Dynamic Analysis of Cultivated Area-Food-Population System in Shrinking Rural Areas of Northeast China and Its Planning Strategies

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Abstract
Rural population decline, an inevitable outcome of urbanization and socioeconomic progress, critically impacts national food security through interactions within the cultivated area-food-population system. This study examined Northeast China, a region emblematic of rural depopulation, to analyse systemic dynamics using 2000–2020 census data. Spatial shrinkage patterns were mapped and categorized, revealing key trends. Proposed strategies advocate proactive "smart shrinkage" aligned with demographic shifts: enforcing farmland protection, enhancing black soil conservation, optimizing agricultural layouts, and boosting grain productivity. These measures aim to harmonize population-land-grain coordination, balancing strict resource governance with regional integration. Findings provide actionable guidance to advance sustainable rural-urban synergies, ensuring resilient food systems amid demographic transitions in Northeast China.

Keywords: rural population shrinkage; food security; cultivated area-food-population system; Sustainable Food Planning; Northeast China

1. Introduction

The development of urbanisation has facilitated the flow of production factors between urban and rural areas, disrupting the original internal equilibrium mechanism that maintained the mutual adaptation of agriculture, peasant communities, and rural settlements. This transformation has altered the relatively closed, land-dependent traditional rural development model characterised by self-sufficiency, gradually fostering more open urban-rural social relations. However, the conflicts arising from rapid large-scale urbanisation have exacerbated the "agriculture, rural areas, and farmers" issues (Zhang et al., 2022). Since China's reform and opening-up, with pivotal milestones in 1995 (economic system transformation) and 2014 (comprehensive deepening reforms), rural population dynamics have evolved through three distinct phases: gradual development, mass migration, and citizenisation of agricultural migrants (Guo, Zhou and Liu, 2020). Contemporary rural regions now demonstrate persistent population decline, with issues such as rural depopulation and hollowed villages attracting increasing scholarly attention. The outflow and shrinkage of rural populations have become inevitable phenomena in the process of socioeconomic development, leading to a shortage of rural labor and an imbalance in rural economic structures, also serving as key issues for alleviating human-land tensions and achieving high-quality development in rural territorial systems (Guo, Zhou and Liu, 2020; Dong et al., 2023). These changes adversely impact food production and security, emphasizing the need to investigate the effects of population decline on farmland protection and food production, particularly in regions such as Northeast China, which is characterized by vast agricultural land and significant rural population decline, while maintaining exceptional agricultural productivity as a vital grain production base (Zhang et al., 2023). The region shoulders dual strategic responsibilities, such as black soil conservation for sustainable farmland management and safeguarding national food security. Therefore, it is necessary to study the degree of rural population shrinkage and the challenges it brings to the dual tasks of protecting cultivated land and ensuring food security.

Current research on rural population contraction primarily focuses on three dimensions: village hollowing quantification, rural population shrinkage measurement methodologies, and empirical case studies. Some scholars have evaluated rural hollowing patterns across national, provincial, and county-level scales (Long, Li and Liu, 2009; She and Qiu, 2024; Zhang et al., 2024), analysing formation mechanisms and proposing governance strategies. Comparative studies drew lessons from developed nations (e.g., USA, Japan, South Korea, Germany, UK) in addressing ageing, low fertility rates, and rural shrinkage (Xiao, Zhang and Liu, 2022; Zhang, Li and Bai, 2022; Feng

et al., 2022). Other investigations examined spatial-temporal patterns of population outflow rates (Guo, Zhou and Liu, 2020), categorised settlement evolution types, and discussed rural human settlement space planning strategies guided by "smart shrinkage" (Zhao, You and Chen, 2015). Existing methodologies predominantly employed qualitative case analyses or quantitative indices assessing natural, social, and economic dimensions of rural vitality, or referring to the definition of "shrinkage" in the study of shrinking cities (Liu and Yang, 2017; Ma, Li and Zhang, 2021), used indicators such as the rate of change of rural permanent population in a certain period and the average annual change of rural permanent population to characterize the degree of rural population shrinkage (She and Qiu, 2024). However, limited attention had been paid to the interaction between rural demographic contraction and the cultivated area-food system. While human geography research has conceptualised the Cultivated Area-Food-Population Complex System (Bao and Fang, 2007), with subsequent studies applying coupled coordination models to analyse regional system evolution (He et al., 2016; Aimaiti, Tuoheti and Xu, 2020; Yang et al., 2016), the mechanisms linking rural depopulation with land-food system dynamics remain underexplored.

To address this gap, this study focused on Northeast China, a region emblematic of rural population shrinkage, as the research area. Through typological identification of population contraction patterns and systematic analysis of its cultivated area-food-population system dynamics, I discussed planning interventions to support synergistic development of high-quality urbanisation and rural revitalisation in this strategic agricultural zone.

2. Definition of concepts

2.1. Rural Shrinkage

The concept of "rural shrinkage" derives from its urban counterpart, "urban shrinkage" (Dong et al., 2023). In American rural demographic studies, analogous terms include "population decline" (defined as the population in 2010 decreasing by more than 25% compared with the historical peak) and "population loss" (referring to sustained demographic decreases across both 1990–2000 and 2001–2010 periods) (Xiao, Zhang and Liu, 2022). Chinese scholars define shrinking villages as rural settlements experiencing either a permanent resident population smaller than the registered population or persistent population decline during urbanisation and agricultural modernisation, accompanied by vacant or derelict residential buildings (Jiao and Zhang, 2021). Population loss constitutes the most direct and effective measurement indicator of shrinkage phenomena (Ma, Li and Zhang, 2021). Building on the research results of existing scholars on rural shrinkage and China's census-based urban-rural classification criteria, this study operationalised rural shrinkage from a demographic perspective, specifically denoting sustained reductions in permanent rural populations across two consecutive decades: 2000–2010 and 2010–2020.

2.2. Cultivated area-food-population system

The cultivated area-food-population system refers to a complex territorial system grounded in the exploitation and utilisation of cultivated area resources, with grain production, consumption, and circulation as its core processes, and the fulfilment of human dietary needs as its ultimate objective. Within specific regional contexts, both the quantity and quality of cultivated area determine grain output, while the interplay between grain production and population dynamics governs per capita grain availability (Bao and Fang, 2007). Coordinated development of this tripartite system manifests through (Yang et al., 2016):

- Effective regulation of sustained population growth;
- Maintenance of population density on cultivated land within its carrying capacity thresholds;
- Dynamic per capita grain availability consistently exceeding dietary demand;
- Preservation of arable land quality achieved without ecological degradation .

3. Data and method

3.1. Study area and data sources

This study focused on Northeast China's Heilongjiang, Jilin, and Liaoning provinces, with county-level administrative units (counties and county-level cities) as analytical subjects. Based on 2020 administrative boundaries, I integrated historical data from 2000-2020 after accounting for jurisdictional adjustments and data availability constraints. Four newly established counties of Tangwang County, Fenglin County, Daqingshan County and Nan-

cha County in Yichun City, Heilongjiang Province were excluded, resulting in a final dataset of 143 county-level units.

The county-level administrative unit vector data used in this study came from the Third National Land Survey database in 2020. Population data came from county-level demographic statistics from the Fifth (2000), Sixth (2010), and Seventh (2020) National Population Censuses. Cultivated area data came from the cultivated land area of "China Agricultural Statistical Yearbook" (2001), the 2010 data of the Second National Land Survey data (https://gtdc.mnr.gov.cn/Share?UiNMsBTfPrya=1712637735952#/secondSurvey) verified with the China Annual Cultivated Land Dataset (CACD) (https://doi.org/10.5281/zenodo.7936885) released by Dr. Tu Ying in Professor Gong Peng's team at Tsinghua University with a resolution of 30m×30m, and the 2020 data of the Third National Land Survey data (https://gtdc.mnr.gov.cn/Share#/thirdSurvey). The grain production data for 2000 and 2010 were derived from the "China County Statistical Yearbook" (2001, 2011), and the grain production data for 2020 were derived from the statistical yearbooks and the statistical bulletin on national economic and social development of various provinces and cities .

3.2. Method

3.2.1. Rural Shrinkage Measurement

This study firstly identified persistently shrinking rural areas through sustained reductions in permanent rural populations across two decadal intervals (2000-2010 and 2010-2020), using triennial census data, then calculated the average annual change rate of rural permanent population in each county from 2000 to 2020. The population outflow rate of each county was calculated using the permanent population in rural areas and the rural registered population in 2010. The two indicators were combined to characterize the degree of rural shrinkage in Northeast China. The formulas were as follows:

$$= \left(\sqrt{\quad_{2}/\quad_{1}} - 1\right) \times 100\%$$

Where: S_i was the average annual change rate of the rural permanent population of the i county (city) in a certain period, P_{i1} and P_{i2} represented the rural permanent population of the county (city) at the beginning and end of the period respectively, and n was the interval year.

$$= (1 - \quad / \quad) \times 100\%$$

Where: R_i was the population outflow rate of county (city) i, H_i and P_i represented the number of rural registered population and rural permanent population of the county (city) respectively.

3.2.2. Rural Shrinkage Typology

Building on existing literature and Northeast China's demographic trends, county-level rural shrinkage was classified into four types according to dual thresholds of annualised rural population change rate (S_i) and population outflow rate (R_i): In-migration Shrinkage (R_i<0), Moderate Shrinkage (0<R_i≤50%, -3%<S_i≤-1%-,) Severe Shrinkage(0<R_i≤50%, S_i≤-3%), Critical Outflow Shrinkage (R_i>50%).

4. Dynamic analysis of the rural cultivated area-food-population system in Northeast China

4.1. Analysis of changes in total volume

4.1.1. Rural population dynamics

Between 2000 and 2020, Northeast China's county-level rural population declined sharply from 41,450,985 to 25,178,835, a decrease of 39.26% and an average annual growth rate of about -2.46%. This demographic shrinkage exhibited accelerating negative growth trends, with Heilongjiang Province experiencing the most pronounced decline, particularly during 2010-2020, where annualised population loss rates exceeded regional averages.

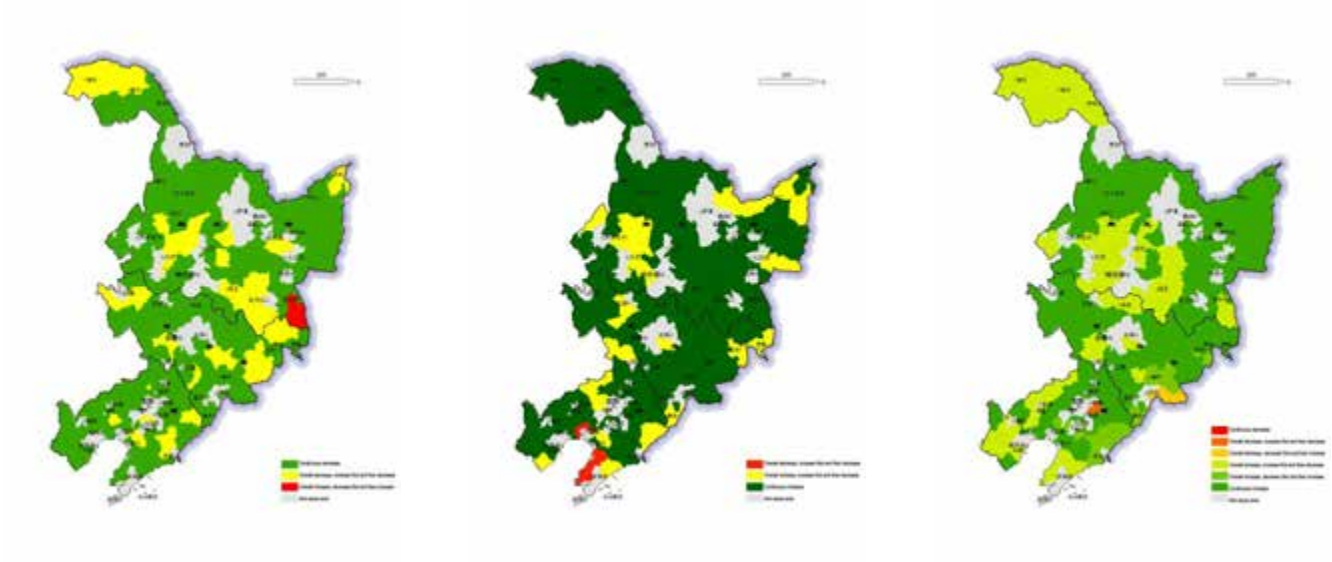
4.1.2. Cultivated land area dynamics

From the perspective of the total scale of cultivated land, the cultivated land area in counties and villages in

Northeast China increased significantly from 2000 to 2020, with a total increase of 106,331 square kilometers, a growth rate of 69.49%. From the perspective of spatial distribution, the cultivated land area of most county units in Northeast China continued to grow, and showed a concentrated and contiguous distribution state. Only the cultivated land area of four county-level units, namely Wafangdian City, Changhai County, Panshan County and Gaizhou City, decreased, and they were concentrated in the Bohai Rim region. Although the total amount of cultivated land in some counties (cities) increased, their cultivated land area decreased in the past decade and was relatively scattered in space. Overall, the protection of cultivated land in Northeast China has achieved good results in terms of quantity and scale.

4.1.3. Grain production dynamics

Grain output in Northeast China surged by 175.57% over the study period, with a relatively large growth rate from 2000 to 2010 and a slowed-down rate from 2010 to 2020, which was related to the reduction of agricultural labor force, the stabilization of cultivated land area and planting structure due to the intensified population loss in Northeast China. In terms of grain production pattern, Heilongjiang Province was the main grain production area in Northeast China, and grain output has basically remained above 50% of the total in the study area. From the perspective of the spatial distribution of changes in grain output, 62.24% of counties continued to increase, and only 5 counties (3.50%) had a decrease in grain output in 2020 compared with 2000, which were scattered around the provincial capital, coastal and border forest areas, attributable to industrial restructuring and topographic constraints.



(a) Rural population (b) Cultivated land area (c) Food production

Figure 1. Changes in the total amount of the rural cultivated area-food-population system in Northeast China

4.2. Per capita/unit analysis

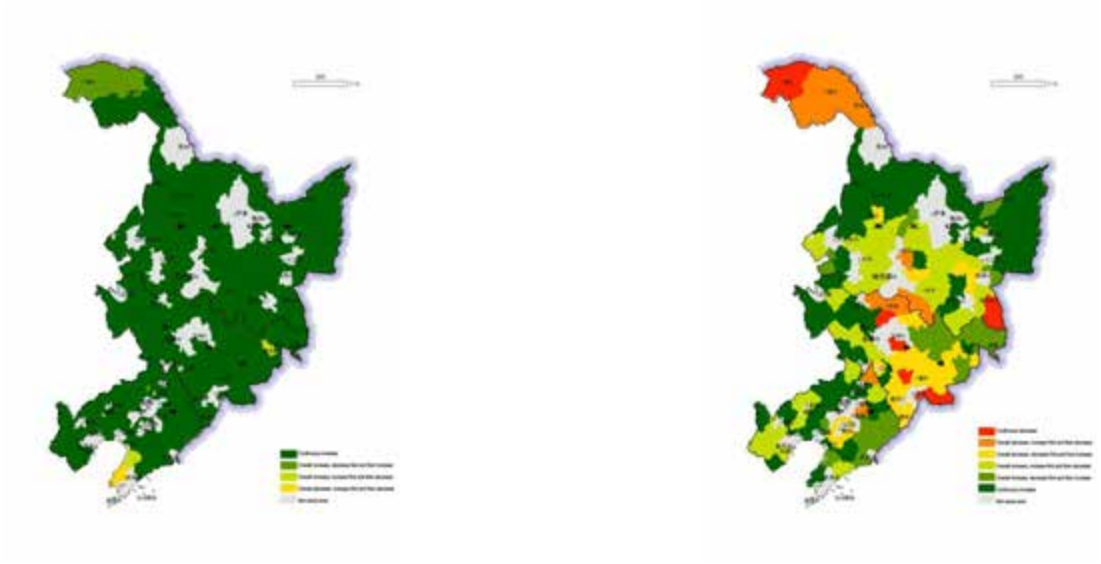
4.2.1. Per capita cultivated land dynamics

Between 2000 and 2020, county-level per capita arable land area in Northeast China exhibited consistent growth, with Heilongjiang Province recording the most pronounced expansion and persistently exceeding the regional average. Spatially, over 95% of counties demonstrated sustained growth in per capita arable land availability, and other counties showed minor volatility, with only the per capita arable land area of Wafangdian City decreasing. This trend reflected the inevitable outcome of rural population contraction coupled with intensified cultivated land conservation measures.

4.2.2. Grain output per cultivated land area dynamics

Grain yield per unit cultivated area across Northeast China increased markedly during 2000-2020, with Heilongjiang Province leading at 90.24% growth, followed by Liaoning Province (72.91%). From the perspective of county

differences, the cultivated land efficiency of 37.76% of counties continued to improve, 37.76% increased with fluctuations, and less than 1/4 of counties decreased, forming two relatively concentrated groups in the Daxing'anling Prefecture and the central-eastern Jilin Province. Spatial patterns revealed optimal productivity concentrated in contiguous agricultural zones consisting of southwestern Heilongjiang Province and western Jilin Province, and plains in northern Liaoning Province and eastern Heilongjiang Province. These high-yield regions benefited from large-scale contiguous farmland conducive to modernised agricultural practices.



(a) Per capita cultivated land area (b) Grain production per land area

Figure 2. Changes in the per capita/unit index of rural cultivated area-food-population system in Northeast China

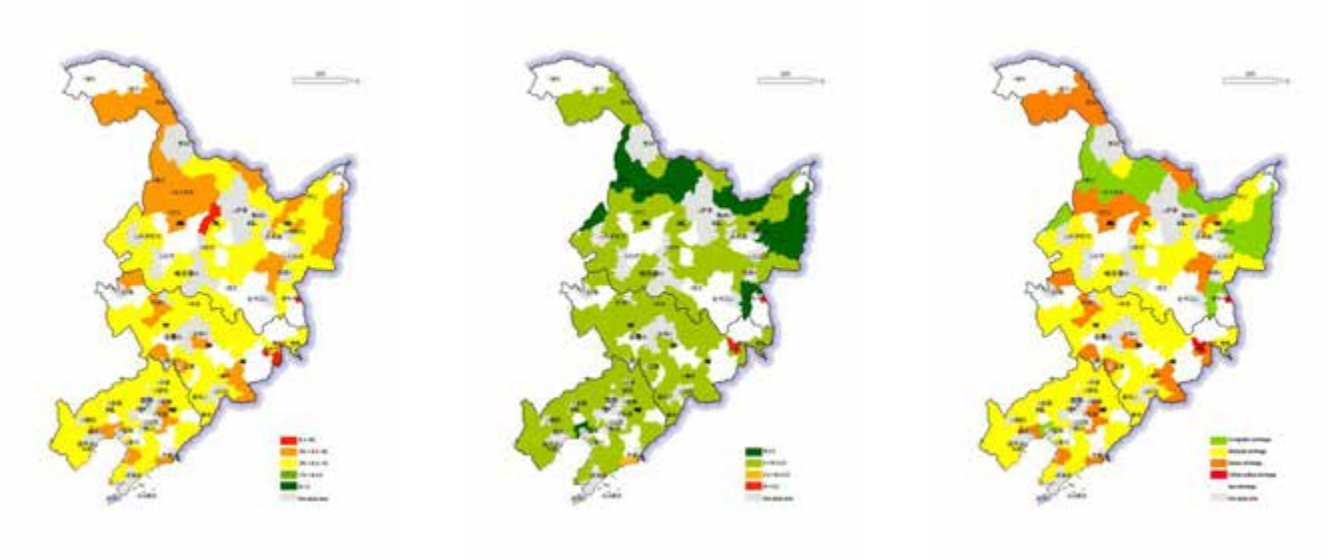
5. Analysis of the types and characteristics of rural population shrinkage in Northeast China

5.1. Identification of the scope of rural population shrinkage

Between 2000 and 2020, 113 county-level units in Northeast China, accounting for 79.02% of the study area, exhibited sustained rural population decline. Among them, there were 35 in Liaoning Province, 31 in Jilin Province, and 47 in Heilongjiang Province, accounting for 85.36%, 79.49% and 74.60% of the total number of study units in each province, respectively. This demonstrated pervasive rural shrinkage across the region, with Heilongjiang Province bearing the largest number of county-level units with rural population shrinkage, and Liaoning Province had the highest proportion of county-level units with rural population shrinkage.

5.2. Classification of rural shrinkage types

Integrating annualised rural population change rate (S_i) and population outflow rate (R_i), four rural shrinkage types emerged, with moderate shrinkage as the main rural shrinkage type in Northeast China, including 73 county-level units, accounting for 64.60% of the total shrinkage units, followed by 25 severe shrinkage units (22.12%), 13 in-migration shrinkage units (11.50%) and 2 critical outflow shrinkage units (1.77%). Spatial patterns showed that, the moderate shrinkage counties were mainly concentrated and contiguous in space, mainly distributed in the southern part of Heilongjiang Province, most of the counties in Jilin Province and Liaoning Province. Besides, the severe shrinkage counties were scattered in the three provinces of Northeast China. The in-migration shrinkage counties were mainly distributed in the northern part of Heilongjiang Province, and there were also scattered points in the eastern part of Heilongjiang Province and the southern part of Liaoning Province. The critical outflow counties were scattered and the number was the smallest, with only two units in Suifenhe City, Heilongjiang Province and Yanji City, Jilin Province. In general, the phenomenon of rural population shrinkage in counties in Northeast China was common, and the rural shrinkage situation in the north part was more severe than that in the south.



(a) Annualised rural population change rate from 2000 to 2020

(b) Rural population outflow rate in 2010

(c) Rural shrinkage type

Figure 3. Distribution of rural shrinkage types in Northeast China

5.3. Characteristics of the cultivated area-food-population system in Northeast China's shrinking rural areas

As demonstrated, Northeast China's rural areas exhibited accelerating population shrinkage alongside expansions in cultivated land area, which was changing inversely compared with rural permanent population, and intensifying spatial disparities in grain production efficiency. The dependence of food production on cultivated land resources was increasing. The four identified rural shrinkage typologies (in-migration, moderate, severe, and critical outflow) manifested distinct systemic characteristics within the cultivated area-food-population system, as synthesised in Figure 4.

Figure 4. Table of characteristics of the cultivated area-food-population system in Northeast China's shrinking rural areas

Type	Number of counties	Characteristics of the cultivated area-food-population system	Distribution
In-migration shrinkage	13	• The rural population has decreased, with increased area of cultivated land and improved efficiency of cultivated land. • Food production was less dependent on population and cultivated land resources. • The concentration of cultivated land in plain areas was conducive to large-scale production, and the improvement of agricultural technology level was the key to maintaining system stability.	Plain arable land in the northern-eastern border counties of Heilongjiang Province.

Moderate shrinkage	73	• The rural population has decreased, with increased cultivated land area. • The efficiency of cultivated land has mainly increased, with the efficiency of cultivated land in counties bordering provinces declined in recent years. • Food production was less dependent on the rural population, showing regional differences in the degree of dependence on cultivated land resources, with the main trend being a decrease in dependence.	Plain arable land in southern Heilongjiang Province, and most counties in Jilin Province and Liaoning Province.
Severe shrinkage	25	• The rural population has decreased, and the cultivated land area has increased. • There were large regional differences in cultivated land benefits. • Food production was less dependent on the rural population. • Natural geographical characteristics caused food production to rely more on cultivated land resources. Attention should be paid to the coordination of cultivated land protection and ecological security.	Scattered distribution, mainly in forest areas, mountainous areas and protected areas.
Critical outflow shrinkage	2	• The rural population has decreased, and the cultivated land area has increased. • The dependence of food production on cultivated land resources has decreased. • Non-agricultural counties with scarce cultivated land resources have developed other industries based on their port advantages.	Border port cities, such as Suifenhe City, Heilongjiang Province, and Yanji City, Jilin Province.
total	113		

6. Planning and regulation strategies for the cultivated area-food-population system in Northeast China's shrinking rural areas

Effective governance of he cultivated area-food-population system necessitates ensuring regional food self-sufficiency, maintaining systemic equilibrium, and coordinating tripartite relationships (Bao and Fang, 2007). As China's primary grain production base, Northeast China secures national food security while requiring targeted interventions to harmonise demographic, land-use, and agricultural dynamics, to acknowledge the inevitable trend of rural population shrinkage, to preserve precious and limited arable land resources, to promote technological progress and enhance food production capacity, so as to achieve the goal of sustainable development.

6.1. Proactive Smart Shrinkage Strategies Aligned with Demographic Trends

Planning should first establish awareness of rural shrinkage, correctly understand the inevitability of rural shrink-

age, abandon the traditional notion of development based on population size, clarify the main theme of "smart shrinkage" (Zhao, You and Chen, 2015), and attach importance to the creation and maintenance of rural vitality (Zhang, 2016). In order to address the coexistence of waste and insufficient supply of public services and generally low quality in rural shrinking areas, it is advised to optimize resource allocation and explore the establishment of a wide-area joint system of local living circles with urban-rural linkage allocation (Zhang, Li and Bai, 2022). The economic function, social structure and spatial evolution of rural areas are deeply influenced by factors such as the natural resource conditions and agricultural foundation of the village itself, the economic location and urbanization development stage, the intensity of interaction between grassroots governance and urban-rural elements, and the level of urban and rural infrastructure and public services (Zhang and Sun, 2019). Therefore, we should respect regional differences and formulate differentiated development paths based on local conditions such as the type of rural shrinkage and natural-economic factors.

6.2. Rigorous cultivated area conservation and black soil enhancement

China's farmland protection has gone through three major stages, from focusing on quantity protection to giving equal weight to quantity and quality, and to the "three-in-one" protection of quantity, quality and ecology. A series of farmland protection systems have been established, including farmland occupation and compensation balance, farmland use control, farmland quality acceptance, permanent basic farmland protection, black soil protection, land development, consolidation and reclamation. Planning should strictly adhere to the awareness of farmland red lines, implement the strictest farmland protection system, and curb the reduction of farmland area. Aiming to improve the quality and benefits of farmland, it is advised to increase the protection of black soil, strengthen agricultural land remediation and high-standard farmland construction, orderly promote rotation and fallow. To strengthen the coordinated protection of farmland and surrounding ecosystems, and to build a healthy and stable farmland ecosystem, are also essential to food and farmland security. By utilising the new generation of information technology to promote the informatization of land and resources, the department of natural resources could timely and effectively track and monitor changes in farmland area and quality.

6.3. Agricultural restructuring for systemic productivity gains

As the national strategic grain base, Northeast China Region needs to build an awareness of serving the implementation of major national strategies, and promote regional agricultural development in a coordinated manner. Planning should adhere to systematic thinking, optimize the agricultural pattern according to the differences in resource endowments in the region, promote cross-county and cross-provincial land resources and grain production coordination, to achieve win-win cooperation. It is also advised to adjust the production structure through reforming the farming system, to establish an ecological agricultural pattern that matches agricultural productivity with resource and environmental carrying capacity, to introduce advanced technology, modern equipment, management concepts, etc. into agricultural production to develop modern large-scale agriculture, so as to achieve the objective of enhancing the overall efficiency of grain production.

7. Conclusion

Rural population contraction constitutes an inevitable urbanisation outcome rather than rural decline. Stabilising the cultivated area-food-population system in rural area, which is an important carrier for ensuring China's food security and sustainable development of land space, remains critical for achieving high-quality development and urban-rural coordination under the general trend of population shrinkage. Northeast China has the dual typicality of rural population shrinkage and cultivated area-food-population system coordination. It is necessary to follow the trend of depopulation to shrink smartly, to strictly protect the stability of the amount of cultivated land and improve its quality, to promote the sustainable development of agricultural production in a regional integrated system, aiming to promote the coordinated development of high-quality new urbanization and rural revitalization in the Northeast China to achieve sustainable development and ensured food security in the face of ongoing demographic and socioeconomic changes.

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