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Population Shrinkage and Aging in Northeast China: Spatio-temporal Coupling, Regional Disparities, and Future Trends in Jilin Province

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Global urbanization and demographic transitions have led to a "dual compression" of population shrinkage and aging, posing severe challenges to sustainable regional development. Taking Jilin Province—a typical region with a shrinking population in northeast China—as a case study, this paper investigates the spatio-temporal evolution and coupling relationship of these two demographic phenomena at the county level from 2000 to 2020. Utilizing data from three National Population Censuses, we applied Pearson correlation analysis, the Dagum Gini coefficient, and the GM(1,1) Grey prediction model to quantify regional disparities and forecast future trends. The results indicate the following: (1) Jilin Province experienced accelerating population shrinkage and a significant deepening of aging, with the correlation coefficient between the two reaching 0.93 over the 2000–2020 period, exhibiting a high degree of coupling. (2) Spatially, shrinkage is concentrated in western agricultural areas and southeastern forestry regions, while aging shows a transition from "Mature" to "Aged III" types. (3) A decomposition analysis reveals that intra-group differences in aging levels are narrowing, whereas inter-group differences are intensifying. (4) The GM(1,1) model predicts that by 2030, Jilin's population will decline by another 12.46%, with the aging rate reaching 29.5%. This study provides critical empirical evidence and predictive insights for optimizing regional planning in regions where populations are shrinking.

Keywords Population shrinkage; Population aging; Spatio-temporal coupling; GM(1,1) Prediction; Northeast China

I. Introduction

Global urbanization and demographic transitions have brought deep structural shifts to contemporary society. Among these, population shrinkage and population aging have emerged as two closely interrelated demographic challenges, confronting many nations in Europe and Asia in the twenty-

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first century. Persistently low fertility, rising life expectancy, and massive labor migration have led to a “dual compression” of demographic decline and age-structure imbalance. Investigating how these two phenomena co-evolve is not only a core academic task for population geography but also a critical practical need for regional sustainable development.

This issue is highly relevant to contemporary Asian regional studies. Many Asian subregions are experiencing a transition characterized by internal migration, uneven regional development, and the weakening of peripheral areas. Within China’s regional demographic landscape, Northeast China—the country’s traditional old industrial base—provides a critical empirical site. As a typical shrinking province in this region, Jilin Province presents a stark demographic reality that is particularly representative of the dual pressures of population shrinkage and aging. Unlike the deindustrialization-driven shrinkage often observed in developed Western countries, shrinkage in Jilin is shaped by a combination of local factors, including industrial restructuring, administrative division adjustments, labor out-migration, and a relatively low-level industrial structure (Tong et al., 2020). According to the Seventh National Population Census, Jilin’s total population declined from 27.45 million in 2010 to 24.07 million in 2020—a decrease of nearly 13% over one decade—while the proportion of the population aged 65 and above rapidly climbed from 8.38% to 15.61%, indicating a significant deepening of population aging. This dramatic shift creates severe structural problems, including labor shortages, mounting social security pressure, an imbalance in public-service allocation, and intensified elderly-care burdens. Despite the growing body of literature on regional demographic change, existing studies often treat population shrinkage and aging as parallel or separate tracks, failing to examine their joint evolution within a single spatial analytical framework. Furthermore, prior research has focused heavily on prefecture-level cities or broad provincial scales, leaving a substantial research gap at the county scale, which serves as the key interface between urban and rural transformation. Retrospective historical analyses also dominate the literature, with fewer studies combining multi-period spatial analysis with predictive modeling to assess future demographic trajectories.

To address these gaps, this study establishes a concise, integrated framework to examine the spatio-temporal evolution, coupling relationship, regional disparity, and future trends of population shrinkage and aging at the county level in Jilin Province from 2000 to 2020. Utilizing authoritative data from the Fifth, Sixth, and Seventh National Population Censuses, we treat 47 county-level units as our basic analysis grid. Methodologically, Pearson correlation analysis is applied to identify the synchronization between shrinkage and aging; the Dagum Gini coefficient is used to decompose the structural sources of aging inequality across different shrinkage tiers; and the GM(1,1) Grey Prediction Model is employed to forecast the population size and aging trajectories for the 2021–2030 decade. By situating the county-level dynamics of Jilin within the broader context of Asian post-growth societies, this study offers new empirical insights into how administrative hierarchy, peripheralization, and structural economic decline reshape regional populations, providing a scientific basis for targeted "smart shrinkage" planning and public resource allocation.

II. Literature Review

Existing literature relevant to the joint evolution of demographic transition and spatial restructuring generally encompasses three interrelated strands, yet their theoretical fragmentation obscures the complex dynamics of regional decline.

1. Spatial Patterns and Conceptual Measurements of Regional Shrinkage

Researchers emphasize that demographic decline should be distinguished from broader, multidimensional urban shrinkage, which typically involves systemic employment contraction, fiscal stress, housing vacancy, and infrastructure underutilization (Martinez-Fernandez et al., 2012; Wolff and Wiechmann, 2018). Within the specific context of Northeast China, empirical studies have mapped a distinct "T-shaped" spatial pattern of localized population loss. This outflow has intensified notably over time, moving away from peripheral county-level units toward primary prefectural centers, accelerating with particular visibility after 2012 (You et al., 2021). Consequently, population shrinkage in this macro-region is increasingly recognized not as a short-term fluctuation, but as a systemic, structural process deeply intertwined with broader economic decline and weakening regional resilience (Ma et al., 2020).

2. Socio-Economic Consequences and Spatial Decoupling

Scholars highlight the necessity of moving beyond growth-oriented planning toward "smart shrinkage" strategies when traditional spatial expansion no longer matches demographic realities (Ma et al., 2020; Wang et al., 2021). In China's traditional northeastern rust belt, absolute population decline and rapid spatial contraction frequently co-occur, severely undermining local industrial productivity and structural innovation capacity (Xie et al., 2022). However, a critical spatial contradiction emerges within this process: despite ongoing demographic decline, empirical observations indicate that physical construction land in multiple non-core areas has paradoxically continued to expand. This creates a severe spatial decoupling between population dynamics and actual land development, intensifying acute structural mismatches between people and land resources (Wang et al., 2025).

3. The Spatial Drivers and Crises of Population Aging

Extensive research demonstrates that a rapidly aging profile exerts a profound inhibitory effect on regional economic performance by compressing the active labor supply and surging healthcare demands (Jarzebski et al., 2021; Yang and Qi, 2024). Yet, a theoretical fragmentation occurs when aging is treated merely as a parallel macroeconomic variable. In shrinking peripheral regions, population aging is not a passive biological transition; it is directly accelerated by the highly selective out-migration of young labor toward urban cores. This demographic drain leaves behind an immobilized, vulnerable "left-behind" elderly cohort, structurally transforming a general demographic shift into a severe spatial crisis of regional inequality.

4. Literature Summary and Research Gaps

Situating these intersecting crises within the broader context of Asian regional studies reveals a profound paradigm shift. While early literature drew heavily from Euro-American experiences of deindustrialization, urban shrinkage in East Asia is uniquely driven by a combination of ultra-low fertility, rapid super-aging, and extreme rural-to-urban population concentration (Nakatani, 2023). Therefore, directly transplanting Western frameworks is conceptually insufficient. Asian shrinking regions must simultaneously manage physical downsizing and confront the acute spatial injustices triggered by an unbalanced, super-aged demographic collapse.

Despite these comprehensive insights, a critical research gap remains unaddressed. Existing analyses largely treat population shrinkage, land-use decoupling, and population aging as parallel, separate tracks, failing to systematically examine their joint spatial evolution and temporal coupling within a unified analytical framework. When evaluated in isolation, it becomes exceedingly difficult to determine whether varying intensities of regional shrinkage correspond to distinct, path-dependent aging trajectories. Furthermore, it restricts our collective ability to identify how this spatial relationship varies across administrative hierarchies. Therefore, an integrated framework is urgently required to explicitly link absolute population change, age-structure transition, spatial differentiation, and future demographic trends at a finer, county-level scale. This study directly addresses these programmatic limitations by providing a joint, multi-method evaluation of a typical shrinking and aging peripheral region.

III. Data Sources and Research Methods

1. Study Area and Data Sources

China's administrative division system is hierarchically organized into four main levels: provincial, prefecture, county, and town. The provincial-level administrative divisions represent the highest tier of local governance and include municipalities directly under the Central Government, provinces, autonomous regions, and special administrative regions, with provinces being the most common type. Prefecture-level administrative divisions serve as the intermediate tier between the provincial and county levels, primarily comprising prefecture-level cities, regions, autonomous prefectures, and leagues. Among these, prefecture-level cities are highly urbanized areas that administer multiple subordinate county-level units. County-level administrative divisions constitute the foundational units of local administration, directly carrying out governance functions at the grassroots. They encompass a diverse range of forms, including municipal districts, county-level cities, counties, autonomous counties, as well as specialized types such as

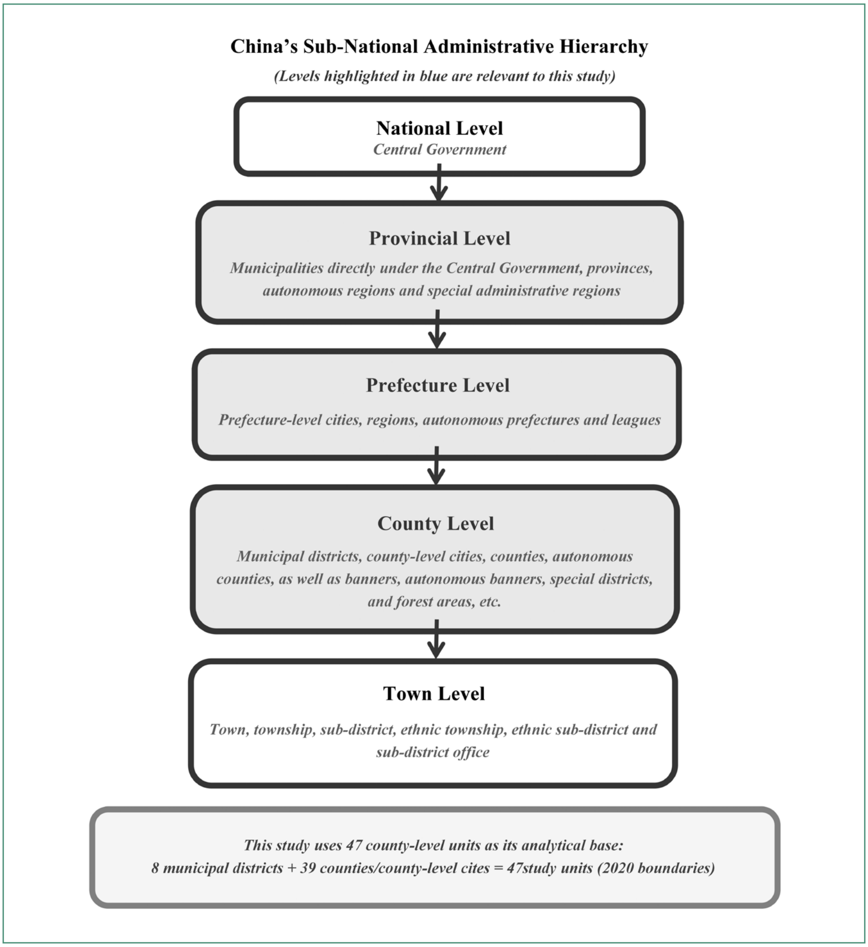

Figure 1 China's Sub-national Administrative Hierarchy

banners, autonomous banners, special districts, and forest areas. Town-level administrative divisions represent the most basic administrative units and mainly include towns, townships, and sub-district offices Figure 1.

To properly understand the empirical analysis at the county level, it is essential to clarify how the distinct types of county-level administrative divisions utilized in this study are distinguished from one another. Although municipal districts, county-level cities, and counties occupy the same administrative tier (the third level of China's sub-national hierarchy), they represent fundamentally different levels of urbanization, socioeconomic structures, and governance focus.

Municipal districts (Shixiaqu) are the core urban areas of prefecture-level cities. They exhibit the highest levels of industrialization, population density, and infrastructure development, with a governance focus primarily centered on urban management, industrial upgrading, and public service agglomeration. County-level cities (Xianjishi) are transitional territorial units with a high level of urbanization but a mixed urban-rural economy. They usually evolved from prosperous agricultural counties and function as sub-regional economic centers, managing both an urban core and a large surrounding rural hinterland. Counties (Xian) represent traditional agrarian and ecological regions where rural populations and agricultural production dominate, and their governance is heavily focused on rural development, primary industries, and basic public infrastructure. Distinguishing among these three types allows this study to capture how demographic trajectories diverge across different structural settings within the same administrative rank.

This study takes Jilin Province as its sample region. Based on the 2020 administrative divisions of Jilin Province, the research is segmented into 47 study units, comprising 8 municipal districts of prefecture-level cities (which represent the aggregated urban cores of their respective prefectures to maintain data consistency across censuses) and 39 counties and county-level cities.

According to data from the Fifth, Sixth, and Seventh National Population Censuses, the total population of Jilin Province increased by 650,000 (a 2.43% increase) between 2000 and 2010. However, during this period, 25 study units had already begun to enter a phase of population shrinkage. From 2010 to 2020, the total population of Jilin Province decreased from 27.45 million to 24.07 million, a decline of 12.31%. By this time, 93.62% of the research units in Jilin Province had entered the population shrinkage stage.

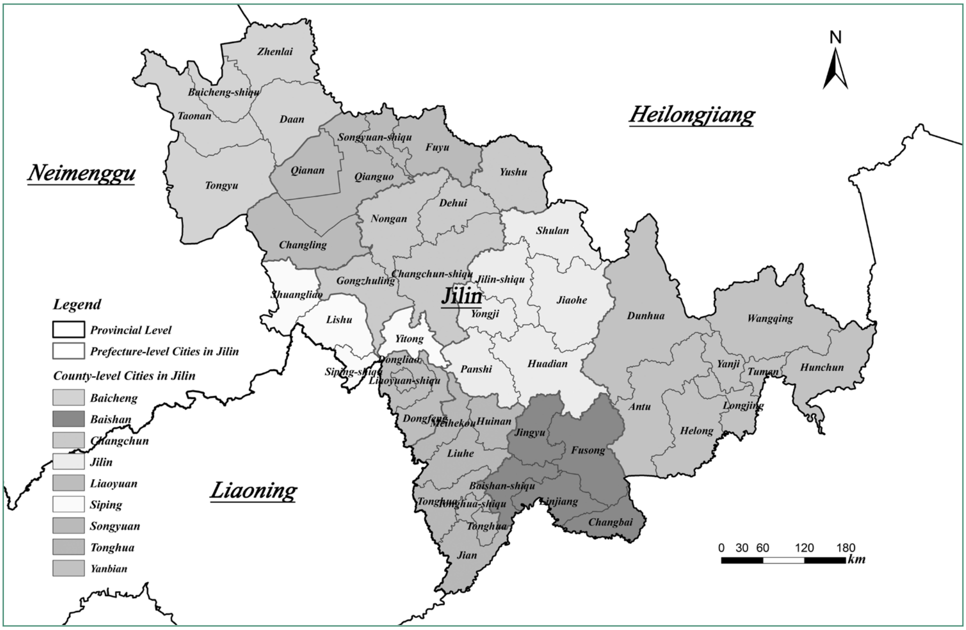

Figure 2 Study Area Map

In terms of population aging, in 2000, the proportion of the population aged 65 and over in Jilin Province was 6.04%, with only 6.38% of the study units classified as being in the aged stage. By 2010, this proportion rose to 8.38%, with 95.74% of the units entering the aged stage. As of 2020, the proportion of the population aged 65 and over had rapidly increased to 15.61%—a significant increase compared to 2010—and all 47 study units had entered the aged stage. Jilin Province has become a typical and severe example of population shrinkage and aging in China, exhibiting characteristics of comprehensive regional contraction. Therefore, selecting Jilin Province as the study area to investigate the dual spatio-temporal coupling relationship between population shrinkage and aging holds significant demonstrative value.

The demographic data for this study are primarily sourced from the Fifth

(2000), Sixth (2010), and Seventh (2020) National Population Censuses.

2. Research Methods

1) Pearson Correlation Analysis

This study utilizes Pearson correlation analysis to explore the correlation between the degree of population shrinkage and the growth of population aging:

$$R_{xy} = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{i=1}^{n}(y_i - \overline{y})^2}} \tag{1}$$

wherein R_{xy} represents the correlation coefficient between variable x and variable y; and x_i and y_i respectively represent the degree of population shrinkage and the growth rate of the population aging level in the i-th stage.

2) Dagum Gini Coefficient

This paper adopts the Dagum Gini coefficient (Dagum, 1997) to measure and analyze regional disparities in population aging levels across different shrinkage categories. Unlike the conventional Gini coefficient, which provides only a single measure of overall inequality, the Dagum approach decomposes the total Gini coefficient G into three additive components:

$$G = G_W + G_{nb} + G_t \tag{2}$$

Where G_W represents the within-group contribution, reflecting inequality within each shrinkage category; G_{nb} represents the net between-group contribution, capturing inequality caused by mean differences across groups; and G_t represents the transvariation density, indicating the overlap of distributions between groups. The contribution rate of each component can be evaluated as its share of the total Gini coefficient. This framework overcomes the limitations of traditional Gini or Theil indices in handling overlapping distributions (Dagum, 1997; Li et al., 2025).

For any two groups j and h ranked by mean aging level ($\mu_j \geq \mu_h$), the inter-group Gini coefficient G_{jh} is calculated as:

$$G_{jh} = \frac{\sum_{i=1}^{n_j} \sum_{r=1}^{n_h} |y_{ji} - y_{hr}|}{n_j n_h (\mu_j + \mu_h)} \tag{3}$$

Where y_{ji} and y_{hr} denote the aging levels of individual units in groups j and h, n_j and n_h are group sizes, The within-group Gini is computed analogously within each group.

3) GM(1,1) Grey Prediction Model

Grey prediction theory focuses on systems with small samples and incomplete information, making it particularly suitable for regional population forecasting where historical data may be inconsistent due to administrative boundary adjustments (Ju-Long, 1982). Caimei, L. et al. (2009) used this method to forecast China's population, and the prediction results were consistent with those of the United Nations. This fully demonstrates that GM(1,1) is an effective mathematical tool for population forecasting. In this study, GM(1,1) is employed to project both the total population and the level of population aging over the next ten years. The modeling procedure involves four main steps: first, Accumulated Generation Operation (AGO), transforming the original sequence into a monotonically increasing sequence $x^{(1)}$ to reduce randomness; second, establishing the core theoretical model, which is represented by the first-order linear differential equation (the whitening equation):

$$\frac{dx^{(1)}}{dt} + ax^{(1)} = b$$

where the parameter a is the development coefficient, reflecting the system's development trend, and b is the grey action quantity, representing the data relationships; third, parameter estimation, in which a and b are estimated via the Ordinary Least Squares (OLS) method; and fourth, prediction and inverse AGO, where the equation is solved to forecast values and inverse accumulation restores predictions to the original sequence. Model accuracy is evaluated using the posterior error ratio C and the small error probability P to ensure the reliability of forecasts.

3. Integrated Methodological Framework

Overall the methodological framework of this study is organized into five sequential steps: data collection and preprocessing, index construction, spatio-temporal pattern analysis, coupling and regional disparity analysis, and future trend prediction Figure 3. First, county-level demographic data for Jilin Province were obtained from the fifth, sixth, and seventh national population censuses, together with relevant statistical yearbooks, and were standardized to ensure comparability across different periods. Second, two core indicators were constructed to measure population shrinkage and population aging, namely the population change rate and the population aging rate. Third, descriptive statistics, classification analysis, and GIS-based spatial visualization were used to examine the temporal evolution and spatial distribution of population shrinkage and aging at the county level.

Based on the above results, Pearson correlation analysis was further applied to identify the association between population shrinkage and population aging. Coupling relationship analysis was then used to examine the interaction between the two demographic processes, while the Dagum

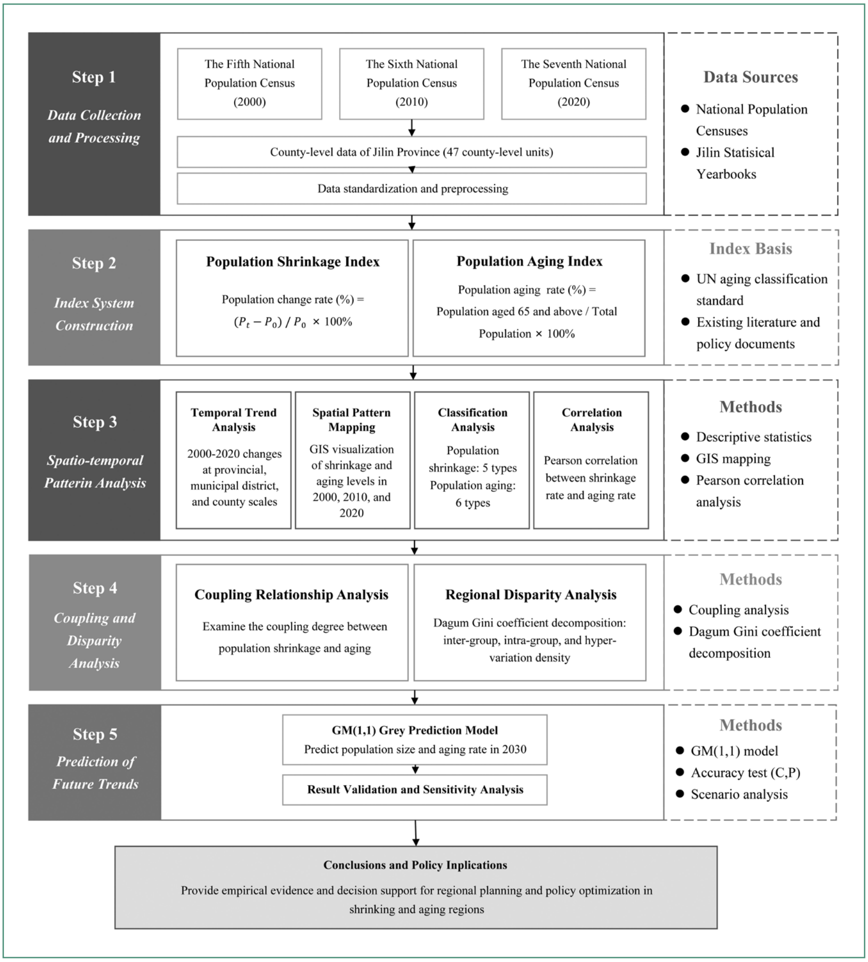

Figure 3 Methodological Framework

Gini coefficient decomposition was employed to reveal regional disparities in population aging among different shrinkage categories. Finally, the GM(1,1) grey prediction model was used to predict future changes in population size and population aging level, and model accuracy was evaluated using the posterior error ratio and small error probability.

IV. Spatio-temporal Pattern Characteristics of Population Shrinkage and Population Aging

1. Spatio-temporal Pattern Characteristics of Population Shrinkage

This study analyzes the dynamic changes in population shrinkage and population aging at three scales—provincial, municipal district, and county level—across three time periods: 2000–2020, 2000–2010, and 2010–2020. Referencing domestic and international classification standards, population shrinkage is categorized into five types: population growth (>0%), mild shrinkage ((-10%, 0]), moderate shrinkage ((-20%, -10%]), heavy shrinkage ((-30%, -20%]), and severe shrinkage (<= -30%). The detailed shrinkage measurements are presented in Table 1 and Table 2, and the spatial pattern of population shrinkage is illustrated in Figure 4.

Overall Table 1, the population size of Jilin Province exhibited a significant shrinkage trend from 2000 to 2020. The degree of shrinkage intensified notably at all scales, particularly at the county level, which became the primary units of population loss. From 2000 to 2010, Jilin's population scale still showed a growth trend; the population in municipal districts increased by 6.08%, while the county-level population experienced a slight decline (-2.72%), indicating significant population mobility between urban and rural areas. However, from 2010 to 2020, Jilin Province entered a comprehensive shrinkage phase. County-level shrinkage exacerbated significantly, reaching

Table 1 Population Shrinkage Degree (%) at Different Spatial Scales by Period

Scale	2000-2020	2000-2010	2010-2020
Province	-10.18102587	2.427503035	-12.30971032
Municipal districts	6.081196043	10.22866349	-4.339984562
County	-27.03456421	-2.721410679	-25.47186272

Table 2 Changes in Unit Count and Shrinkage Degree by Population Shrinkage Type and Period

Shrinkage Type	2000-2020			2000-2010			2010-2020		
	Unit Count	Proportion (%)	Shrinkage Degree (%)	Unit Count	Proportion (%)	Shrinkage Degree (%)	Unit Count	Proportion (%)	Shrinkage Degree (%)
Growth	5	10.64	49.64	22	46.81	8.94	3	6.38	28.94
Mild shrinkage	3	6.38	-2.21	17	36.17	-3.04	4	8.51	-3.01
Moderate shrinkage	5	10.64	-10.42	7	14.89	-12.02	8	17.02	-16.05
Heavy shrinkage	14	29.79	-26.58	0	0	0	18	38.30	-25.16
Severe shrinkage	20	42.55	-35.86	1	2.13	-50.57	14	29.79	-34.13

-25.47%, making counties the primary source of the province-wide population decline. Although municipal districts demonstrated a smaller shrinkage magnitude, this still suggests that their population agglomeration effect, driven by urbanization, is gradually weakening. This indicates a trend of population shrinkage diffusing from rural to urban areas. In the future, mitigating population shrinkage through industrial diversification, improving the regional economic environment, and optimizing population policies will be a critical challenge for Jilin Province.

Analyzing the distribution of different population shrinkage types Table 2, 42 study units (89.36% of the total) experienced population shrinkage from 2000 to 2020. Among these shrinking units, 80.95% reached heavy or severe shrinkage levels. During the 2000–2010 period, growth-type units accounted for 46.81% of the total, while mild-shrinkage units accounted for 36.17%. In this phase, population loss had not yet shown a significant acceleration trend, and overall population mobility was moderate, primarily concentrated in the outflow of agricultural labor and the unidirectional flow typical of initial urbanization. The 2010–2020 period was a crucial transition period,

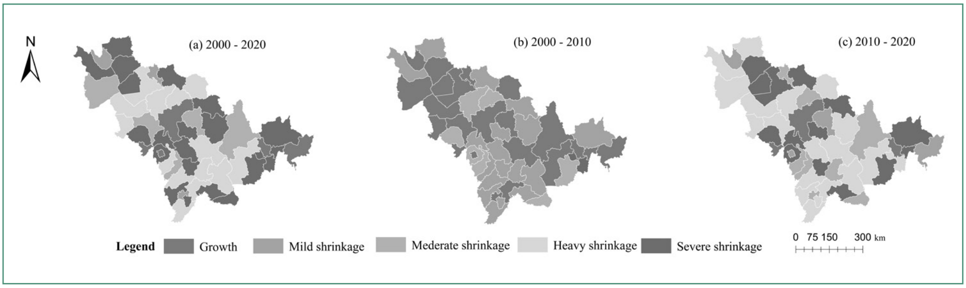

Figure 4 Spatial Differentiation of Population Shrinkage

marked by a shift from growth-type and mild-shrinkage units to moderate-, heavy-, and severe-shrinkage units. In this stage, 44 study units experienced population shrinkage; heavy- and severe-shrinkage units increased rapidly, accounting for 38.30% and 29.79% of the total, respectively. Compared with the previous period, the combined number of heavy- and severe-shrinkage units increased from 1 to 32. This accelerated population shrinkage is closely related to slow economic structural transformation, reduced employment opportunities, and intensified out-migration from resource-based regions.

Regarding the spatial differentiation of regional population shrinkage Figure 4, the high-value areas (hotspots) of shrinkage are primarily located in the western part of Jilin Province, such as Baicheng and Songyuan. This region has long relied on agriculture and animal husbandry, possessing a monolithic industrial structure. With the advancement of agricultural modernization, a large-scale outflow of rural labor occurred, increasing the number of migrant workers. Furthermore, this area has relatively poor natural conditions and low land resource utilization rates, which has accelerated population shrinkage. The southeastern areas, such as Yanbian, Tonghua, and Baishan, are typical forestry resource-based regions. Due to the implementation of national ecological protection policies, forestry resource development has been restricted. Compounded by difficulties in industrial transition, this has led to tepid economic growth and severe population outflow, making these areas typical zones of heavy and severe shrinkage. In contrast, the more developed central cities of Changchun and Jilin, along with their surrounding municipal districts, exhibited a strong capacity for population absorption, becoming low-value areas (coldspots) of shrinkage. This is because Changchun, as the provincial political, economic, and cultural center, possesses comprehensive public service resources, including education and healthcare. Jilin City, as the second most developed city in the province, also has leading economic and service resources. Consequently, they exert a strong "siphon effect" on surrounding counties, attracting continuous population inflow and forming spatial characteristics distinct from the surrounding counties. The eastern border city, Hunchun, benefits from its locational advantages and policy advantages in foreign trade and cross-border economic cooperation. As a result, its population shrinkage has been relatively mild, forming a localized growth-type or mild-shrinkage-type area.

In terms of temporal changes, from 2000 to 2010, population shrinkage in Jilin Province was mainly concentrated in the central-northern and southeastern resource-based regions. However, from 2010 to 2020, as urbanization accelerated and regional economic development became more unbalanced, the western agricultural areas and the southeastern forestry areas emerged as the regions experiencing the most severe population shrinkage.

2. Spatio-temporal Pattern Characteristics of Population Aging

This study adopts the United Nations' population aging classification standard, utilizing the percentage of the population aged 65 and over relative to the total population to characterize the degree of population aging. The levels of population aging are classified into six types for

Table 3 Population Aging Level and Change (%) in Jilin Province by Scale and Period

Scale	Aging Level-2000	Aging Level-2010	Aging Level-2020	Growth Rate 2000-2020	Growth Rate 2000-2010	Growth Rate 2010-2020
Province	6.04	8.38	15.61	132.00	42.03	63.35
Municipal districts	6.38	8.87	14.35	182.05	56.33	80.42
County	5.88	8.10	16.64	106.92	34.29	54.08

Table 4 Change in Unit Count by Population Aging Type

Type	2000		2010		2020	
	Unit Count	Proportion (%)	Unit Count	Proportion (%)	Unit Count	Proportion (%)
Youthful	0	0.00	0	0.00	0	0.00
Mature I	11	23.40	0	0.00	0	0.00
Mature II	33	70.21	5	10.64	0	0.00
Aged I	3	6.38	32	68.09	0	0.00
Aged II	0	0.00	10	21.28	3	6.38
Aged III	0	0.00	0	0.00	44	93.62

reference analysis: Youthful (0, 4%], Mature I (4%, 5.5%], Mature II (5.5%, 7%], Aged I (7%, 10%], Aged II (10%, 14%], and Aged III (> 14%). The detailed measurements of population aging are presented in Table 3 and Table 4, and the spatial pattern of aging levels is illustrated in Figure 5.

From a general perspective across different scales Table 3, the characteristics of population aging in Jilin Province exhibit significant differentiation and evolutionary patterns at the provincial, municipal district, and county scales. At the provincial scale, the overall aging level has undergone a significant climb, rising from 6.04% in 2000 to 8.38% in 2010, and then rapidly increasing to 15.61% by 2020. This change reflects the profound adjustment of the demographic structure against the backdrop of Jilin's socio-economic transformation. Since the end of the 20th century, the province has experienced a rapid transition from

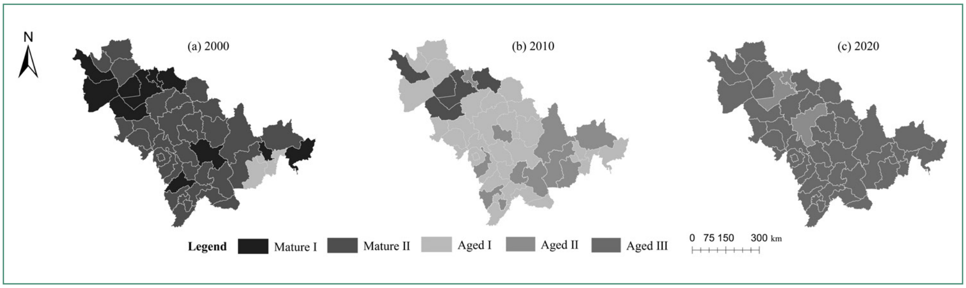

Figure 5 Spatial Differentiation of Population Aging

industrialization to urbanization, where the accelerated flow of young and middle-aged labor from rural areas to municipal districts has led to a rapid increase in the overall provincial aging rate. Furthermore, persistently low fertility rates and a continuous decline in the natural population growth rate have accelerated the rise in aging levels. At the municipal district scale, population aging demonstrates dual characteristics of rapid growth and spatial agglomeration. Although municipal districts serve as economic centers with concentrated resources, the phenomenon of "aging in place" is particularly prominent, making the structural transition toward an aging population evident. The aging level in municipal districts rose from 6.38% in 2000 to 14.35% in 2020. While industrial upgrading in urban areas has attracted some population, a large number of migrant laborers are progressively entering the aging stage, further exacerbating aging pressure. At the county scale, population outflow is the key factor accelerating aging. Between 2000 and 2020, massive out-migration of the labor force, coupled with lagging economic development and underdeveloped infrastructure, resulted in a resource deficit for the elderly. This caused the county-level aging level to rise from 5.88% to 16.64%, creating a vicious cycle of "population out-migration—resource deficit—intensified aging."

Regarding the transition between different population aging types Table 4, Jilin Province experienced a significant phased evolution and spatial diffusion from 2000 to 2020. In 2000, the aging types were dominated by Mature I and Mature II, accounting for 23.4% and 70.21% respectively, with a relatively balanced spatial distribution. By 2010, influenced by declining natural growth rates and labor out-migration, the aging types transformed rapidly; the number of Aged I units increased significantly, particularly in the southeastern and central regions, demonstrating a trend of spatial diffusion. By 2020, the population aging types had comprehensively shifted towards Aged II and Aged III, and the range of high-value aging areas expanded significantly. This transformation process reveals that population aging in Jilin has shifted from a low-level, balanced distribution to a high-level, agglomerated development, reflecting the complex socio-economic context of population migration and unbalanced regional economic development.

In terms of spatial differentiation Figure 5, the overall pattern is characterized by intensifying spatial agglomeration and significant regional differentiation. As shown in the spatial distribution maps, Jilin's overall aging level in 2000 was low and relatively balanced, reflecting a youthful demographic structure during the early industrialization phase. By 2010, high-value aging areas gradually emerged in the southeastern and central regions, influenced primarily by industrial transformation and rural population out-migration. By 2020, population aging entered a stage of comprehensive deepening. The northeastern and southeastern regions became core agglomeration zones for aging, with levels widely entering the Aged III stage. High-value areas became highly concentrated, especially in resource-depleted cities and agricultural economic zones where demographic imbalances overlap with regional development predicaments. In contrast, some municipal districts and border areas in the central and western parts exhibited lower aging levels, presenting a "low-value mosaic" characteristic due to relatively higher population inflow and economic vitality. Overall, the spatial pattern of population aging in Jilin exhibits an evolutionary trend from a balanced distribution to an agglomeration in core high-value areas, with spatial disparities clearly widening between the southeast/northeast and other regions.

V. Analysis of the Spatio-temporal Coupling Relationship between Population Shrinkage and Population Aging

1. Overall Correlation Characteristics

To explain the intrinsic correlation between the degree of population shrinkage and the growth of the population aging level, this study defines population shrinkage and the growth of aging as positive values, and their opposites as negative values. Pearson correlation analysis was employed to systematically analyze these two factors (results in Table 5).

The findings indicate a significant positive correlation between the degree of population shrinkage and the growth of the aging level; the correlations in all periods passed the significance test at the 1% level. Analyzing the evolutionary trend, the correlation coefficient for 2000–2010 was 0.758. This suggests that during this period, some areas in Jilin began to show synchronous trends in shrinkage and aging growth, but the overall relationship had not yet reached a high degree of coupling. From 2010–2020, although the coefficient slightly decreased to 0.695, it remained at a high level, reflecting the persistent impact of accelerating population shrinkage on aging. In the long-term 2000–2020 dimension, the correlation coefficient reached 0.93, demonstrating a highly synchronous coupling relationship between population shrinkage and aging growth. This rapid evolution of the population structure has become one of the core challenges for regional development.

Table 5 Pearson Correlation Results between Population Shrinkage Degree and Population Aging Level Growth

Period	2000-2010	2010-2020	2000-2020
Pearson Correlation Coefficient	0.758	0.695	0.930
Significance Level (p-value)	0.000	0.000	0.000

To further examine the relative development relationship between population shrinkage and aging, this study classifies the 47 research units into five categories based on the relative development ratio x, defined as

$$x = P_{shrink} / P_{aging} \tag{4}$$

where P_{shrink} denotes the absolute population shrinkage rate (%) and P_{aging} represents the growth rate of the aging population (%) over the same period. A positive x indicates that shrinkage and aging increase in the same direction (positive coupling), whereas a negative x suggests divergence between the two processes. The five grades are defined as follows: Low Positive ($0 < x \leq 0.1$), Moderate Positive ($0.1 < x \leq 0.2$), High Positive ($x > 0.2$), Low Negative ($-0.1 \leq x < 0$), and Moderate Negative ($x < -0.1$) Table 6. The results reveal a significant increase in positively correlated units. From 2000–2010, there were 9 low positive, 6 moderate positive, and 10 high positive correlation units. By 2010–2020, as population outflow and declining natural growth rates intensified, the number of high positive correlation units rapidly increased to 38, indicating that the spatial coupling relationship between population shrinkage and aging growth was further strengthened. Conversely, the number of negatively correlated units decreased significantly. The count of low negative correlation units dropped from 12 in 2000–2010 to just 1 in 2010–2020, suggesting that population-growth-type regions are progressively diminishing and that accelerated aging has now covered almost all regions.

Spatially Figure 6, the relationship between population shrinkage and

Table 6 Distribution of Units by Relative Development Type of Population Shrinkage and Aging Growth

Relative Development Type	Grade (Ratio x)	2000-2010	2010-2020	2000-2020
Positive Correlation	Low Positive (0,0.1]	9	3	4
	Moderate Positive (0.1,0.2]	6	3	8
	High Positive (x>0.2)	10	38	30
Negative Correlation	Low Negative [-0.1,0]	12	1	2
	Moderate Negative (x<-0.1)	10	2	3

aging growth in Jilin Province exhibits significant regional differentiation. In the southeastern region, such as Baishan City and Tonghua City, which are constrained by aging industrial structures and resource depletion, population outflow is particularly severe, and their aging problems are the most prominent. In contrast, central cities like Changchun City and Jilin City, as the province's economic core, still attract some young labor due to urban development (despite some population return flow). However, these cities also face severe aging challenges. Changchun, in particular, shows clear "central aging" (or "aging at the core") characteristics: although its population remains relatively stable, the proportion of the elderly population continues to rise. This indicates that even with high economic attractiveness, the aging problem is intensifying with social development, especially in the face of labor shortages and mounting social security pressure. Additionally, the border port city of Hunchun, benefiting from an export-oriented economy, experiences high population mobility. This attraction of an external population has resulted in a relatively slower aging level. However, as economic globalization deepens, despite high mobility, the city must prepare to address structural issues within its migrant population. A potential demographic imbalance—especially a disequilibrium in the labor structure and aging levels—is highly likely and poses a potential risk to

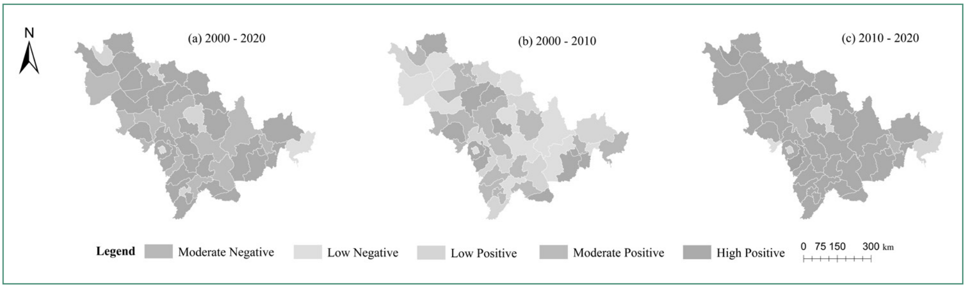

Figure 6 Spatial Differentiation of the Relative Development between Population Shrinkage Degree and Population Aging Level Growth

local economic and social development.

2. Characteristics of Population Aging Across Different Shrinkage Types

Population shrinkage levels are classified into types for three distinct periods: 2000–2020, 2000–2010, and 2010–2020. The population aging types corresponding to these different shrinkage types and periods are then analyzed Table 7, Table 8, and Table 9. Overall, the population aging level for all shrinkage types demonstrates an evolutionary trend from the Mature type toward the Aged III type. The aging level in any subsequent period is consistently higher than in the preceding period.

However, a clear positive correlation was not observed in all periods; only during 2010–2020 did the growth rate of aging accelerate as the degree of shrinkage intensified. This indicates that while the degree of population shrinkage influences the growth of population aging to a certain extent, it is not a simple linear positive relationship. This relationship is likely influenced by multiple factors, such as the level of regional economic development, industrial structure adjustments, and the directionality of population flows.

From the perspective of shrinkage types defined by the 2000–2020 period, population aging levels show a concentration, evolving from the

Table 7 Population Aging Level and Unit Count Distribution by Different Shrinkage Types (2000–2020)

Shrinkage Type	2000				2020				Growth Rate 2000–2020 (%)
	Aging Level (%)	Unit Count			Aging Level (%)	Unit Count			
		Youthful	Mature	Aged I		Aged I	Aged II	Aged III	
Population growth	6.41	0	5	0	13.45	0	1	4	109.83
Mild shrinkage	5.42	0	3	0	15.30	0	1	2	182.29
Moderate shrinkage	6.36	0	5	0	16.57	0	0	5	160.53
Heavy shrinkage	5.66	0	14	0	16.36	0	1	13	189.05
Severe shrinkage	6.09	0	17	3	17.58	0	0	20	188.67
Maximum Difference	0.99				4.13				79.22

Table 8 Population Aging Level and Unit Count Distribution by Different Shrinkage Types (2000–2010)

Shrinkage Type	2000				2010				Growth Rate 2000–2010 (%)
	Aging Level (%)	Unit Count			Aging Level (%)	Unit Count			
		Youthful	Mature	Aged I		Mature	Aged I	Aged II	
Population growth	6.05	0	21	1	8.44	5	12	5	39.50
Mild shrinkage	5.93	0	17	0	8.32	0	14	3	40.30
Moderate shrinkage	6.09	0	6	1	8.03	0	6	1	31.80
Severe shrinkage	8	0	0	1	12.84	0	0	1	60.50
Maximum Difference	2.07				4.81				28.64

Mature type to the Aged III type. The aging problem is most prominent in the shrinkage-type regions. In 2000, there were 44 Mature type units, accounting for 93.62% of the total. The units already in the Aged I stage (Tumen City, Longjing City, and Helong City) are all located in the Yanbian Korean Autonomous Prefecture. Since the 1990s, these resource-depleted and border cities have suffered from insufficient population attractiveness. Relying on linguistic advantages, the young labor force migrated to central cities and overseas, resulting in significant net population outflow. This left behind a "left-behind population" (relict population) dominated by the elderly, accelerating the societal transition into an aged stage. By 2020, 44 research

Table 9 Population Aging Level and Unit Count Distribution by Different Shrinkage Types (2010–2020)

Shrinkage Type	2010				2020				Growth Rate 2010–2020 (%)
	Aging Level (%)	Unit Count			Aging Level (%)	Unit Count			
		Youthful	Mature	Aged I		Aged I	Aged II	Aged III	
Population growth	8.38	0	3	0	13.23	0	1	2	57.88
Mild shrinkage	9.70	0	2	2	16.41	0	0	4	69.18
Moderate shrinkage	8.19	1	6	1	16.07	0	1	7	96.21
Heavy shrinkage	8.22	2	13	3	16.73	0	0	18	103.53
Severe shrinkage	8.03	2	8	4	17.22	0	1	13	114.45
Maximum Difference	1.67				3.99				56.57

units (93.62% of the total) had entered the Aged III stage. Over these 20 years, the statistical range (max-min difference) of aging levels increased from 0.99% to 4.13%, expanding by more than fourfold.

During the 2000–2010 period, the aging types in Jilin Province primarily transitioned from the Mature type to the Aged I type, indicating an initial stage of aging. In 2000, there were 44 Mature type units (93.62% of the total); by 2010, there were 32 Aged I type units, accounting for 68.09%. During the 2010–2020 period, the aging types began to shift from the Aged I type to the Aged III type, marking a significant acceleration in the aging process.

During the long-term period of 2000–2020 and the accelerated shrinkage stage of 2010–2020, the population-growth type maintained the lowest aging growth rate. However, during 2000–2010, the moderate-shrinkage type showed the lowest aging growth rate, indicating that the relationship between shrinkage and aging was not strictly linear in the early stage. This is because these regions, represented by Changchun City, possess stronger economic vitality and population absorption capacity, which alleviates some of the aging pressure. Comparing the two development stages (2000-2010 and 2010-2020), both population shrinkage and aging levels exhibit an accelerating trend. Based on the 2000–2020 shrinkage classification, all severe-shrinkage units had entered the Aged III stage by 2020, demonstrating a clear characteristic of spatial consistency.

3. Regional Differences in Population Aging Levels Across Different Shrinkage Types

To further examine the disparities in population aging levels across different shrinkage types from 2000 to 2020, this study employs the Dagum Gini coefficient to measure the overall inequality of population aging, intra-group differences within each shrinkage type, inter-group differences between different shrinkage types, trans-variation density, and their respective contribution rates. Table 10 reports the intra-group disparities in population aging and their contribution rates across different shrinkage categories. Overall, except for the population-growth type, the intra-group differences within all shrinkage types showed a downward trend over the two decades, indicating that regional population aging gradually shifted from spatial differentiation toward relative convergence and more balanced development. However, this process was not linear and exhibited clear stage-specific characteristics. From 2000 to 2010, intra-group differences increased across all shrinkage types, reflecting the uneven spatial effects of early-stage labor outmigration. In contrast, from 2010 to 2020, intra-group disparities declined markedly, suggesting that the gaps in aging levels among counties within the same shrinkage category had achieved significant convergence. Notably, the increase in population aging during 2010–2020 was substantially faster than that during 2000–2010, further indicating an increasingly consistent spatial relationship between the degree of population shrinkage and the level of population aging.

The decomposition results further reveal that this pattern of aging disparity is shaped by two interrelated mechanisms. First, the narrowing of intra-group differences, particularly the decline in intra-group Gini values across nearly all shrinkage categories between 2010 and 2020, is consistent with a path-dependency mechanism. Once counties within the same shrinkage category experience sustained labor outmigration and the weakening or exhaustion of endogenous growth capacity, they tend to converge toward similar trajectories of structural decline, characterized by declining fertility, accelerating elderly shares, and eroding local fiscal capacity. This process produces demographic homogenization within the same shrinkage tier, not because development conditions improve uniformly, but because deterioration follows similar institutional and economic logics. From the perspective of evolutionary economic geography, this reflects a lock-in effect: peripheral localities lacking institutional thickness, diversified industrial foundations, and agglomeration economies are increasingly constrained to parallel "homogeneous decline paths," thereby reducing the possibility of divergent demographic recovery within the same shrinkage category.

Second, the changing structure of contribution rates points to a simultaneous intensification of inter-group differentiation. Specifically, both the intra-group contribution rate and the contribution of trans-variation density showed a fluctuating decline, whereas the inter-group contribution rate exhibited a fluctuating upward trend, rising sharply from 21.29% in 2010 to 60.23% in 2020. This indicates that aging disparities are increasingly shaped by structural differences between shrinkage types rather than by heterogeneity within the same type. Such a pattern can be interpreted through a core–periphery framework. Under China's hierarchical administrative system, higher-order cities, particularly prefecture-level cities and above, generally possess stronger access to fiscal transfers, infrastructure investment, employment opportunities, and public service provision, which enable them to retain younger populations and moderate aging pressures. By contrast, counties experiencing heavy or severe shrinkage—often located in resource-depleted forestry zones and remote agricultural areas—occupy a peripheral position within the administrative and economic hierarchy and continue to lose young labor to urban cores. This "administrative siphon effect" has therefore made administrative rank and development capacity increasingly important axes of demographic stratification, amplifying the structural polarization of aging across shrinkage categories.

Meanwhile, although the contribution of trans-variation density declined slightly, its persistently high level suggests the existence of a boundary-dissolution mechanism. In other words, population aging no longer follows fixed administrative boundaries; rather, the demographic crisis associated with shrinkage spills across traditional territorial divisions, causing the aging trajectories of core and peripheral areas to overlap and interact. This further confirms the spatial consistency between the degree of population shrinkage and the level of population aging: while aging differences within the same shrinkage type are gradually converging, differences between different shrinkage types are becoming increasingly pronounced.

Table 11 further illustrates the inter-type differences in population aging levels from 2000 to 2020. The results show that disparities between different shrinkage types changed continuously across 2000, 2010, and 2020. As Jilin Province underwent rapid urbanization and economic restructuring, spatial polarization in demographic aging became increasingly evident. Based on the mean values over the three years, the largest inter-type differences were observed in the pairings of "Mild Shrinkage vs. Severe Shrinkage," "Growth Type vs. Severe Shrinkage" and "Heavy Shrinkage vs. Severe Shrinkage" These results highlight the extreme aging characteristics of severely shrinking regions and visually map a highly polarized "Matthew Effect" in regional vitality. Taken together, the findings from Tables 10 and 11 indicate that the spatial dynamics of aging in Jilin Province are not merely

Table 10 Intra-group Differences in Population Aging Levels and Contribution Rates Across Shrinkage Types

Year	Overall G	Intra-group Differences (Gini)					Contribution Rate (%)		
		Growth	Mild Shrink-age	Moderate Shrinkage	Heavy Shrinkage	Severe Shrinkage	Intra-group	Inter-group	Trans-variation Density
2000	0.067	0.044	0.08	0.061	0.049	0.069	27.820%	36.680%	35.497%
2010	0.097	0.053	0.093	0.081	0.088	0.106	30.268%	21.290%	48.442%
2020	0.056	0.049	0.052	0.026	0.044	0.042	22.687%	60.229%	17.084%

Table 11 Differences in Population Aging Levels Between Different Shrinkage Types (Inter-type Differences)

Comparison Group	2000	2010	2020	Mean Value
Growth & Mild Shrinkage	0.076	0.084	0.056	0.0720
Growth & Moderate Shrinkage	0.057	0.073	0.053	0.0610
Growth & Heavy Shrinkage	0.057	0.082	0.062	0.0670
Growth & Severe Shrinkage	0.063	0.087	0.095	0.0817
Mild Shrinkage & Moderate Shrinkage	0.084	0.092	0.051	0.0757
Mild Shrinkage & Heavy Shrinkage	0.072	0.098	0.058	0.0760
Mild Shrinkage & Severe Shrinkage	0.092	0.108	0.083	0.0943
Moderate Shrinkage & Heavy Shrinkage	0.066	0.091	0.037	0.0647
Moderate Shrinkage & Severe Shrinkage	0.069	0.098	0.058	0.0750
Heavy Shrinkage & Severe Shrinkage	0.069	0.104	0.058	0.0770

descriptive demographic outcomes, but the observable results of deeply embedded institutional and economic processes operating simultaneously within and across shrinkage categories. They also underscore the urgent need for targeted "smart shrinkage" interventions to address the dual pressures of population loss and accelerated aging in structurally depleted peripheral counties.

VI. Prediction of Trends in Population Size and Population Aging Level

Based on the foundational demographic data from 2010 to 2020,[1] this study employs the GM(1,1) Grey Prediction Model to forecast population size and aging levels for both China and Jilin Province for 2021–2030. Four separate GM(1,1) models are estimated: (1) national total population, (2) national aging level, (3) Jilin total population, and (4) Jilin aging level. Model goodness-of-fit is validated via the posterior error ratio C (ratio of residual standard deviation to original data standard deviation) and the small error probability P (proportion of residuals within 0.6745 standard deviations of the mean residual). The C values are 0.0144, 0.0132, 0.0101, and 0.0191 for the four models respectively, all well below the Grade I (excellent) threshold of 0.35; the P values are all 1.0, substantially exceeding the Grade I threshold of 0.95. These statistics confirm excellent model fit and high forecast reliability. The results are presented in Table 12.

The results indicate that over the next decade, the national population will experience slight growth, with a projected increase of 5.8% compared to 2020. The national population aging level is expected to continue rising, increasing by 50.37% compared to 2020 to reach 20.3%.

In contrast, Jilin Province is projected to show a trend of continuous decline. The total population will shrink further; by 2030, the population is expected to decrease by approximately 3 million compared to 2020, representing a decline of 12.46%. The provincial population aging level will consistently remain higher than the national average and exhibit a continuous upward trend. By 2030, the aging level in Jilin is projected to

1 [Except for the data from 2010 and 2020, all other data are sourced from the annual statistical yearbooks of Jilin Province, China.

Table 12 Prediction of Population Size and Population Aging Level for China (National) and Jilin Province (2021–2030)

Prediction Year	National Total Population (×104persons)	National Aging Level (%)	Jilin Total Population (×104persons)	Jilin Aging Level (%)
2021	142549.794	13.7	2383.396	16.9
2022	143295.891	14.4	2350.139	18.0
2023	144045.892	15.0	2317.346	19.1
2024	144799.819	15.7	2285.011	20.3
2025	145557.692	16.4	2253.127	21.6
2026	146319.532	17.1	2221.688	23.0
2027	147085.359	17.8	2190.688	24.5
2028	147855.194	18.6	2160.120	26.1
2029	148629.059	19.5	2129.979	27.7
2030	149406.974	20.3	2100.258	29.5

reach 29.5%, an increase of 88.28%.

When combining the actual population size and aging levels for the nation and Jilin Province from 2021 to 2023, the overall predicted values are relatively accurate. However, the rate of the national total population change is slower than predicted. This may be because China's population quantity has already reached its peak (Chen, 2022) and the country is facing the issue of a low national fertility rate; consequently, the overall population trend may level off or even decline. Conversely, the aging level has risen faster than predicted; by 2023, the national population aging level had already reached 15.3%.

Regarding Jilin Province, the magnitude of population shrinkage in 2021 and 2022 was basically consistent with the prediction. However, by 2023, the total population of Jilin Province was 23.394 million. While this single data point does not confirm a trend reversal, it hints at a possible deceleration or short-term fluctuation in the shrinkage trajectory—a development that warrants close attention and verification with future census data.

VII. Discussions and Conclusions

Based on data from the 2000, 2010, and 2020 National Population Censuses, this study examined the spatio-temporal evolution, coupling relationship, regional disparity, and future trends of population shrinkage and aging at the county level in Jilin Province. By integrating Pearson correlation analysis, the Dagum Gini coefficient, and the GM(1,1) Grey Prediction Model, the study provides a systematic understanding of how demographic decline and age-structure change have jointly reshaped a typical shrinking region in Northeast China.

The results show that Jilin Province has shifted from localized population decline to comprehensive and structural shrinkage. Although the provincial population still increased slightly between 2000 and 2010, many county-level units had already begun to shrink. After 2010, population decline accelerated: the total population decreased from 27.45 million in 2010 to 24.07 million in 2020, while the proportion of people aged 65 and above rose from 8.38% to 15.61%. Spatially, population shrinkage was mainly concentrated in western agricultural areas and southeastern forestry and resource-based regions, where aging also deepened rapidly.

Correlation analysis confirms the close relationship between population shrinkage and aging. The Pearson correlation coefficient reached 0.93 for the overall 2000–2020 period, indicating a strong long-term coupling relationship. This high correlation reflects the cumulative effects of youth out-migration, declining fertility, and age-structure imbalance. In many counties, the outflow of young and working-age populations has weakened demographic reproduction capacity, while the remaining population has become increasingly older, forming a self-reinforcing cycle between shrinkage and aging.

The Dagum Gini decomposition further shows that intra-group disparities in aging within the same shrinkage type have narrowed, while inter-group disparities between different shrinkage types have become more prominent. This suggests that counties within the same shrinkage category are converging toward similar aging trajectories, whereas the gap between lightly shrinking, heavily shrinking, and severely shrinking areas is widening. Therefore, aging inequality in Jilin Province is increasingly shaped by structural differences in regional development.

Overall, the coupling between population shrinkage and aging in Jilin Province is deeply embedded in broader regional development mechanisms. As part of China's old industrial base, Jilin has long faced industrial restructuring, limited employment opportunities, and the decline of resource-dependent local economies. Meanwhile, administrative resources, public services, and employment opportunities have become increasingly concentrated in central cities such as Changchun and Jilin City. This core–periphery structure has intensified youth out-migration from peripheral counties and accelerated aging in agricultural, forestry, and resource-depleted areas. More broadly, the case of Jilin Province provides a useful reference for understanding demographic restructuring in East Asian old industrial and peripheral regions. Similar to Japan's peripheral municipalities and South Korea's non-metropolitan regions, Jilin Province faces the combined pressures of low fertility, youth out-migration, regional concentration of resources, and rapid population aging. These shared challenges indicate that population shrinkage and aging are not isolated demographic events, but are closely associated with regional inequality, public-service allocation, and local governance capacity. At the same time, the Jilin case has its own institutional and developmental specificity. Unlike Japan and South Korea, Jilin's demographic transformation is more deeply embedded in China's old industrial base restructuring, hierarchical administrative system, and county-level urban–rural relations. Therefore, this study not only reveals the spatial coupling between population shrinkage and aging in Northeast China, but also contributes to broader Asian regional studies by showing how demographic decline and accelerated aging unfold under the combined influence of industrial restructuring, administrative hierarchy, and peripheralization.

The GM(1,1) results suggest that Jilin Province will continue to face population decline and accelerated aging in the coming decade. By 2030, its total population is projected to decrease by another 12.46% compared with 2020, while the aging rate is expected to reach 29.5%. These forecasts indicate that aging pressure will remain difficult to reverse, even if the pace of population decline fluctuates. However, as GM(1,1) mainly extrapolates historical trends and has limited ability to account for policy changes, migration shifts, economic shocks, or public-health events, the results should be interpreted as trend-based references rather than precise predictions.

In response to these demographic challenges, this study advocates a fundamental paradigm shift in regional planning and governance. Local governments must move beyond the traditional "growth-oriented" ideology to acknowledge and adapt to the objective laws of population shrinkage. In severely shrinking counties, differentiated "smart shrinkage" strategies should be implemented, including strict control of new construction land expansion, optimization of existing spatial resources (Kang et al., 2024), and enhancement of public service efficiency rather than blind urban expansion. Enhancing industrial resilience in resource-depleted cities is crucial to breaking single-industry path dependence. By leveraging local ecological assets to develop alternative sectors such as eco-tourism and the ice-and-snow economy, these regions can create employment opportunities to retain young workers, severing the negative feedback loop between population outflow and accelerated aging. Given that the aging rate is projected to approach 30%, proactive strategic planning for the "silver economy” is essential. Older adults face higher vulnerability, including challenges related to access to healthcare, safety, disaster resilience, susceptibility to diseases, and mobility (World Health Organization, 2015; Luiu et al., 2018). Future investments should therefore prioritize healthcare and elderly care infrastructure to establish a social security system resilient to these demographic shifts. Finally, the radiation capacity of central metropolitan areas must be strengthened. Policy mechanisms should facilitate industrial collaboration and bidirectional flows of production factors between core cities and peripheral counties, mitigating the excessive siphoning effect and fostering a rebalanced regional development pattern (Ma et al., 2020).

This study also has several limitations. First, the analysis is mainly based on census data from 2000, 2010, and 2020. Although these data are authoritative and suitable for identifying long-term trends, they cannot fully capture annual population mobility and short-term fluctuations. Second, the study focuses primarily on population shrinkage rates and aging levels, while explanatory variables such as employment structure, fiscal capacity, healthcare resources, transportation accessibility, housing vacancy, and industrial composition are not fully incorporated into the empirical model. Therefore, the causal mechanisms between shrinkage and aging require further examination. Third, while the GM(1,1) model is useful for trend prediction, its single-variable structure limits its ability to explain multi-factor demographic change. Future studies could combine spatial econometric models, panel data, multi-source geospatial data, and comparative regional analysis to further examine the relationship between population shrinkage, aging, and regional development.

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