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Trade-off and Synergy of Rural Functions Under County Depopulation in the Typical Black Soil Region of Northeast China

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Abstract: As the population continues to shrink in the black soil region of Northeast China since 2000, it is critical to master the impact of population shrinkage on rural functions to realize rural revitalization and sustainable development. In this study, we focused on the impacts of depopulation on the evolution and interrelationship of rural subfunctions. Based on the rural function indexes system, the TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method, spatial analysis method, and mathematical statistics analysis method were used to summarize the spatial and temporal characteristics of rural function development, as well as the effect of population shrinkage in the typical black soil region of Northeast China. The results showed that depopulation varied in the extent and duration between the forested region and plain areas, which both impacted the trajectories of rural subfunctions evolution. For the economic development function and ecological conservation function, the effect of continuous slight depopulation was beneficial, while the effect of rapid depopulation was adverse, which was exactly opposite to the agricultural production function. All forms of population shrinkage were conducive to the development of the social security function. With the deepening population shrinkage, depopulation mainly promoted the collaborative development between subfunctions in this study, except the relationship between agricultural production and social security function. But effects of depopulation on the interrelationship of rural subfunctions varied between the forested region and plain areas in some cases. The results provided evidence for the cognition that population shrinkage had complicated effects on rural subfunctions.

Keywords: rural function; depopulation; trade-off and synergy; typical black soil region; Northeast China

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1 Introduction

The original concept of the multifunctional countryside came from the term multifunctional agriculture, which originated from the theoretical framework of agricultural policy reforms carried out by the Organization for Economic Cooperation and Development (OECD) and the European Union (EU) in the late 1990s (Long et al., 2022). Similarly, the multifunctional land use in the countryside emphasized many services outside the primary purpose that land use involves (Wiggering et al., 2006). A rural regional system is an open system with a certain function and structure, which is composed of the natural environment, resource endowment, location con-

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ditions, economic foundation, human resources, cultural customs, and other factors interacting within a specific rural area (Long and Tu, 2017), and the complexity of internal components of the rural regional system leads to the diversity and regional differentiation of rural regional functions (Gu et al., 2019; Tan et al., 2019). Along with the diversity of human needs and changes in people's value perception, the land use functions in the countryside have experienced continuous evolution (Holmes, 2006), such as a shift from the formerly dominant production goals towards a more complex, contested, variable mix of production, consumption and protection goals (Pinto-Correia et al., 2014). The steady improvement and transformation of rural functions is the key to improving rural areas' unbalanced and inadequate development (Liu et al., 2012; Tang et al., 2016). Due to the widespread population decrease and regional decline in the agricultural heartland, increasing food production while maintaining a steady supply of ecosystem services has become a central challenge for global sustainable development (Lambin and Meyfroidt, 2011).

For sustainable development in rural areas, some conceptual frameworks of Land Use Functions (LUFs) in rural regions have been developed based on various data (Pérez-Soba et al., 2008; Fan et al., 2018), but a widely accepted practice is divided into three (Zou et al., 2020) or four (Long et al., 2022) subfunctions nowadays, i.e., economic, production, social, and ecological functions, or added one type for a specific purpose (Huang and Wang, 2022). Since then, the existing studies of the relationship among rural functions are mainly divided into two categories. The first one is a comprehensive study of multiple functions, focusing on the evolution and interaction of subfunctions, such as coupling coordination (Beardmore et al., 2019; Yang et al., 2020; Zou et al., 2020) and trade-off/synergistic features (Bruno et al., 2021; Gatariće et al., 2022; Dai et al., 2022). The other one is the evolution characteristics of individual functions under the influence of factors, and the impact on rural subfunctions is the core issue of concern. For example, rural household livelihoods have been proven to be close to agricultural functions (Liu and Fang, 2021). From county to village, and then to grid (Shi et al., 2022), the research scale presents a trend of diversification and refinement. And the regional scale involves typical hilly area (Liao et al., 2022), urban agglomeration area (Tan et al., 2019), coastal area (Beardmore et al., 2019), urban-rural integration area (Gu et al., 2019), border area (Verkuleviciute-Kriukienė et al., 2018) and other areas. With the development and change of social and ecological systems, many associate factors will affect the changes in human-environmental systems in rural areas during the important process of social and ecological development, such as migration and rural depopulation caused by urbanization (Ribeiro Palacios et al., 2013). In addition, land functional priorities differ under various land use sustainable scenarios and there may be conflicts between different priorities, such as the conversion of food security and return of farmland to forests (Brown and Castellazzi, 2014). Even though a few relevant studies have been carried out (Huang et al., 2022), the research on the impact of the rapid change of man-land relationship on the overall rural regional function is still lacking.

According to the National Population Development Plan (2016–2030), significant changes have taken place in the urban-rural structure of China's population, but the population flow is still active, and agglomeration characteristics will be further enhanced. According to the latest figures from the National Bureau of Statistics of China (http://www.stats.gov.cn/), the number of births in China fell below 10 million in 2022 for the first time since 1950, and the natural growth rate of the permanent population was –0.6‰. Then, county depopulation would become a signature demographic phenomenon in broad regions of rural China, and China's population development would meet a critical turning point. Rural population shrinkage has been a problem faced by many countries around the world. Most of the rural depopulation has occurred in remote rural counties and adjacent nonmetropolitan counties (Johnson and Lichter, 2019). The most important themes of existing depopulation research identified were related to specific geographical areas (Rodríguez-Soler et al., 2020), for example, rural areas of Eastern Europe and Central Europe characterized by a shrinking population (Wirth et al., 2016; Dax and Fischer, 2018; Sheludkov et al., 2021), but there was some population flowing into Czech Countryside (Šimon and Bernard, 2016).

Scientific understanding of the evolution law of rural functions and the effect of population flow in the new era is of great significance for the realization of rural revitalization and urban-rural integrated development in China (Chen, 2020). However, the effects of rural depopulation on the rural subfunctions are complicated, and there are conflicts and contradictions. For example, depopulation and economic marginalization of rural areas have led to the gradual abandonment of land and shrinkage of agricultural structure in farming and pastoral areas (Quaranta et al., 2020), but depopulation also has enhanced food production services in fertile plains (Bruno et al., 2021) and drove land transfer and farmland expansion in the farming-pastoral ecotone (Liu, 2022a). It is agreed that agricultural activities are necessary to achieve sustainable development in rural areas (Hrabankova and Bohackova, 2007), but the effects of depopulation on agricultural functions and other rural subfunctions are regional and varied. The impacts of population shrinkage are also inconsistent among different functions in human-environmental systems. Population reduction is helpful for the improvement of ecological and environmental quality (Liu, 2022b), however, depopulation in a small town has been observed at the same time as economic decline (Bowns, 2013). Population decrease and increase have changed the regional human-environmental relationship, which has a certain impact on the interaction of elements within the human-environmental system, such as the transformation of rural landscapes and functions (Ribeiro Palacios et al., 2013; Verkuleviciute-Kriukiene et al., 2018). Along with the strengthening or weakening of the interaction between elements in the rural regional system, the relationship between rural functions also appears to be one of decline and gain or mutual benefit (Willemen et al., 2010; Wen et al., 2022a).

The Northeast Black Soil White Paper (2020) (Chinese Academy of Sciences, 2021) pointed out that black soil in Northeast China has superior soil fertility and is very suitable for crop growth, which significantly contributes to ensuring food security in China. Therefore, the black soil region of Northeast China is an important national grain production area, whose economic activities mainly revolve around agricultural production (Han and Li, 2018). However, land reclamation and land utilization in the past had caused obvious degradation of black soil (Chinese Academy of Sciences, 2021). To ensure the stability of grain production capacity, land use was combined with black soil protection since the 21st century. Because of differences existing in regional economic development state and natural conditions, rural regional functions had diversity and spatial heterogeneity, and rural functions in the black soil region of Northeast China were also affected by the regional man-land relationship. With the process of urbanization and industrialization, the flow of urban and rural factors intensified and the rural regional functions constantly evolved. Northeast China was facing an unprecedentedly rapid and serious population decline, which brought new challenges to the rural functions of this region (Liu et al., 2021c; Tong et al., 2022). Rapid population decline changed the man-land relationship in Northeast China, then would affect the evolution process of regional functions in the rural areas. Although there have been a certain number of studies on the impact of population shrinkage, which mainly focused on a specific rural subfunction. There are still insufficient studies on the evolution of rural overall functions and the interactions among each subfunction under the influence of population shrinkage, especially the impact of depopulation on rural functions in the black soil region of Northeast China is unknown. At present, scientific understanding of the evolution law of rural functions in the black soil region of Northeast China, exploring the interaction between the multiple functions in the rural regional system, and adapting to the objective needs of the rural regional human-environmental system evolution caused by population shrinkage has become the crucial issues to promote the sustainable and stable development of rural regions in the black soil region of Northeast China. Based on this, the assessment of rural regional functions would be carried out in the typical black soil region in Northeast China. The purpose of this study is to reveal the spatial and temporal evolution rules and trade-offs and synergies of rural subfunctions affected by depopulation, then to analyze the impact of population shrinkage on rural regional functions, which expands the theoretical research on the relationship between population shrinkage and rural function evolution and provides a case study on the impact of population shrinkage on rural function in the black soil region of Northeast China.

2 Materials and Methods

2.1 Study area

The black soil region of Northeast China, one of the four major black soil regions in the world, is mainly distributed in the Hulunbuir grassland, Hinggan Ling region, Sanjiang Plain, Songnen Plain, part of Songliao Plain, and Changbai Mountains region. The area of this region is 1.09 million km^2, accounting for about 12% of the total area of the global black soil region. According to Northeast Black Soil White Paper (2020) (Chinese Academy of Sciences, 2021), the black soil region of Northeast China covers 246 counties and districts in Heilongjiang, Jilin, Liaoning, and the Eastern Fourth League in Inner Mongolia.The black soil types in Northeast China mainly include black soil, chernozem soil, dark brown soil, brown soil, alba soil, and meadow soil. Based on the black soil region shown in the Northeast Black Soil White Paper (2020), the coverage of two major types of black soil (black soil and chernozem soil) was superimposed with county-level administrative units to determine the scope of the typical black soil region of Northeast China and the counties involved in this study (Liu et al., 2021a). Then urbanized areas were removed to accurately depict rural functions. As shown in Fig. 1, 84 counties in the typical black soil region of Northeast China were finally selected as research units, including three counties with slightly increasing populations from 2000 to 2020. According to the data from National Population Census, the total population of Northeast China was 108.89 million in 2020, which was less than 116.48 million in 2000 (https://www.citypopulation.de/). Depopulation occurred both in the urban and rural areas. Under this trend, the black soil region of Northeast China experienced widespread and severe population decline, especially in the study area (Fig. 1). The rapid and severe depopulation brought great challenges to regional economics and functions.

2.2 Data sources

The spatial data of land use, soil type, and administrative division in this study were derived from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn/). Then, the different types of land use data were extracted, such as cultivated land area used in the calculation of ecological service value in corresponding years. The demographic data were mainly extracted from the Fifth (2000), Sixth (2010), and Seventh (2020) National Population Censuses (https://www.citypopulation.de/), and the change rates of the permanent resident population in counties were used to classify the types of counties. Social and economic data were mainly derived from China County Statistical Yearbook (Xian, 2001; Zhang, 2011; Wang, 2021). A small amount of missing data was supplemented by other yearbook data, such as the statistic-

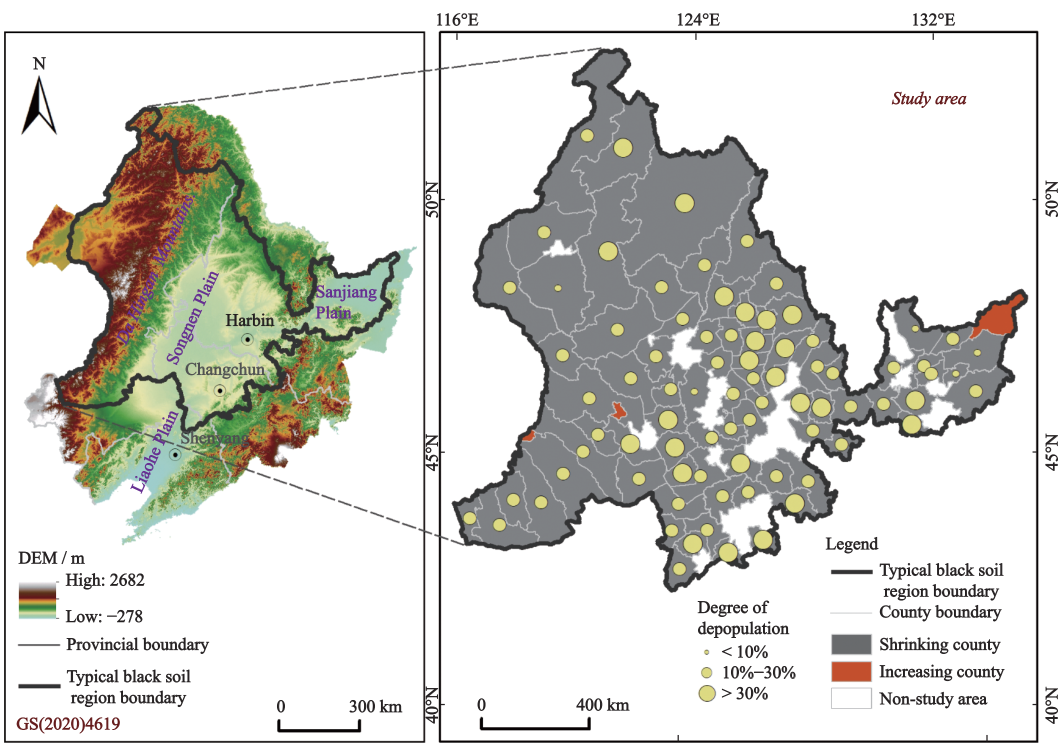

Fig. 1 Location of the typical black soil region of Northeast China

al yearbooks of Heilongjiang, Jilin, Liaoning, and Inner Mongolia, and national economic and social development bulletins of counties and urban areas in the relevant years.

2.3 Methodology

2.3.1 Construction and assessment of the comprehensive index model

Among the existing related research, the structure of rural multifunction is the foundation of others, which mainly focuses on two points of view. One is that rural areas provide agricultural production functions, living security functions, and ecological conservation functions for human beings, which are based on production space, living space, and ecological space (Yang et al., 2020; Dai et al., 2022). The other is that the index system could be constructed from four dimensions of agricultural production, economic development, social security, and ecological conservation to evaluate rural regional functions (Tan et al., 2019; Jiang et al., 2020; Long et al., 2022).

It is generally believed that rural areas are obliged to ensure stable production of grain and the supply of other important agricultural products to maintain national food security, especially in the black soil region of Northeast China (Chen, 2020). Therefore, the agricultural production function (APF) should be one of the primary rural functions, which mainly refers to the ability of rural areas to provide food and other agricultural products for residents in the process of city-driving regional development. Based on relevant research results (Tan et al., 2019), land reclamation rate, per capita grain yield, agricultural mechanization degree, and paddy field ratio were selected to represent agricultural production capacity in this study. Under the influence of population urbanization and agricultural modernization, rural economic development functions are also reflected in diversified economic activities and are no longer completely limited to traditional food production activities (Yang et al., 2021). Therefore, the function of economic development (EDF) needs to be reflected by the overall economic vitality of a region. In this study, grain commodity rate, per unit area agricultural output, economic structure, and financial contribution rate were selected to represent the economic development function. Social security function (SSF) refers to the ability of rural areas to provide employment opportunities and living space for farmers, so healthcare status, percentage of students in school, the proportion of village land area, and per capita farmland area were selected to evaluate the social security function in this study. The countryside should provide a good ecological buffer, environmental protection, and green products for the cities and the whole country, especially for environmental pollution caused by agricultural production and changing consumer goods. Ecological conservation function (ECF) is the ability to provide ecological products and environmental regulation services for human beings, which is the premise of sustainable rural development. Especially, after the improvement of economic development and people's needs, it has become one of the more and more important functions of rural areas. And we selected the climate regulation function, environmental purification function, maintaining nutrient cycling function, biodiversity function, and landscape aesthetics function as the evaluation indexes of ECF in this study (Xie et al., 2015).

Combined with the existing literature and the functional characteristics of the black soil region of Northeast China (Jiang et al., 2020; Long et al., 2022), as shown in Table 1, the rural function evaluation index system was constructed from four dimensions, namely agricultural production, economic development, social security, and ecological service. Finally, the improved TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method (Huang and Wang, 2022) whose weight was determined by the distance from the optimal and the worst solutions, was used to determine the index weights of different functions in this study. Each function index value was calculated separately by Eq. (1) as follows.

$$RF_{ik} = \sum X_{ij} \times w_j \quad (1)$$

where RF_{ik} represents the kth single functional value of the ith county, k = 1 (APF), 2 (EDF), 3 (SSF), 4 (ECF); X_{ij} is the normalized value of the jth index in the ith county from Table 1 and w_j is the weight of the jth index which was calculated by the TOPSIS model.

2.3.2 Types of counties with different depopulation degrees

The rate of population change was used to identify the county types, including whether the county shrunk and to what extent. A negative rate of population change

Table 1 Rural function evaluation index system in the typical black soil region of Northeast China

Functions	Indexes / unit	Index connotation and calculation method	Effect (weight)
Agricultural production function (APF)	Land reclamation rate / %	Farmland area/total land area	+ (0.348)
	Per unit area grain yield / (t/ha)	Total grain output/farmland area	+ (0.136)
	Agricultural mechanization degree / (kW·h/ha)	Total power of agricultural machinery/farmland area	+ (0.296)
	Paddy field ratio / %	Paddy field area/total cultivated land area	+ (0.220)
Economic development function (EDF)	Grain commodity rate / %	(Grain output –400 kg × permanent population)/total grain output	+ (0.460)
	Per unit area agricultural output / (10^4yuan RMB/ha)	The output value of primary industry/total land area	+ (0.130)
	Economic structure / %	The sum of the output value of secondary and tertiary industries/GDP	+ (0.267)
	Financial contribution rate / %	Financial revenue/GDP	+ (0.143)
Social security function (SSF)	Healthcare / per 10^4 person	Number of beds in health institutions owned by 10 000 people	+ (0.245)
	Percentage of students in school / %	Sum number of middle school students and primary school students/number of the permanent population	+ (0.391)
	Proportion of village land area / %	Village land area/total construction land area	–(0.101)
	Per capita farmland area / ha	Farmland area/number of the permanent population	+ (0.263)
Ecological conservation function (ECF)	Climate regulation function / (yuan/ha)	Per unit area ecological service, the equivalence factor method of ecological service value	+ (0.215)
	Environmental purification function / (yuan/ha)		+ (0.190)
	Maintaining nutrient cycling function / (yuan/ha)		+ (0.237)
	Biodiversity function / (yuan/ha)		+ (0.185)
	Landscape aesthetics function / (yuan/ha)		+ (0.173)

Note: Per capita grain demand (400 kg) referred to the paper ‘Rural Multi-function Evaluation and Evolution Characteristics in Liaoning Province; +, positive index, –, negative index

represents population shrinkage, and the larger the negative value, the deeper the population shrinkage. To further analyze the spatiotemporal differences and impact of depopulation, the counties were classified into five types, namely, slight shrinking, moderate shrinking, severe shrinking, extreme shrinking, and increasing population county according to the population change rates (Guan et al., 2021; Tong et al., 2022). The population change rates were then calculated by Eq. (2).

$$PC_i = (POP_{it} - POP_{io})/POP_{it} \quad (2)$$

where PC_i is the population change rate of the *i*th county, and the value of PC_i is divided into five levels, corresponding to five types of counties (Table 2); POP_{io} and POP_{it} are the numbers of permanent residents of the *i*th county in the initial state and final state, respectively.

2.3.3 Evaluation model of rural function evolution and trade-off/synergy

To reflect the direction and extent of interactions between RFs, as well as their changes, the deformation of ecosystem service trade-off and synergy degree index (RFTD) was used in this study. RFTD is an index based on the linear fitting of data, which can better reflect the relative changes between *RF*s. In this study, for example, $RFTD_{12}$ was the average of the relative rate of change between RF_1 (APF) and RF_2 (EDF) which was calculated by the change index of the RF_k ($RFCI_k$) (Gong et al., 2019; Wen et al., 2022b). Then $RFCI_k$ and $RFTD_{12}$ can be calculated by Eq. (3) and Eq. (4), respectively.

$$RFCI_k = (RF_{kt} - RF_{ko})/RF_{ko} \quad (3)$$

$$RFTD_{12} = (RFCI_1/RFCI_2 + RFCI_2/RFCI_1)/2 \quad (4)$$

where $RFCI_k$ value indicates the change types of the RF_k. If the value of $RFCI_k$ is greater than 0, it means that RF_k has enhanced during this time, otherwise, RF_k is diminished. In our study, the positive and negative average of the value was used to classify the change degree of RF_k; RF_{ko} and RF_{kt} are the value of the RF_k in the initial state and final state, respectively; $RFTD_{12}$ is the trade-off/synergy degree between RF_1 and RF_2. If the value of $RFTD_{12}$ is positive, it means that they have a synergy relationship. Conversely, negative values represent a trade-off relationship. And the magnitude of its absolute value reflects the level of the trade-off/synergy, so a value of 1 indicates the weakest interaction. In our

Table 2 Types of the county according to population change degrees in the typical black soil region of Northeast China

County types	Population change degrees	Description
County with increasing population	Population growth	$PC_i \geq 0$
Slight shrinking county	Slight depopulation	The PC_i range is [–5%, 0)
Moderate shrinking county	Moderate depopulation	The PC_i range is [–10%, –5%)
Severe shrinking county	Severe depopulation	The PC_i range is [–30%, –10%)
Extreme shrinking county	Extreme depopulation	PC_i < –30%

Note: PC_i was the change rate of permanent residents

study, because of the large standard deviation and asymmetrical extreme value of functional scores, the positive and negative median was used for grading criteria of $RFTD_{12}$, thus the interrelationship was divided into four types, including strong synergy, weak synergy, weak trade-off, and strong trade-off.

3 Results

3.1 Spatial and temporal evolution of population and rural subfunctions

3.1.1 Spatial and temporal pattern of population change

In the typical black soil region of Northeast China, there was an obvious spatial characteristic of the population at the county scale (Fig. 2). In 2000, the population of the Da Hinggan Mountains region was small, with most counties less than 0.25 million. The population density was larger in the eastern plains, especially in the Harbin-Changchun urban agglomeration area. Then the spatial characteristics of the county population have changed. Before 2010, about a quarter of counties population was less than 0.25 million, mainly located in the forested regions. By 2020, most counties had a population of less than 0.25 million. The proportion of larger counties dropped from 2000 to 2020 and the depopulation counties scattered throughout the whole study area. During the study period, depopulation gradually spread from the western forested region to the eastern plain areas.

Between 2000 and 2010, increase and decrease coexisted in the population change in the typical black soil region of Northeast China, and then the change type transitioned to a predominant decrease between 2010 and 2020 (Table 3). In the first 10 yr of the study period, 42.86% of the counties with population growth were in plain areas, while only 5.95% were in the forested region, totally accounting for 48.81% of the counties with population growth. However, the percentage of counties with population growth declined to 3.57% in the last 10 yr. These increasing counties were all located in the forested region whose population growth rate also slowed down significantly.

In addition, as shown in Table 3, 51.19% of the counties experienced population shrinkage in the first 10 yr, which was dominated by slight shrinkage and mainly located in the plains. The proportion of the medium population shrinkage in the plain area was higher than that in the forested region. The counties with

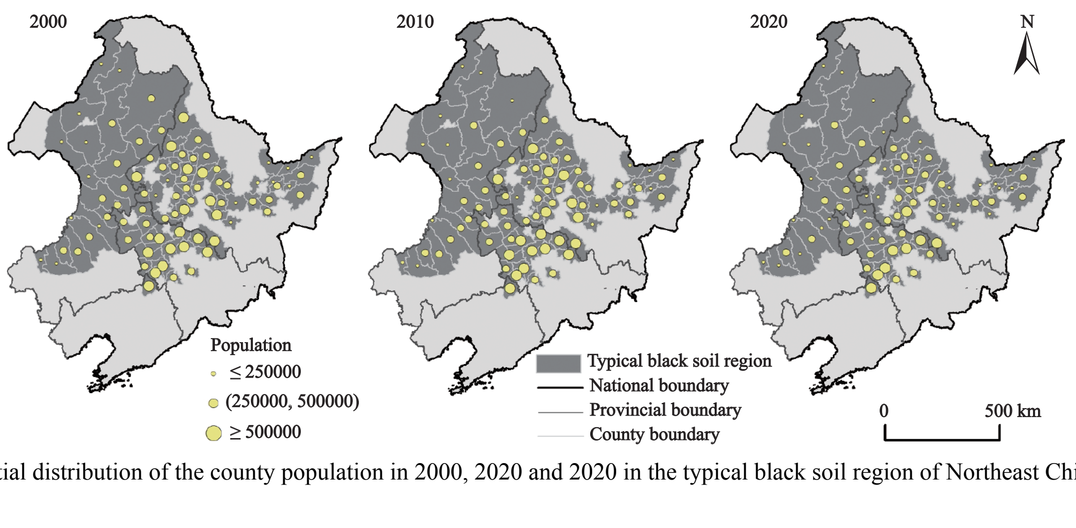

Fig. 2 Spatial distribution of the county population in 2000, 2020 and 2020 in the typical black soil region of Northeast China

severe shrinkage were mainly distributed in the forested region, accounting for 9.52%, and only 3.57% in the plain area. Therefore, from 2000 to 2010, the population shrinkage in the plain area was slight, while the population shrinkage in the forested region was mild and severe. However, the problems of population decline in the plain areas and forested regions were both aggravated in the last 10 yr, with more serious population shrinkage in the plains. The population shrinkage was dominated by severe and extreme types, and a lot of counties with population growth in the early period changed to population shrinkage, especially in plain areas. It could be seen that the degree of depopulation gradually intensified from 2000 to 2020 in the typical black soil region of Northeast China.

3.1.2 Spatial and temporal pattern of rural subfunctions evolution under various population change types

As the increased population and slight depopulation turned to significant shrinkage, there were apparent spatial differences in the evolution of APF (Fig. 3a). Between 2000 to 2010, the APF substantially enhanced in the Da Hinggan Mountains region with slight depopulation, and the APF weakened in Songnen Plain and Sanjiang Plain where the population increased. Between 2010 to 2020, the APF slightly weakened in the Da Hinggan Mountains region with a continuous population shrinkage. While in the Songnen Plain and Sanjiang Plain, the APF enhanced in the counties with severe population shrinkage. It could be seen that the depopulation was a benefit to APF both in the forested region and plain areas, except for the continuous depopulation.

From 2000 to 2020, the EDF diminished with the depopulation intensification (Fig. 3b). In the Da Hinggan Mountains region with the continually slight depopulation, the EDF changed from a substantial enhancement to a slight enhancement. In the plain areas where the population increase has changed to a large depopulation, the EDF changed from substantially enhanced to slightly weakened. It could be seen that depopulation had an attenuated effect on economic development, no matter continually a slight or rapid depopulation.

The changes in SSF were complex and spatially heterogeneous during the study period (Fig. 3c). In the Da Hinggan Mountains region where the population continuously shrank, for SSF, the coexistence of slightly enhanced and diminished counties changed to most counties' function diminished. In most counties in the Songnen Plain, the SSF changed from slightly diminished in the earlier period to enhanced in the later period. The areas of function change overlapped with regions where the population shifted from growth to sharp shrinkage. Moreover, the deeper the population shrank, the more the SSF enhanced. It could be seen that population reduction contributed to the enhancement of SSF in plain areas, which differed from forested regions.

The ECF enhanced as the population changed from increased to decreased (Fig. 3d). From 2000 to 2010, the ECF was substantially enhanced in the northern part of the study area, while it was weakened in the southern region with population growth. From 2010 to 2020, in the Da Hinggan Mountains region where the population continued to shrink, the ECF slightly enhanced. The ECF slightly enhanced in the plain areas where the population increase changed to decrease, but the ECF slightly weakened in the areas with rapid depopulation. As a result, the ecological disturbance caused by the population growth would diminish the ECF. As the population decreased, the ECF was gradually restored. However, excessive depopulation was detrimental to the development of ECF.

Table 3 Structure of population changes during 2000–2010 and 2010–2020 in the typical black soil region of Northeast China

Change types	2000–2010		2010–2020	
	Plain areas / %	Forested region / %	Plain areas / %	Forested region / %
Population growth	42.86	5.95	0	3.57
Slight shrinkage	21.43	4.76	1.19	1.19
Medium shrinkage	7.14	4.76	3.57	4.76
Severe shrinkage	3.57	9.52	44.05	13.10
Extreme shrinkage	0	0	26.19	2.38
Total	100		100	

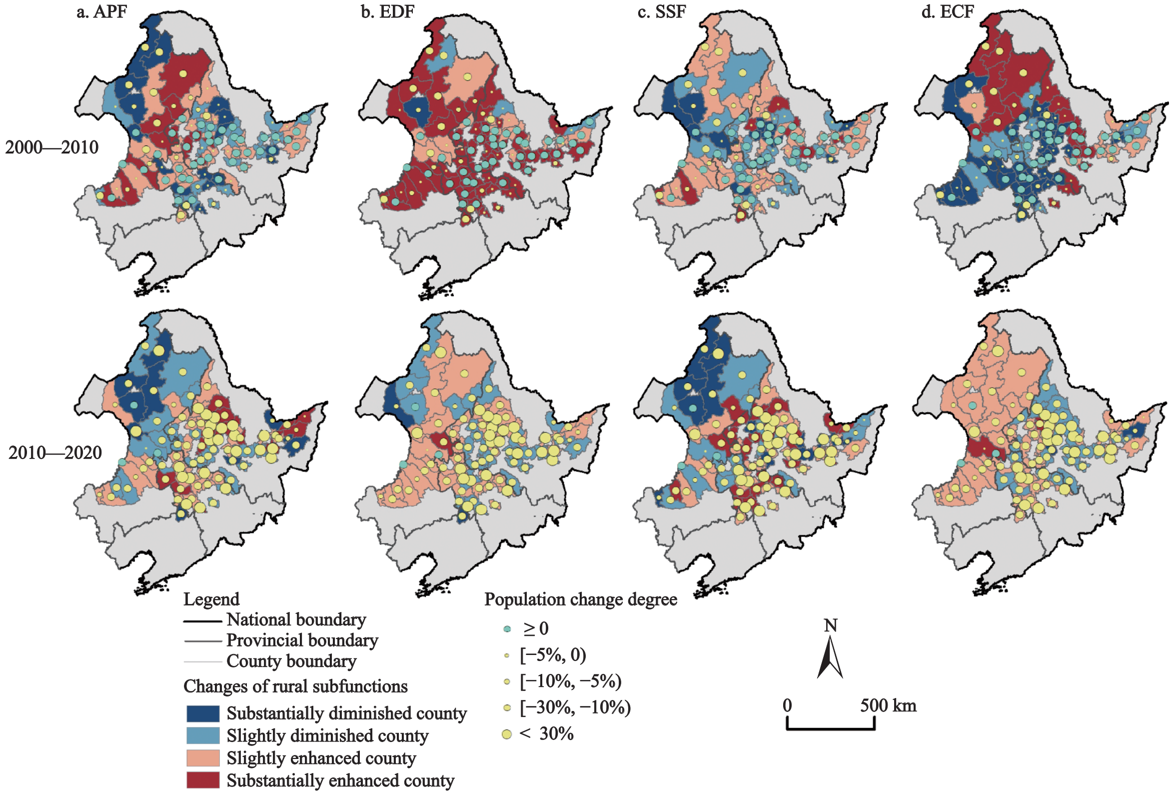

Fig. 3 Spatial changes in the rural subfunctions with various population change types from 2000 to 2020 in the typical black soil region of Northeast China. APF, agricultural production function; EDF, economic development; SSF, social security function; ECF, ecological conservation function

3.2 Interrelationships between the rural subfunctions under various population change types

3.2.1 The structure characteristics of the interrelationships between rural subfunctions under various population change types

As shown in Fig. 4, when the population grew, the synergy relationship accounted for 59% of the overall relationship between APF and EDF. As the depopulation deepened, the proportion of the severe trade-off relationship decreased from 25% in slight shrinkage to 4% in extreme shrinkage, showing a decreasing trend. Thus, the trade-off intensity between APF and EDF decreased as the depopulation deepened.

When the population shrank slightly, the relationship between APF and SSF mainly experienced a trade-off relationship, accounting for 57%, which was approximately consistent with the situation when the population increased. The effect of population changes on the relationship between APF and SSF was complicated. Overall, as the depopulation deepened, the proportion of the strongsynergyincreasedinafluctuatingtendency,showinga not obvious increased tendency of synergy.

The relationship between APF and ECF was mainly a trade-off when the population slightly shrank and increased. As population shrinkage deepened, the overall proportion of trade-offs decreased between APF and ECF. Among them, the proportion of the severe trade-off relationship decreased from 42% in slight shrinkage to 21% in extreme shrinkage. Thus, their trade-off intensity decreased as the depopulation deepened.

The relationship between EDF and SSF was dominated by trade-offs when the population increased. Population decrease did not have an obvious effect on the relationship between EDF and SSF. However, as the depopulation deepened, the proportion of severe trade-offs and strong synergy both decreased. Of these, the proportion of the severe trade-offs relationship decreased from 29% in slight shrinkage to 8% in extreme shrinkage. It could be seen that with the deepening population shrinkage, the intensity of the trade-off decreased.

The relationship between EDF and ECF was dominated by trade-offs when the population slightly shrank, which was the same with the condition of the population increase. As population shrinkage deepened, the

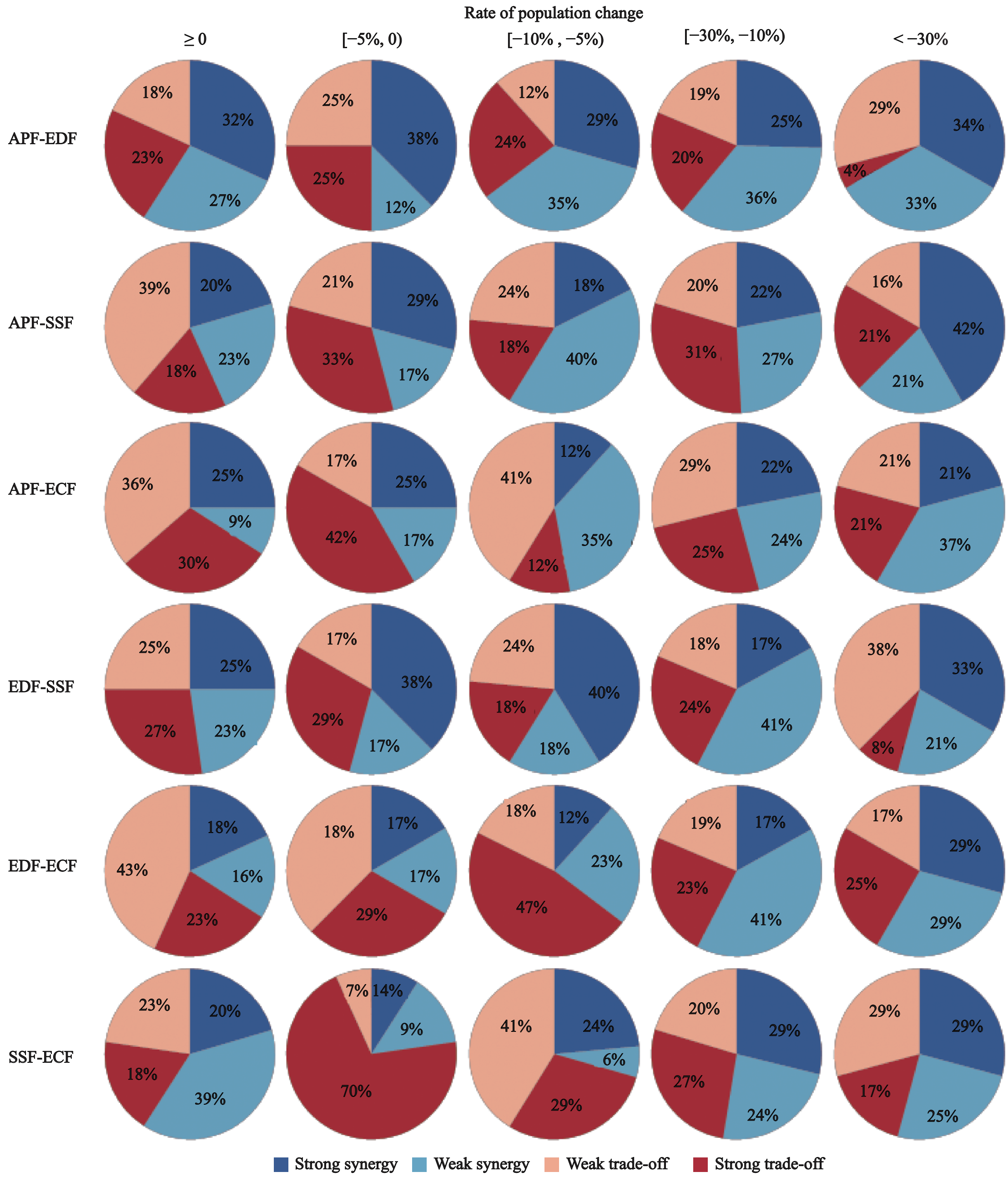

Fig. 4 Structures of trade-offs and synergies of the rural subfunctions under various population change types from 2000 to 2020 in the typical black soil region of Northeast China

proportion of severe and weak trade-offs both decreased, and their intensity also reduced. Therefore, population shrinkage promoted compatibility between the EDF and ECF.

The synergy relationship between SSF and ECF accounted for 59% when the population increased. The deeper the population shrank, the smaller the proportion of trade-offs between SSF and ECF accounted for. Among them, the proportion of the severe trade-off relationship decreased from 70% in slight shrinkage to 17% in extreme shrinkage. The proportion of weak trade-offs increased first and then decreased. Both the proportion and intensity of the trade-off decreased as depopulation deepened. Thus, the population decline reduced the conflict between SSF and ECF.

3.2.2 Spatial and temporal pattern of the interrelations between rural subfunctions under various population change types

From 2000 to 2020, as the depopulation deepened, the trade-off relationship weakened between APF and EDF, but there was spatial heterogeneity (Fig. 5a). Among them, in the Da Hinggan Mountains region with slight population shrinkage, the relationship between APF and EDF changed from trade-off to synergy. And, in the plain areas where population growth changed to population decrease, the severe trade-offs changed to weak trade-offs. However, the relationship changed from weak synergy to weak trade-off in plain areas with severe depopulation. Overall, population shrinkage alleviated the conflict between the APF and EDF, but it didn't apply to the case of excessive depopulation.

During the study period, the law of change between APF and SSF was not significant with the deepening population shrinkage (Fig. 5b). In the plain areas, with the population growth turning to rapid shrinkage, the weak synergistic relationship mostly turned into a weak trade-off relationship, and even part of it turned into a strong trade-off relationship. The trade-off intensity between APF and SSF also increased in most counties in the Da Hinggan Mountains region where the population continued to decrease. But in the southern Da Hinggan Mountains region, a few counties had trade-off relationships changed from synergy relationships. It could be seen that the population shrinkage had an uncertain impact on the relationship between APF and SSF.

As the population shrinkage deepened, the trade-off relationship between APF and ECF weakened from 2000 to 2020 (Fig. 5c). Among them, in the northern Da

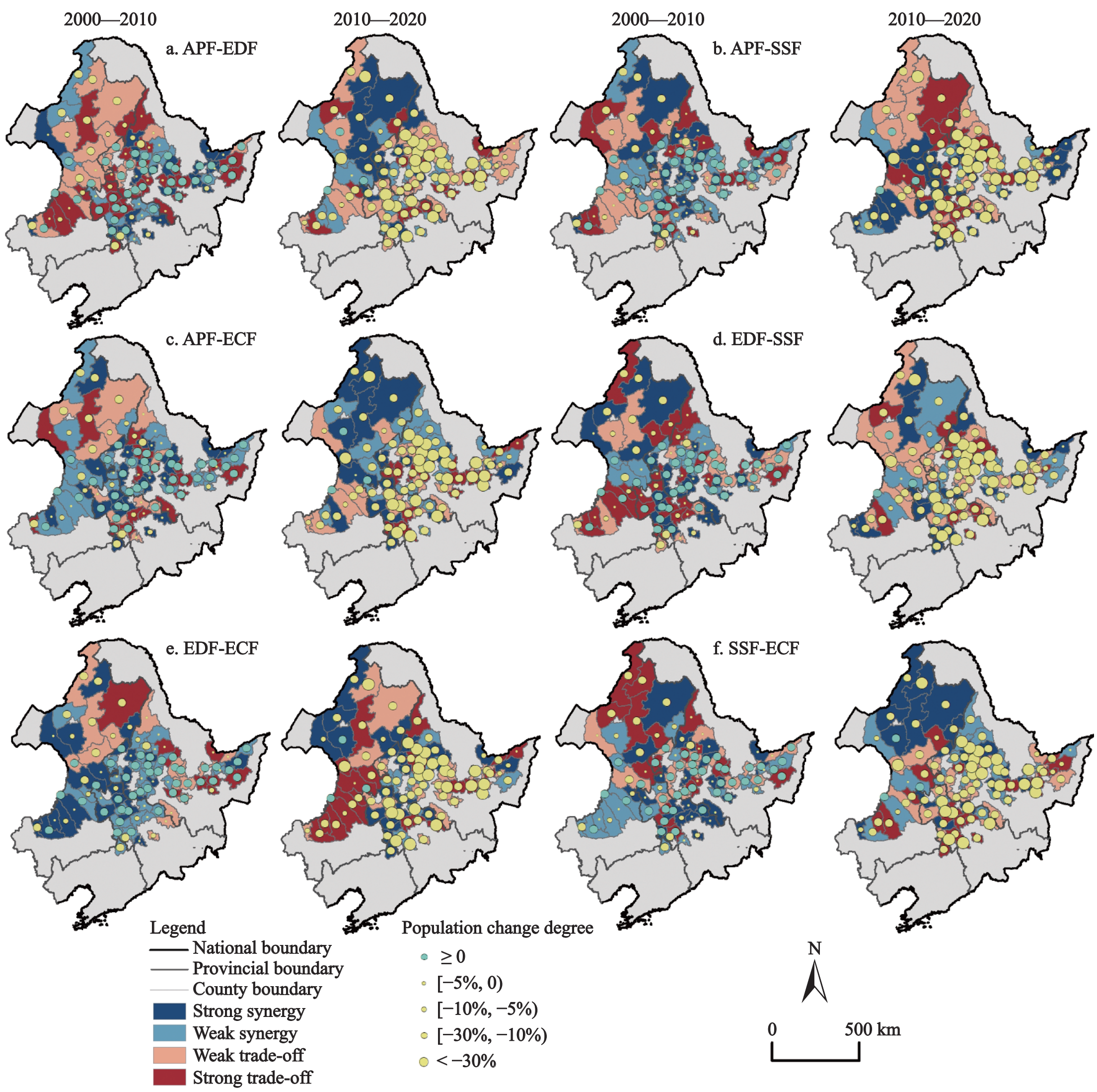

Fig. 5 Spatial and temporal characteristics of the trade-offs and synergies of the rural subfunctions under various population change types from 2000 to 2020 in the typical black soil region of Northeast China. APF, agricultural production function; EDF, economic development; SSF, social security function; ECF, ecological conservation function

Hinggan Mountains region where the population continued to shrink, the relationship changed from trade-offs to synergies, and the proportion of synergistic relationships increased. However, in Songnen Plain and Sanjiang Plain where the population changed from increased to decreased, the intensity of trade-offs and synergies weakened. It showed that, with the deepening population shrinkage, the conflicted relationship would weaken between APF and ECF.

The degree of trade-off between EDF and SSF weakened as population shrinkage deepened from 2000 to 2020 (Fig. 5d). Spatially, the impact of population shrinkage on the relationship between EDF and SSF was complex. In the plain areas, the relationship between EDF and SSF mainly manifested a severe trade-off in the early stage of the study period. When the population experienced a severe shrinkage, there was a reduction in the strength of the trade-off relationship. The Da Hinggan Mountains region with continued population shrinkage had changed from a serious trade-off to a weak trade-off. So severe population shrinkage might not completely transform a trade-off relationship into a synergistic relationship, but it would reduce the degree of a trade-off. So population shrinkage was conducive to the synergistic development of EDF and SSF to a certain degree.

Spatially, the impact of depopulation on the relationship between EDF and ECF was complex. And there was a spatial difference between the forested region and plain areas (Fig. 5e). In the Da Hinggan Mountains region, the relationship between EDF and ECF changed from synergy to trade-off. But the synergy was enhanced in the plain areas where the population increase changed to extreme depopulation. The differences might due to a combination of factors, such as a shrinking population. In the plain areas with the deepening depopulation, the synergistic relationships increased, indicating that population decline was beneficial to the synergistic development of EDF and ECF.

From 2000 to 2020, with the deepening depopulation, the synergistic relationship became stronger between the SSF and ECF (Fig. 5f). In most counties of the Da Hinggan Mountains region, where the population continued to shrink, the relationship between SSF and ECF changed from severe trade-offs to severe synergies. In most counties of the plain areas, the trade-off intensity between SSF and ECF weakened when the population increase turned to decrease, and the synergy proportion increased. However, the relationship changed from synergy to trade-off in some counties, too. On the whole, the synergistic relationship enhanced as population shrinkage deepened, so population shrinkage was a benefit to the synergistic development of SSF and ECF.

4 Discussion

4.1 Diversified impacts of depopulation on rural functions change

4.1.1 Regional overall heterogeneity of impacts

It was found that since 2000, along with the deepening of population shrinkage, rural subfunctions in the typical black soil region of Northeast China had different trajectories, for example, a smaller depopulation helped to strengthen the social security function, but the agricultural production function weakened in the situation of long-term loss in rural population. The conclusion demonstrated the complicated effects of demographic change, which was not exactly the same as the conclusion of the continuous decline of rural production and living functions in Heilongjiang Province (Ni et al., 2022), and was not completely contrary to the conclusion that all rural functions in Liaoning Province were enhanced (Xu and Fang, 2021). Therefore, the differences represented that the population decline in rural areas of Northeast China did have a certain impact on rural functions.

Differences in population density and depopulation between the plain areas and the forested region, might be rooted in the differentiated physical and geographical conditions, which was also the cause of different trajectories of function evolution. The extent and timing of population decline all affected the trajectories of rural functional changes. Thus the impacts of population shrinkage on rural functions of different regions were very different. This was similar to the situation that the population reduction enhanced food production services in the fertile plains (Bruno et al., 2021), but led to land abandonment in other places (Quaranta et al., 2020). Similar results were found for forest cover changes, that is, depopulation stop deforestation in Vršac mountain, and the opposite situation occurred in the suburb of a special nature reserve (Gataric et al., 2022). When analyzing the negative influences of population decline, the regional characteristics and inter-regional differences should be considered to improve accuracy, which objectively required our research scale to be more and more refined.

4.1.2 Different impacts of depopulation degrees on rural subfunctions

Under the trend of population shrinkage, the evolution tracks of rural subfunctions were not all identical in our study. It showed that the effects of population shrinkage on the evolution of each rural subfunctions were different. For agricultural production function, because of the positive effect of population outflow on the transfer of agricultural land (Long et al., 2016), short-term depopulation indirectly promoted the food production function (Xue and Zhen, 2018). However, this was only the first half of our conclusion. Due to the negative influences of population decline, long-term depopulation led to the weakening of agricultural production function. Various degrees of population shrinkage had different effects. When the shrinking population reached a certain level, the mode of action might change qualitatively (Hu and Lin, 2023). This situation also applied to the change of other subfunctions. Population shrinkage reduced human disturbance to the rural landscape, which was beneficial to the restoration of the natural environment in some habitat-rich areas (Veteikis et al., 2011). At first, the slow depopulation was helpful for the recovery of ecological conservation, but then the rapid loss had a negative effect. It was similar to economic development in our study. This suggested that we must pay attention to differences in the degree of depopulation when analyzing the effects of population shrinkage on rural functions.

4.2 Complicated relationships and trade-offs between subfunctions

4.2.1 Dominant function or balanced functional development?

Functions were constantly being transformed and diversified, and were not always in sync with each other (Beardmore et al., 2019). We assessed the multiple possible functions of rural areas to understand systematically what patterns of land use provide the most likely outcomes. In terms of the range of material goods and services provided, it was obvious that rural areas should serve both urban development and sustainable rural development and revitalization, that was, i.e., the function of rural areas was to serve the integrated development of urban and rural areas. However, there were trade-offs in practice when it came to specific product and feature type. Different from regions with low suitability for large-scale agricultural production, the coordinated development of multiple functions could guarantee farmers' welfare and sustainable land use (Milestad et al., 2011). The black soil region of Northeast China with abundant cultivated land resources was a potential area of large-scale production (Liu et al., 2011). Rural depopulation made it possible for land transfer and scale management (Long et al., 2016; Liu, 2022a). Under the trend of rural depopulation, rural functions continued to alternate, and functional trade-offs and synergies were also changing. Should rural areas with regional particularity focus on improving one function, such as food production, or balance multiple functions at the same time, namely rural revitalization? How to choose the functions that rural areas need to provide was also crucial. If the function of agricultural production to ensure food security was the ultimate choice, then land consolidation and population concentration were needed to achieve more scale management. And innovation and diversification in the countryside besides conventional agriculture should be supported to realize the competitiveness and sustainability of rural regions, too. Otherwise, if taking into account multiple functions was the ultimate choice, then while focusing on the development of agricultural production functions, it was necessary to carry out ecological industrial transformation and upgrading in rural areas to provide enough employment opportunities for the local population, such as rural tourism, to guarantee the social welfare of rural residents and sustainable development of rural areas.

4.2.2 How to realize spatial equilibrium?

According to our conclusions, the impact of depopulation was a broadly consistent trend, i.e., population shrinkage diminished the conflict between subfunctions in most cases except APF and SSF. However, the effects of depopulation on the interaction between rural functions varied between the plain areas and the forested region. For example, the population shrinkage may promote the coordinated development of ECF and EDF as well as SSF in plains, but aggravate the conflict between ECF and EDF as well as SSF in the forested region. Hence, for sustainable development of rural regions in the black soil region of Northeast China, it would be necessary to focus on the areas with negative impacts of the depopulation, which would contribute to the rural development in whole areas (Hrabánková and Bohácková, 2007). The change and development of functions should be considered from a regional coordination perspective to balance the advantaged and disadvantaged regions. And the suitable development mode should always be judged regarding the regional specifics, especially whether the growth poles were needed, namely, dominant functional areas. Meanwhile, the scale on which the adverse effects of depopulation should be addressed also needs in-depth consideration.

The difficulty of land management is how to develop land use to meet multiple objectives and functional needs of different groups (Radel et al., 2019). Because of spatial differences in functional evolutions and depopulation effects, it was necessary to carry out zoning control measures according to the characteristics of the coordination and trade-off relationship between functions (Zou et al., 2020). Specifically, for counties dominated by functional synergies, coordinated development among functions should be promoted to enhance functional synergy and realize balanced development of rural multi-functions (Dai et al., 2022). For counties dominated by functional trade-offs, the leading functions of counties should be explored, and their impacts on other secondary functions should be taken into account, to avoid overvaluing and neglecting single functions and maximize the comprehensive benefits of multiple functions in rural areas (Liu et al., 2021b). In addition, the advantages of resource factors in the black soil region of Northeast China should be taken as important conditions to drive the development of rural regional functions, and the population transformation and rural space reconstruction should be taken as opportunities for rural industrial transformation. We should give play to the driving role of the dominant functional area, and reduce the conflict impact of trade-off relationships in space. So, the natural resources in the black soil region of Northeast China could be utilized for the rural industrial transformation, and then the new unique industrial types and economic formats should be cultivated on a regional scale (Long and Tu, 2017), such as ecological agriculture experience areas and traditional agricultural sightseeing belts.

4.3 Scientific response to population shrinkage

From the current development trend, the shrinking trend of the population in Northeast China caused by the double decrease in population base and fertility rate will continue in the future period, and the aging degree of agricultural operation population will be further deepened. The effects of population shrinkage on rural regional functions were complex in our study, with positive and negative effects, and spatial heterogeneity. For example, population shrinkage was conducive to the synergistic development of most functions, but the population shrinkage also aggravated the conflict between APF and SSF in some cases, but the conflict weakened with the increase of population shrinkage. We must dialectically look at the impact of population shrinkage and scientifically deal with the problem of population shrinkage, especially in areas with the unstable settlement, insufficient economic efficiency, and a high rate of non-farm employment.

So formulating countermeasures for both population and rural economic development is necessary. On the one hand, we should actively promote the reform of the rural land system, promote the orderly transfer of cultivated land, implement the large-scale management of agricultural land, accelerate the modernization process of agricultural production, enhance the function of agricultural production, reshape the value of rural areas, and effectively guarantee the national food security. On the other hand, it is necessary to prevent the adverse effects of population decline as early as possible. We should strengthen policies to support employment, expand local employment, and encourage surplus agricultural workers to stabilize non-agricultural employment in nearby areas and promote the nearby urbanization of the rural population to retain the local population as much as possible (Anríquez and Daidone, 2010). At the same time, facing the development process of modern agriculture, we should develop an effective new professional farmer cultivation system to promote the transformation of the rural labor force(Li et al., 2019). And, the employment skills and competitiveness of the older agricultural workers should be improved to avoid their premature withdrawal from the rural job market. While guaranteeing the function of agricultural production, the rural social security function should be improved to promote the coordinated development of human beings and land use in the new era (Dong et al., 2022).

4.4 Shortcomings and research prospects

It was found that the core area of the black soil region of

Northeast China has been the key area of population decline from 2000 to 2020. The depopulation during this period was a contemporaneous decrease in the urban and rural populations. With the deepening population shrinkage, the impact of depopulation on rural functions was more and more complex. Population shrinkage was mainly due to a lack of economic and employment opportunities (Li et al., 2020; Wang et al., 2022), which led to the cultivated land resource dependence and poverty of farmers (Li et al., 2021). The black soil region of Northeast China bears the important responsibility of ensuring national food security, but the loss of young and middle-aged labor force inevitably accompanies the aging of the agricultural working population. It is generally recognized that population shrinkage has the most significant impact on urban economic development and has received the most attention. However, this analytical framework was not suitable for rural areas. To analyze the impact of population shrinkage on rural functions from the county scale, one of the presuppositions was that urban and rural populations shrank at the same rate. The current depopulation in rural areas in Northeast China was more serious than that in urban areas, and the instability of population change in urban and rural areas increased. In addition, the population aging was accelerated in Northeast China, which might further strengthen the impact of depopulation on rural regional functions or made the mechanism more complex. However, due to the limitation of research data, we did not make further analysis, which was a pity and further discussion.

5 Conclusions

To analyze the impact of population shrinkage on rural subfunctions, based on the land use data, census data, and socio-economic statistical data from 2000 to 2020, a case study was carried out on the process of population change and its impact on the evolution characteristics and interaction of rural functions in the counties in the typical black soil region of Northeast China. The main conclusions were as follows. Firstly, there was a small quantity of population in the western forested region with an early and slight depopulation, while the depopulation in the plain areas with a larger density was late and fast. Between 2000 and 2020, the evolutions of rural subfunctions showed differentiated characteristics with the deepening depopulation. Short-term depopulation was a benefit to the enhancement of the APF, while the long-term loss would weaken the APF. The population decline would enhance the SSF in the whole study area. The population increase and slight decrease could promote EDF and ECF to a certain extent, but rapid depopulation disadvantaged the enhancement of EDF and ECF. That was to say, the impact of depopulation on rural subfunctions varied from each other.

Population shrinkage also had various effects on the interrelationship of rural subfunctions. Depopulation could alleviate the conflict between APF and EDF as well as ECF. The slight spatial difference between the plain areas and the forested region was that increased synergistic relationship or weakened trade-off relationship. It was a similar situation for EDF and SSF. Even though the relationships between ECF and EDF as well as SSF were complex, the population decline was generally beneficial to their synergistic development. There was a fine distinction in spatial heterogeneity between ECF-EDF and ECF-SSF. For ECF and EDF, the spatial difference was between the forested region and plain areas, while the difference was between the northern region and the southern region of the study area for ECF and SSF. Population change had a distinctively complex impact on the relationship between APF and SSF. Population shrinkage might aggravate the conflict between APF and SSF, and the conflict would ease with the deepened depopulation, which was spatial heterogeneous between the forested region and plain areas.

In conclusion, the population shrinkage indeed had an obvious effect on the evolution and interaction of rural functions in our study. The impact varied from regions and kinds of functions in the typical black soil region of Northeast China. Facing the background of continuous population shrinkage, the impact of population change on rural subfunctions and their interactions should be evaluated scientifically, and the adverse effects and good opportunities of population shrinkage should be faced squarely, so as to explore ways for rural revitalization and sustainable development in the black soil region of Northeast China and contribute to the improvement and transformation of rural functions in the period of population transition development. However, the formation and development of rural functions may be affected by various internal and external factors, too. We had only focused on the effects of population decline, which was the first limitation of this study. In addition, rural functions have strong regional heterogeneity, this study is only a preliminary exploration of the influencing factors of rural functions in the typical black soil region of Northeast China. We only deeply analyzed the impact of population shrinkage on the evolution and interaction of rural functions and did not carry out targeted functional zoning and differential functional regulation measures based on this. So, the specific strategy of functional collaborative development of rural functions needs to be further explored.

References

Anríquez G, Daidone S, 2010. Linkages between the farm and nonfarm sectors at the household level in rural Ghana: a consistent stochastic distance function approach. *Agricultural Economics*, 41(1): 51–66. doi: 10.1111/j.1574-0862.2009.00425

Beardmore L, Heagney E, Sullivan C A, 2019. Complementary land use in the Richmond River catchment: evaluating economic and environmental benefits. *Land Use Policy*, 87: 104070. doi: 10.1016/j.landusepol.2019.104070

Bowns C, 2013. Shrinkage happens in small towns too: responding to de-population and loss of place in Susquehanna River Towns. *Urban Design International*, 18(1): 61–77. doi: 10.1057/udi.2012.27

Brown I, Castellazzi M, 2014. Scenario analysis for regional decision-making on sustainable multifunctional land uses. *Regional Environmental Change*, 14(4): 1357–1371. doi: 10.1007/s10113-013-0579-3

Bruno D, Sorando R, Álvarez-Farizo B et al., 2021. Depopulation impacts on ecosystem services in Mediterranean rural areas. *Ecosystem Services*, 52: 101369. doi: 10.1016/j.ecoser.2021.101369

Chen Xiwen, 2020. The core of China's rural revitalization: exerting the functions of rural area. *China Agricultural Economic Review*, 12(1): 1–13. (in Chinese)

Chinese Academy of Sciences, 2021. T*he Northeast Black Soil White Paper*. Beijing: Chinese Academy of Sciences.

Dai Ruilian, Wang Cheng, Wu Xinyue, 2022. Path of rural sustainable development based on the evolution and interaction of rural functions: a case study of Chongqing Municipality, China. *Chinese Geographical Science*, 32(6): 1035–1051. doi: 10.1007/s11769-022-1312-2

Dax T, Fischer M, 2018. An alternative policy approach to rural development in regions facing population decline. *European Planning Studies*, 26(2): 297–315. doi: 10.1080/09654313.2017.1361596

Dong Wei, Zhou Chuyan, Xia Lei, 2022. Enlightenment of minnesota's rural sustainable development path to Northeast China under the background of population shrinkage. *Urban Planning International*, 37(3): 17–25. (in Chinese)

Fan Y T, Jin X B, Gan L et al., 2018. Spatial identification and dynamic analysis of land use functions reveals distinct zones of multiple functions in eastern China. *Science of the Total Environment*, 642: 33–44. doi: 10.1016/j.scitotenv.2018.05.383

Gatariće D, Đerčan B, Živković M B et al., 2022. Can depopulation stop deforestation? the impact of demographic movement on forest cover changes in the settlements of the South Banat District (Serbia). *Frontiers in Environmental Science*, 10: 897201. doi: 10.3389/fenvs.2022.897201

Gong J, Liu D Q, Zhang J X et al., 2019. Tradeoffs/synergies of multiple ecosystem services based on land use simulation in a mountain-basin area, western China. *Ecological Indicators*, 99: 283–293. doi: 10.1016/j.ecolind.2018.12.027

Gu X K, Xie B M, Zhang Z F et al., 2019. Rural multifunction in Shanghai suburbs: Evaluation and spatial characteristics based on villages. *Habitat International*, 92: 102041. doi: 10.1016/j.habitatint.2019.102041

Guan D J, He X J, Hu X X, 2021. Quantitative identification and evolution trend simulation of shrinking cities at the county scale, China. *Sustainable Cities and Society*, 65: 102611. doi: 10.1016/j.scs.2020.102611

Han Xiaozeng, Li Na, 2018. Research Progress of Black Soil in Northeast China. *Scientia Geographica Sinica*, 38(7): 1032–1041. (in Chinese)

Holmes J, 2006. Impulses towards a multifunctional transition in rural Australia: gaps in the research agenda. *Journal of Rural Studies*, 22(2): 142–160. doi: 10.1016/j.jrurstud.2005.08.006

Hrabánková M, Boháčková I, 2007. Conditions of sustainable development in the Czech Republic in compliance with the recommendation of the European Commission. *Agricultural Economics*, 53(3): 285–289. doi: 10.17221/980-AGRICECON

Hu X L, Lin S L, 2023. Rural depopulation on agricultural technological choice in China. *Ciência Rural*, 53: e20210413. doi: 10.1590/0103-8478cr20210413

Huang S H, Wang Y, Liu R J et al., 2022. Identification of land use function bundles and their spatiotemporal trade-offs/synergies: a case study in Jiangsu coast, China. *Land*, 11(2): 286. doi: 10.3390/land11020286

Huang Tianneng, Wang Nian, 2022. Spatial-temporal evolution analysis on land use multifunctionality in the China-Vietnam Border Area. *Chinese Geographical Science*, 32(6): 995–1012. doi: 10.1007/s11769-022-1316-y

Jiang G H, Wang M Z, Qu Y B et al., 2020. Towards cultivated land multifunction assessment in China: applying the "influencing factors-functions-products-demands" integrated framework. *Land Use Policy*, 99: 104982. doi: 10.1016/j.landusepol.2020.104982

Johnson K M, Lichter D T, 2019. Rural depopulation: growth and decline processes over the past century. *Rural Sociology*, 84(1): 3–27. doi: 10.1111/ruso.12266

Lambin E F, Meyfroidt P, 2011. Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences of the United States of America*, 108(9): 3465–3472. doi: 10.1073/pnas.

1100480108

Li D M, Yang Y Y, Du G M et al., 2021. Understanding the contradiction between rural poverty and rich cultivated land resources: a case study of Heilongjiang Province in Northeast China. *Land Use Policy*, 108: 105673. doi: 10.1016/j.landusepol.2021.105673

Li He, Lo K, Zhang Pingyu, 2020. Population shrinkage in resource-dependent cities in China: processes, patterns and drivers. *Chinese Geographical Science*, 30(1): 1–15. doi: 10.1007/s11769-019-1077-4

Li Y H, Westlund H., Liu Y S, 2019. Why some rural areas decline while some others not: an overview of rural evolution in the world. *Journal of Rural Studies*, 68: 135–143. doi: 10.1016/j.jrurstud.2019.03.003

Liao G T, He P, Gao X S et al., 2022. Land use optimization of rural production-living-ecological space at different scales based on the BP-ANN and CLUE-S models. *Ecological Indicators*, 137: 108710. doi: 10.1016/j.ecolind.2022

Liu B C, Fang Y G, 2021. The Nexus between rural household livelihoods and agricultural functions: evidence from China. *Agriculture*, 11(3): 241. doi: 10.3390/agriculture11030241

Liu Baoyuan, Zhang Ganlin, Xie Yun et al., 2021a. Delineating the black soil region and typical black soil region of northeastern China. *Chinese Science Bulletin*, 66(1): 96–106. (in Chinese)

Liu Yansui, Liu Yu, Chen Yufu, 2011. Territorial multi-functionality evaluation and decision-making mechanism at county scale in China. *Acta Geographica Sinica*, 1379–1389. (in Chinese)

Liu Yu, Gao Yunbing, Pan Yuchun et al., 2021b. Spatial differentiation characteristics and trade-off/synergy relationships of rural multi-functions based on multi-source data. *Geographical Research*, 40: 2036–2050. (in Chinese)

Liu Z, 2022a. Rural population decline, cultivated land expansion, and the role of land transfers in the farming-pastoral ecotone: a case study of Taibus, China. *Land*, 11(2): 256. doi: 10.3390/land11020256

Liu Z, 2022b. Empirical examinations of whether rural population decline improves the rural eco-environmental quality in a chinese context. *Remote Sensing*, 14(20): 5217. doi: 10.3390/rs14205217

Liu Zhen, Qi Wei, Liu Shenghe, 2021c. The differences of urban-rural population change and the underlying mechanism in the population shrinking counties in China. *Scientia Geographica Sinica*, 41(7): 1116–1128. (in Chinese)

Liu Ziqiang, Zhou Ailan, Lu Qi, 2012. The transition of rural territorial leading function and the classification of rural development stages. *Journal of Arid Land Resources and Environment*, 26(4): 49–54. (in Chinese)

Long H L, Ma L, Zhang Y N et al., 2022. Multifunctional rural development in China: pattern, process and mechanism. *Habitat International*, 121: 102530. doi: 10.1016/j.habitatint.2022

Long H L, Tu S S, Ge D Z et al., 2016. The allocation and management of critical resources in rural China under restructuring: Problems and prospects. *Journal of Rural Studies*, 47: 392–412. doi: 10.1016/j.jrurstud.2016.03.011

Long Hualou, Tu Shuangshuang, 2017. Rural restructuring: theory, approach and research prospect. *Acta Geographica Sinica*, 563–576. (in Chinese)

Milestad R, Ahnström J, Björklund J, 2011. Essential multiple functions of farms in rural communities and landscapes. *Renewabal Agriculture and Food Systems*, 26(2): 137–148. doi: 10.1017/S1742170510000529

Ni Weiqiu, Xia Yuan, Zhao Ningning, 2022. The functional evolution and coupling coordination measurement of production-living-ecological space in rural areas: taking Heilongjiang Province as an example. *China Land Science*, 36: 111–119. (in Chinese)

Pérez-Soba M, Petit S, Jones L et al., 2008. Land use functions—a multifunctionality approach to assess the impact of land use changes on land use sustainability. In: Helming K, Pérez-Soba M, Tabbush P (eds.). *Sustainability Impact Assessment of Land Use Changes*. Berlin, Heidelberg: Springer, 375−404. doi: 10.1007/978-3-540-78648-1_19

Pinto-Correia T, Menezes H, Barroso L F, 2014. The Landscape as an asset in southern European Fragile agricultural systems: contrasts and contradictions in land managers attitudes and practices. *Landscape Research*, 39(2): 205–217. doi: 10.1080/01426397.2013.790948

Quaranta G, Salvi R, Salvati L et al., 2020. Long-term impacts of grazing management on land degradation in a rural community of Southern Italy: Depopulation matters. *Land Degradation & Development*, 31(16): 2379–2394. doi: 10.1002/ldr.3583

Radel C, Jokisch B D, Schmook B et al., 2019. Migration as a feature of land system transitions. *Current Opinion in Environmental Sustainability*, 38: 103–110. doi: 10.1016/j.cosust.2019.05.007

Ribeiro Palacios M, Huber-Sannwald E, García Barrios L et al., 2013. Landscape diversity in a rural territory: Emerging land use mosaics coupled to livelihood diversification. *Land Use Policy*, 30(1): 814–824. doi: 10.1016/j.landusepol.2012.06.007

Rodríguez-Soler R, Uribe-Toril J, De Pablo Valenciano J, 2020. Worldwide trends in the scientific production on rural depopulation, a bibliometric analysis using bibliometrix R-tool. *Land Use Policy*, 97: 104787. doi: 10.1016/j.landusepol.2020.104787

Sheludkov A, Kamp J, Mueller D, 2021. Decreasing labor intensity in agriculture and the accessibility of major cities shape the rural population decline in postsocialist Russia. *Eurasian Geography and Economics*, 62(4): 481–506. doi: 10.1080/15387216.2020.1822751

Shi Z H, Ma L B, Zhang W B et al., 2022. Differentiation and correlation of spatial pattern and multifunction in rural settlements considering topographic gradients: evidence from Loess Hilly Region, China. *Journal of Environmental Management*, 315: 115127. doi: 10.1016/j.jenvman.2022

Šimon M, Bernard J, 2016. Rural Idyll without rural sociology? Changing features, functions and research of the Czech countryside. *Eastern European Countryside*, 22(1): 53–68. doi: 10.1515/eec-2016-0003

Tan X L, Ouyang Q L, An Y et al., 2019. Evolution and driving forces of rural functions in urban agglomeration: a case study of the Chang-Zhu-Tan region. *Journal of Geographical Sciences*, 29(8): 1381–1395. doi: 10.1007/s11442-019-1665-3

Tang Linnan, Liu Yu, Tang Xiumei, 2016. Temporal characteristics and coupling of urban-rural transformation and rural regional multifunction in Beijing: from 1978 to 2012. *Human Geography*, 31(6): 123–129.

Tong Y, Liu W, Li C G et al., 2022. County town shrinkage in China: Identification, spatiotemporal variations and the heterogeneity of influencing factors. *Journal of Rural Studies*, 95: 350–361. doi: 10.1016/j.jrurstud.2022.09.029

Verkulevičiūtė-Kriukienė D, Bučienė A, Beteika L, 2018. Rural landscape status, functions and human factors in the transboundary Nemunas delta region. *Area*, 50(3): 353–363. doi: 10.1111/area.12383

Veteikis D, Šabanovas S, Jankauskaite M, 2011. Landscape structure changes on the coastal plain of Lithuania during 1998-2009. *Baltica*, 24(2): 107–116.

Wang Minghua, 2021. *China Statistical Yearbook* (*County-Level*). Beijing: China Statistic Publishing House. (in Chinese)

Wang Tingting, Wu Kang, Yao Cuiyou et al., 2022. Complex pathways to population shrinkage: case study of Hegang City, China. *Chinese Geographical Science*, 32(3): 418–437. (in Chinese)

Wen Q, Shen C T, Xia S Y et al., 2022. Analysis of spatiotemporal variations and effects of regional functions in rural China. *Growth and Change*, 53(3): 1414–1435. doi: 10.1111/grow.12628

Wen Yuling, Zhang Xiaolin, Wei Jiahao et al., 2022. Temporal and spatial variation of ecosystem service value and its trade-offs and synergies in the peripheral region of the Poyang Lake. *Scientia Geographica Sinica*, 42(7): 1229–1238.

Wiggering H, Dalchow C, Glemnitz M et al., 2006. Indicators for multifunctional land use-linking socio-economic requirements with landscape potentials. *Ecological Indicators*, 6(1): 238–249. doi: 10.1016/j.ecolind.2005.08.014

Willemen L, Hein L, van Mensvoort M et al., 2010. Space for people, plants, and livestock? quantifying interactions among multiple landscape functions in a Dutch rural region. *Ecological Indicators*, 10(1): 62–73. doi: 10.1016/j.ecolind.2009.02.015

Wirth P, Elis V, Mueller B et al., 2016. Peripheralisation of small towns in Germany and Japan Dealing with economic decline and population loss. *Journal of Rural Studies*, 47: 62–75. doi: 10.1016/j.jrurstud.2016.07.021

Xian Zude, 2001. *China County Statistical Yearbook.* Beijing: China Statistic Publishing House. (in Chinese)

Xie Gaodi, Zhang Caixia, Zhang Leiming et al., 2015. Improvement of the evaluation method for ecosystem service value based on per unit area. *Journal of Natural Resources*, 30(8): 1243–1254. (in Chinese)

Xu Kai, Fang Yangang, 2021. Rural multi-function evaluation and evolution characteristics in Liaoning Province. *Economic Geography*, 41(1): 147–157. (in Chinese)

Xue Z C, Zhen L, 2018. Impact of rural land transfer on land use functions in Western China's guyuan based on a multi-level stakeholder assessment framework. *Sustainability*, 10(5): 1376. doi: 10.3390/su10051376

Yang Ren, Zhang Jing, Chen Yanchun, 2021. Differentiation and dynamic mechanism of rural development in metropolitan fringe based on the functional perspective in Guangzhou City. *Scientia Geographica Sinica*, 41(2): 232–242. (in Chinese)

Yang Y Y, Bao W K, Liu Y S, 2020. Coupling coordination analysis of rural production-living-ecological space in the Beijing-Tianjin-Hebei region. *Ecological Indicators*, 117: 106512. doi: 10.1016/j.ecolind.2020.106512

Zhang Shuying, 2011. *China County Statistical Yearbook.* Beijing: China Statistic Publishing House. (in Chinese)

Zou L L, Liu Y S, Yang J X et al., 2020. Quantitative identification and spatial analysis of land use ecological-production-living functions in rural areas on China's southeast coast. *Habitat International*, 100: 102182. doi: 10.1016/j.habitatint.2020.102182