compare estimates from ordinary least squares (OLS) with those from two-stage least squares (2SLS) using a Bartik (shift–share) instrument. Regarding instrument validity, the first-stage results in column (5) show that the instrument Minority1982×CAgi is significantly negatively correlated with the endogenous regressor Agi, with a coefficient of −0.0128 significant at the 1% level. This pattern is consistent with China's historical demographic institutions: minority-concentrated areas faced relatively looser family-planning constraints and thus sustained higher fertility rates over time, which delayed the pace of population aging in these regions today. The Kleibergen–Paap rk Wald F statistic equals 126.327, well above the Stock–Yogo critical values for weak-instrument tests, indicating that the instrument is not weak.

The regression results indicate that, after correcting for endogeneity, rural population aging significantly promotes agricultural green development. The OLS estimates in columns (1)-(2) yield a negative and statistically insignificant coefficient on aging, whereas the 2SLS estimate in column (6) turns positive and becomes significant at the 5% level. The pronounced downward bias in the OLS estimates suggests omitted-variable concerns. For example, economically lagging regions often simultaneously experience (i) high aging due to substantial outmigration of prime-age workers and (ii) low green development due to insufficient agricultural capital investment. If such negative endogenous correlations are not controlled for, they can mask the positive causal effect of aging operating through factor substitution. In economic terms, the coefficient in column (6) implies that, holding other factors constant, a 1-percentage-point increase in the rural elderly share raises the agricultural green development index by about 0.008 units. As aging intensifies, agricultural labor becomes increasingly scarce and costly relative to capital and technology. This shift in relative prices reshapes farmers' input choices, pushing production from labor-intensive toward technology-intensive modes. To cope with physical constraints, farmers become more inclined to adopt mechanized operations and coordinated pest-control services. This factor-scarcity-induced process of capital deepening improves allocative efficiency and reduces extensive input use that relies on labor rather than technology, thereby fostering agricultural green development. In sum, the baseline results provide strong support for H1: once endogeneity is addressed, rural population aging becomes a positive force for China's agricultural green development by inducing greener substitution and upgrading of production inputs.

Table 3: Benchmark Regression Results

VARIABLES	OLS AGD	OLS AGD	First stage Agi	Second stage AGD	First stage Agi	Second stage AGD
$Minority_{1982}$×CAgi			-0.0142***		-0.0128***	
			(0.002)		(0.002)	
Agi	-0.3348	-0.2160		0.5841***		0.8080**
	(0.301)	(0.251)		(0.216)		(0.315)
Cri		-0.0006			0.0000	-0.0003
		(0.000)			(0.000)	(0.000)
LnPat		0.0187			-0.0134*	0.0365**
		(0.026)			(0.007)	(0.016)

Fin		0.0315**			-0.0053	0.0266**
		(0.012)			(0.008)	(0.011)
LnPro		0.0127*			-0.0020	0.0158***
		(0.007)			(0.003)	(0.005)
LnInf		-0.0067			-0.0076**	0.0043
		(0.009)			(0.003)	(0.007)
Gov		-0.1157			0.0092	-0.1697**
		(0.140)			(0.032)	(0.072)
LnGdp		0.0310			-0.0452***	0.0700***
		(0.025)			(0.012)	(0.023)
LnLab		-0.0201			0.0212*	-0.0381*
		(0.051)			(0.012)	(0.020)
Urb		-0.1654			0.1842**	-0.3068*
		(0.356)			(0.086)	(0.184)
Province FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Kleibergen-Paap rk LM	-	-	-	0.0000	-	0.0000
Kleibergen-Paap rk Wald F	-	-	-	215.4990	-	126.3270
Constant	0.3205***	0.3529	0.1123***		0.0636	
	(0.027)	(0.428)	(0.003)		(0.100)	
Observations	420	420	420	420	420	420
R-squared	0.6822	0.7143	0.8873	0.6119	0.9175	0.6550
Number of id	30	30	30	30	30	30

Note: *, **, and * indicate significance at the 10%, 5%, and 1% levels, respectively. Numbers in parentheses are cluster-robust standard errors clustered at the provincial level. The same applies to all subsequent tables.**

4.3 Robustness Checks

To verify the reliability of the baseline results, we conduct a series of robustness checks, with the results reported in Table 4. First, we replace the dependent variable. Given that the entropy-weight method may overlook correlations across indicators, we re-measure agricultural green development using entropy weights combined with TOPSIS. Column (1) shows that the coefficient on the key explanatory variable remains significantly positive, indicating that our conclusion does not hinge on a specific measurement method. Second, we replace the key explanatory variable by using the rural elderly dependency ratio as an alternative proxy for aging. Column (2) indicates that an increase in the dependency ratio also significantly improves agricultural green development. Third, we adjust the sample. Considering the special characteristics of municipalities directly under the central government in terms of agricultural shares and policy resources, we exclude Beijing, Tianjin, Shanghai, and Chongqing and re-estimate the model. Column (3) shows that both the magnitude and significance of the coefficient remain robust, suggesting that the baseline findings are not driven by regional outliers. Fourth, we mitigate the influence of extreme values. After winsorizing all continuous variables at the 1% level on both tails, the results in Column (4) are broadly consistent with the baseline estimates, indicating strong statistical robustness.

Table 4: Robustness Check Results

2SLS VARIABLES	Replace dependent variable Second stage AGD(TOPSIS)	Replace explanatory variable Second stage AGD	Exclude special samples Second stage AGD	Winsorize variables Second stage AGD
Agi	0.9541*** (0.321)		1.2044*** (0.385)	0.7551** (0.298)
Dep		0.4129*** (0.158)		
Controls	YES	YES	YES	YES
Province FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Kleibergen-Paap rk LM	0.0000	0.0000	0.0000	0.0000
Kleibergen-Paap rk Wald F	126.3270	133.8340	84.4690	124.1480
Observations	420	420	364	420
R-squared	0.4991	0.6666	0.6755	0.6728
Number of id	30	30	26	30

4.4 Mechanism Test of Impacts

Hypothesis H2 proposes that the development of agricultural socialized services is a key transmission mechanism through which rural population aging drives agricultural green development. Table 5 reports the results of the mechanism test based on 2SLS.

The results in column (2) show that rural population aging has a significantly positive effect on agricultural socialized services, with a coefficient of 1.8384. This indicates that for every 1% increase in the share of the rural elderly population, the level of agricultural socialized services rises by about 1.84%. This reflects a concrete pathway of factor substitution: constrained by declining physical capacity, elderly farmers find it difficult to independently undertake labor-intensive tasks such as deep tillage and plant protection. To maintain agricultural output, they are compelled to outsource these operations to service organizations equipped with specialized machinery and skills. Such service outsourcing induced by aging generates significant green spillover effects. Compared with dispersed smallholders, agricultural socialized service providers enjoy economies of scale and are more inclined to adopt standardized and precision-oriented operational technologies. Therefore, aging effectively improves the level of agricultural green development by transferring agricultural production decision-making power from dispersed farm households to professional service entities.

Columns (3)–(6) present a series of robustness checks for the agricultural socialized service mechanism. The testing approaches are consistent with those used in the baseline regressions above. In column (3), the measure of agricultural socialized services is replaced by the share of the output value of the agriculture, forestry, animal husbandry, and fishery services sector in total agricultural output value (SerP). The results in column (3) indicate that rural population aging not only promotes the absolute scale of agricultural socialized services, but also increases the relative size of the agricultural socialized service market within the overall agricultural market. The remaining test results are also consistent with column (2) in terms of coefficient signs and statistical significance, suggesting that the regression results for the mechanism test are reliable.

Table 5: Agricultural Socialized Service Mechanism and Robustness Checks

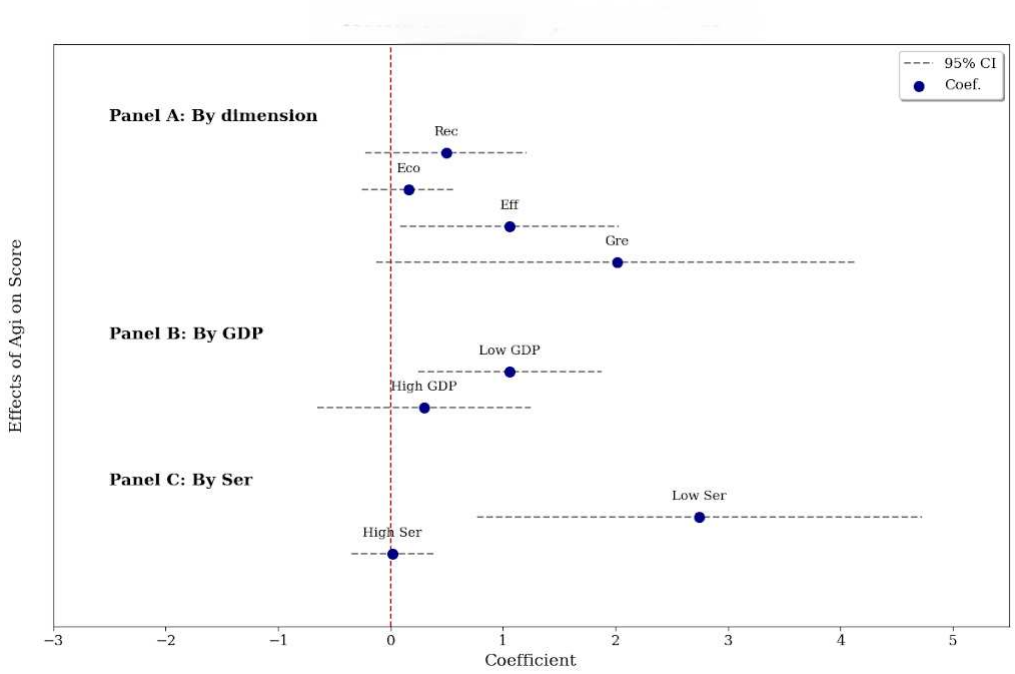
Inspection method			Replace dependent variable	Replace explanatory variable	Exclude special samples	Winsorize variables
2SLS	Second stage	Second stage	Second stage	Second stage	Second stage	Second stage
VARIABLES	LnSerG	LnSerG	SerP	LnSerG	LnSerG	LnSerG
Agi	2.1769***	1.8384***	0.1721**		2.0683**	1.2521***
	(0.451)	(0.623)	(0.077)		(0.844)	(0.485)
Dep				0.9394***		
				(0.307)		
Controls	NO	YES	YES	YES	YES	YES
Province FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Kleibergen-Paap rk LM	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Kleibergen-Paap rk Wald F	215.4990	126.327	126.327	133.834	84.469	124.148
Observations	420	420	420	420	364	420
R-squared	0.4973	0.6435	0.4356	0.6726	0.7017	0.6998
Number of id	30	30	30	30	26	30

4.5 Heterogeneity Analysis

To further examine structural heterogeneity in the effects of aging, Figure 3 reports heterogeneity test results by dimension and by regional characteristics. Panel (A) of Figure 3 shows that the promoting effect of aging is concentrated in the dimensions of output efficiency and green supply, while its effects on resource conservation and the ecological environment are not statistically significant. This pattern may arise because, under labor constraints, farmers prioritize maintaining output and income by substituting labor with machinery and outsourced services. Standardized mechanized operations and the involvement of service providers can also improve product consistency, thereby facilitating local agricultural product certification. In contrast, purely environmental and ecological restoration actions generate strong positive externalities but limited direct private returns. Therefore, they are unlikely to be spontaneously realized through aging-induced market pressure alone and may still require government public policies.

Panels (B) and (C) of Figure 3 split the sample into low and high groups based on provincial rankings of the sample-period means of economic development and agricultural socialized service levels. The results indicate that the promoting effect of aging is more pronounced in provinces with lower economic development and less developed socialized service markets, whereas the effect is insignificant in more developed regions. This is consistent with the law of diminishing marginal returns. In less developed regions where agricultural practices remain relatively traditional, aging acts as a strong exogenous shock that can break a low-level equilibrium and trigger substantial demand for factor substitution and gains from technology diffusion. By contrast, in more modernized regions where mechanization and service markets are closer to saturation, demographic structure changes alone are no longer the dominant force driving green development.

Figure 3: Heterogeneity Analysis Results



5. Conclusions and Policy Implications

5.1 Conclusions

As the world's largest developing country, China is undergoing an unprecedented process of rural population aging in recent decades. This profound demographic shift poses formidable challenges to the green transformation of agricultural production. Grounded in the theory of induced technological change, this study uses panel data from 30 Chinese provinces over 2011–2024 and constructs a Bartik instrumental variable to address severe endogeneity bias, thereby systematically evaluating the impact of rural population aging on green agricultural development and its transmission mechanisms. The main findings and discussions are as follows:

First, rural population aging is not a "stumbling block" to green agricultural development; rather, it serves as a "catalyst" that forces transformation. After correcting the bias in OLS estimates using an instrumental-variable approach, rural population aging is found to significantly improve the level of green agricultural development. This finding challenges the pessimistic view that aging necessarily leads to extensive and inefficient farming practices. By generating relative labor scarcity and physical constraints, aging reshapes relative factor prices and disrupts the traditional production equilibrium characterized by high input use and labor intensity. This compels the agricultural production system to introduce new substitute factors to maintain output, thereby inducing a shift in production modes toward greater intensification and greener practices.

Second, the market for agricultural socialized services is a key mechanism through which aging yields a "green dividend." Aging significantly expands both the absolute and relative scale of agricultural socialized services, which in turn enhances agricultural greenness. Because older farmers face dual constraints in physical capacity and skills, they are forced to cede decision-making power over specific production stages and substitute labor inputs by purchasing services. This process shifts the dominance of agricultural production from dispersed, experience-driven smallholders to professional, data-driven service organizations. Motivated by cost minimization and economies of scale, these organizations can control fertilizer and pesticide

inputs more precisely, thereby not only addressing the question of “who will farm,” but also unexpectedly achieving the goal of “farming well.”

Third, the driving effect of aging exhibits pronounced heterogeneity. The positive impact of aging is most evident in the dimensions of output efficiency and green supply, and it is stronger in regions with lower levels of economic development and a later start in socialized services. This suggests that in less-modernized late-developing regions, aging—as an exogenous shock—can generate substantial marginal improvements and help break low-level traps. In more developed regions, however, as the scope for technological substitution becomes increasingly saturated, the marginal effectiveness of relying solely on demographic pressure to drive green development is diminishing.

5.2 Policy Implications

Based on the above conclusions, this paper proposes the following policy recommendations aimed at transforming the pressure of population aging into a driving force for the green transformation of agriculture:

First, shift the perception of rural population aging from passive response to active adaptation. Policymakers should not be overly alarmed by the loss and aging of rural labor but should recognize that this demographic shift provides a window of opportunity for fundamental changes in agricultural production methods. Policy priorities should shift from attempts to reverse demographic trends or simply subsidize elderly farmers to accelerating the introduction of capital and technology into rural areas through policy guidance, using the pressure of demographic changes to phase out outdated production methods.

Second, focus on cultivating the agricultural socialized service market and creating a green service supply system. Government agricultural subsidy policies should shift from subsidizing purchases to subsidizing services, with an emphasis on supporting service sectors with clear green spillover effects, such as integrated pest management, drone-based plant protection, and soil testing and formula-based fertilization. At the same time, digital tools should be used to reduce transaction costs for elderly farmers in accessing services. Simplified and user-friendly models, such as the "Didi Agricultural Machinery" model, should be promoted to ensure that rural elderly populations, even those facing digital divides, can easily access modern service networks.

Third, implement differentiated regional intervention strategies to precisely leverage latecomer advantages. Regions with lower levels of economic development and where agricultural socialized services are just beginning to take off should be prioritized for policy intervention. In these areas, small investments may yield significant green marginal returns. For developed regions, the focus should shift to higher-level green technological innovations to overcome the bottleneck of diminishing marginal returns.

5.3 Research Limitations and Future Directions

Although this paper provides robust macro-level evidence, there are still some limitations. First, due to the reliance on macro-level data, the study cannot provide a detailed micro-level exploration of the decision-making "black box" regarding how aging impacts green behavior at the farmer level. Second, the paper focuses primarily on crop farming and does not comprehensively cover other agricultural sectors, such as livestock farming. Future research could further utilize micro-level tracking data to explore the nonlinear effects of aging on farmers' green production behaviors under different intergenerational interaction patterns.

Data Availability

The datasets used and analysed in this study, covering 30 Chinese provinces from 2011 to 2024, together with the relevant variable definitions, data processing procedures, and Stata codes used for the empirical analyses, are provided as supplementary files accompanying this manuscript. These materials include the provincial panel dataset, data used to construct the agricultural green development index, and the code supporting the empirical analyses. The supplementary materials are available to the editors and reviewers for verification and replication of the reported findings.

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Supplementary Files

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- SupplementaryDataandCode.zip