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Spatio-temporal patterns and driving mechanism of farmland fragmentation in the Huang-Huai-Hai Plain

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Abstract: Exploring the spatio-temporal variations of farmland landscape patterns in a traditional agricultural region can provide scientific support for decision-making on sustainable rural land use and rural vitalization development. This study established a comprehensive evaluation index for farmland fragmentation with multiple aspects (dominance, integrity, aggregation, regularity, and connectivity) at the county scale. The goal was to identify the evolution of farmland fragmentation in the traditional agricultural region of the Huang-Huai-Hai Plain during 2000–2015 and investigate underlying drivers using panel data of 359 counties. Results showed an accelerating but fluctuating fragmentation pattern of the farmland landscape. The indexes of dominance, integrity, and aggregation of farmland decreased most sharply, while the index of connectivity increased. Furthermore, the evolution of the farmland fragmentation pattern showed significant spatio-temporal heterogeneity, which is similar to the trajectory of urbanization and land use transition. Farmland fragmentation in municipal districts also emerged earlier and was more severe than in county-level cities and counties. Factors influenced by advancing urbanization include the proportion of artificial land, population density, and proportion of primary industry; these factors drove the evolution of farmland fragmentation. In contrast, the increase in income of rural residents and production efficiency of farmland were the key factors contributing to the improvement in farmland connectivity.

Keywords: landscape fragmentation; divergent pattern; driving mechanism; farmland; Huang-Huai-Hai Plain

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1 Introduction

Over the past four decades, China has undergone rapid industrialization and urbanization. These changes have been accompanied by the expense of rural development and agricultural interests, of which the loss of farmland is the most distinct manifestation (Long *et al*., 2011; Zuo *et al*., 2018). The sharp decline in the amount of high-quality farmland has led to landscape fragmentation: the separation of farmland into scattered patches of various sizes, and ultimately presents a complex and heterogeneous farmland landscape (Cheng *et al*., 2015).

A common and significant feature of farmland landscapes, farmland fragmentation is caused by multiple natural and manmade factors (Sklenicka and Salek, 2008). Changes in farmland landscapes exert profound effects on the functioning of human–land systems. From the local perspective, farmland fragmentation causes a decline in agricultural productivity and adjustments in agricultural land management (Latruffe and Piet, 2014; Jiang *et al*., 2020), and it is also closely related to farmland abandonment (Liang *et al*., 2020b). From the regional perspective, landscape fragmentation impacts ecosystem services such as soil conservation, biodiversity, and climate regulation (Costanza *et al*., 1997; Haddad *et al*., 2015). Global impacts include food security, employment, and sustainable development in rural areas (Liu *et al*., 2010; Long *et al*., 2018). Thus, farmland fragmentation has received widespread cross-disciplinary attention. Many countries and regions designate specific management practices and governance strategies according to local conditions, e.g., land consolidation, cooperative farming, and land banking; other agricultural policies are developed to mitigate and address the negative impact of farmland fragmentation (Tang *et al*., 2017; Ntihinyurwa and de Vries, 2020).

In China, the Household Responsibility System and farmland distribution based on the number of family members are the historical factors that have led to farmland fragmentation in China (Tan *et al*., 2006). Coupled with the expansion of urbanization and the transformation of rural livelihood patterns, the fragmented farmland landscape presents multiple dilemmas, such as inefficient small-holding decentralized businesses and farmland degradation or overuse (Chen *et al*., 2014). Currently, research mainly focuses on two aspects. (1) Ownership fragmentation from the traditional micro-scale perspective, i.e., scattered and downsized ownership determined by the historical land allocation policy (Tan *et al*., 2006). Household surveys, cadaster, and econometric statistics are basic analysis methods used by researchers (Tran and Van Vu, 2019; Xu *et al*., 2021). These studies provide a perspective on the impacts of households, farms, and individual or collective land use decision-making on farmland fragmentation. (2) Physical fragmentation measured by combining remote sensing and landscape indicators (Su *et al*., 2011). However, existing evaluations generally focus on a single aspect, e.g., the number of farmland patches or the size, while lacking the systematic knowledge and fundamental assessment criteria to quantify multiple aspects of farmland fragmentation patterns (Liu *et al*., 2019; Wei *et al*., 2020). Studies that have focused on the changes of the farmland internal structure, the regional or macro-scale spatial differentiation, and the driving factors are relatively limited. Although there might be a relationship between physical and ownership fragmentation, few studies combine these aspects to analyze their interactions (Yu *et al*., 2017). Therefore, it is essential to build a more comprehensive evaluation framework to identify farmland landscape stuctural features and changes within multiple perspectives.

Exploring the changes and mechanisms of farmland landscape fragmentation will help understand the relationship between urbanization and regional land use, as well as further promote the localized agricultural policies of farmland resource protection and land consolidation, which could provide a scientific basis for regional planning of sustainable utilization of farmland at various developmental stages. County-level areas usually serve as the basic unit for macro policy formulation and implementation in the Chinese administrative system. Counties are considered the transition between "city" and "village" stages (Zhou *et al*., 2018). Hence, it is practically significant to explore farmland fragmentation at the county-level in addressing land consolidation and fragmentation alleviation.

The Huang-Huai-Hai Plain (HHHP) is one of the major grain-producing areas of China. Dense populations and the demand for economic growth have led to sharp conflicts between humans and land. Land allocation to households and small-scale fragmented agricultural operations have been the dominant types of management in the region, which hinder agricultural production efficiency and large-scale modern agriculture (Liu and Long, 2016).

This study proposes a comprehensive evaluation system of farmland landscape fragmentation that integrates land use data and a set of multidimensional landscape metrics. Based on the evaluation framework, we selected the HHHP as the study area and comprehensively analyzed farmland landscape pattern changes in the region between 2000 and 2015. We then explored the spatial heterogeneous characteristics of farmland fragmentation among counties with hierarchical development. Further, we quantified the driving factors behind the trend of farmland fragmentation using panel data of geographic and socio-economic information from 359 counties. Finally, some policy suggestions are proposed to promote the optimal regulation and management of farmland resources.

2 Materials and methods

2.1 Study area

The HHHP (29°24′–42°36′N and 110°21′–122°45′E) includes five grain-producing provinces (Hebei, Henan, Shandong, Jiangsu, and Anhui), as well as parts of Beijing and Tianjin (Figure 1). There are approximately 300 large grain-producing counties in HHHP that make up 30.8% of the total national grain production, which bear the responsibility of ensuring national food security (Ge and Long, 2017). Under rapid urbanization, many counties have experienced intense land-use transition accompanied by non-agriculturalization, farmland abandonment, decentralized management, and agricultural management aging (Zhang *et al*., 2018; Liu *et al*., 2019).

2.2 Data source and processing

The land-cover data were provided by the Ministry of Land and Resources of the People's Republic of China. The data have been produced from Landsat Thematic Mapper (TM)/Enhanced Thematic Mapper Plus (ETM+) images with a spatial resolution of 30 m since the 1990s and updated every five years (Liu *et al*., 2014). The climate data were provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences. Socio-economic data at the county level were mainly collected from the *China*

Statistical Yearbook (*County Level*) (2000–2015) and *China City Statistical Yearbook* (2000–2015) from National Bureau of Statistics of China (NBS). Considering the accessibility and adjustment of administrative divisions, 359 county units in HHHP were ultimately identified in this study. To eliminate the impact of price changes on the subsequent analysis, we used 2000 as the base year to convert the economic indicators for interannual comparison.

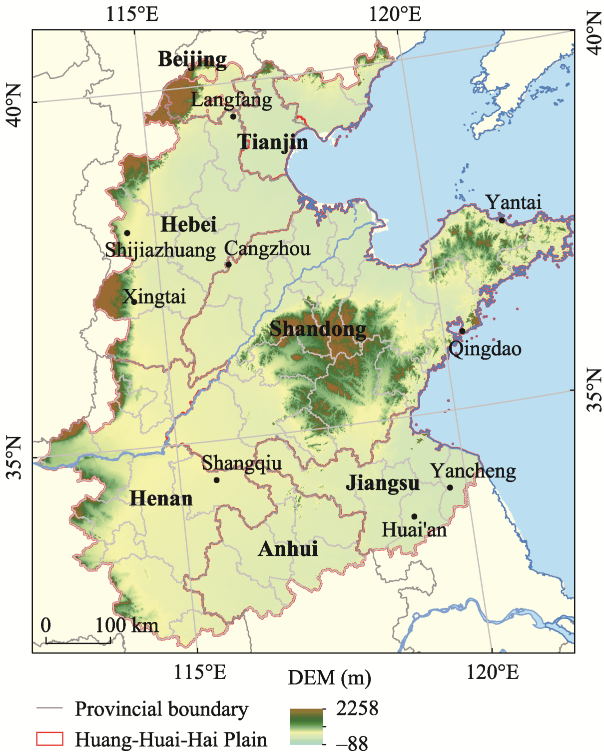

Figure 1 Location of the Huang-Huai-Hai Plain (HHHP)

2.3 Methods

2.3.1 Construction of comprehensive evaluation system

A landscape index is a series of simple quantitative indicators that can summarize the information of landscape patterns and reflect the attributes of landscape structure composition and spatial distribution (Sun and Zhou, 2016; Liu *et al*., 2019). FRAGSTATS is a common platform for calculating landscape metrics; it provides eight types of measurement indicators such as Shape, Connectivity, Diversity, etc. (McGarigal, 1995). Referring to the literature about farmland fragmentation (Su *et al*., 2014; Zhou and Lv, 2020), we proposed an evaluation index system for farmland landscape fragmentation combined with the parameters calculated by FRAGSTATS. The index of farmland fragmentation (FFI) in the system based on five assessment dimensions: dominance, integrity, regularity, aggregation, and connectivity, containing 11 landscape metrics with low redundancy, which reflect the quantitative and morphological attributes, as well as the evaluating features in spatial pattern and utilization conditions. The definitions, weights, and quantification of these indexes are shown in Table 1.

Farmland dominance index (FDI) in the evaluation system is the dimension that aims to measure the scales of farmland endowment. As the material foundation of agricultural production activities, farmland ensures rural livelihoods and rural development (Long *et al*., 2021). The limited availability and scarcity of farmland impact future sustainability (Jiang *et al*., 2019). The decomposition and encroachment of core farmland will increase the vulnerability of the remaining farmland to external occupation and degradation (Cheng *et al*., 2015). Therefore, the quantity of farmland can serve as a core indicator of farmland endowment and fragmentation trends.

Farmland integrity index (FII) quantifies attributes such as the amount and size of farmland patches, which are directly related to the changes caused by landscape fragmentation (Jiang *et al*., 2020). When the core farmland patches decomposed into multiple scattered patches of varying sizes, the usual consequence is a reduction in farmland size and increase in the number of patches, which will further affect the efficiency and productivity of farmland (Jia and Petrick, 2014; Rudel and Meyfroidt, 2014).

Table 1 The comprehensive evaluation system of farmland landscape patterns in the Huang-Huai-Hai Plain

Target level	Standard level	Indicators	Impact	Weight
Index of farmland fragmentation (FFI)	Farmland dominance index (FDI)	Largest patch index (LPI) Percentage of landscape (PLAND)	+ +	0.254
	Farmland integrity index (FII)	Patch density (PD) Area-weighted mean patch area (AREA_AM)	– +	0.080
	Farmland regularity index (FRI)	Area-weighted shape index (SHAPE_AM) Edge density (ED)	– –	0.106
	Farmland aggregation index (FAI)	Landscape shape index (LSI) Landscape division index (DIVISION)	– –	0.291
	Farmland connectivity index (FCI)	Connectance index (CONNECT) Interspersion juxtaposition index (IJI) Splitting index (SPLIT)	+ + –	0.269

Farmland regularity index (FRI) measures the characteristics of shape or edge structure closely related to farmland use. The irregularly shaped edges caused by the external and internal encroachment are also an evident fragmentation form (Cheng *et al*., 2015; Sun and Zhou, 2016). For farmers, the shape of farmland patches affects their utilization. Studies have shown that farmers are not keen to invest in modern agricultural technologies when the patches become small or irregularly (Di Falco *et al*., 2010; Tan *et al*., 2010; Hou *et al*., 2021).

Farmland aggregation index (FAI) and farmland connection index (FCI) will reflect the spatial agglomeration and the degree of accessibility between farmland patches. To some extent, the distribution and spatial relationships of farmland have a close correlation to the efficiency of farmland utilization and production cost (Kawasaki, 2010) and effect on the convenience of agricultural production (Gonzalez *et al*., 2004). The fragmentation decreases connectivity between patches, and the original concentrated distribution of farmland endowment is divided into a loosely organized and scattered pattern. The reduction and decentralization of contiguous farmland will increase the transportation and machinery operation cost of agricultural production (Hartvigsen, 2014; Guo *et al*., 2019).

2.3.2 Calculating the farmland fragmentation indexes and characterization

The entropy weight method was used to determine the weight of each index. Then the sub-evaluation indexes of five dimensions and FFI were calculated as follows:

$$I'_i = \sum_{j=1}^{n} W'_j \times X'_{ij} \tag{1}$$

I'_i is the subdimension evaluation index of the farmland landscape of county *i*, X'_{ij} is the value of evaluating indicator *j* within county *i*. W'_j is the weight of indicator *j* which is determined by the entropy weighting method.

$$FFI_i = W_D \times FDI_i + W_I \times FII_i + W_R \times FRI_i + W_A \times FAI_i + W_C \times FCI_i \tag{2}$$

where FFI_i is the comprehensive evaluation index of the farmland landscape pattern. W_D, W_I, W_R, W_A, and W_C represent the weights of dominance, integrity, regularity, aggregation, and connectivity index respectively. The value of the indexes ranges from 0 to 1, with higher values reflecting better conditions and less fragmentation of the farmland landscape.

Further, to visualize the interannual trend and the distribution of farmland landscape patterns, the Freedman-Diaconis rule (Yu *et al*., 2018) was used to classify the variability within the comprehensive and sub-evaluation indexes of counties in HHHP.

Hot spot analysis was adopted to assess whether there was a significant spatial aggregation in the variability of the farmland landscape index (Getis and Ord, 2010). A statistically significant hot spot area indicates that the regional farmland fragmentation improved or is in good condition. In contrast, a cold spot represents worsening fragmentation.

2.3.3 Driving factors

Farmland is shaped by the coupling of natural ecosystems and the socio-economic systems (Garrett *et al*., 2013; Long *et al*., 2021). Natural factors (e.g., topography, rivers, and elevation) usually determine the endowment characteristics, while human activities (e.g., land property rights, regional policy, decision-making behavior of operators, and socio-economic development) influence the utilization and development of farmland (Rignall and Kusunose, 2018; Gao *et al*., 2020; Zhu *et al*., 2020). In summary, the driving factors can be classified broadly into four categories: geography, demographics, socio-economics, and administration factors (Zhang *et al*., 2018). Based on the realistic conditions of HHHP, we selected nine driving factors from the four aspects; a specific explanation and description are given below (Table 2).

Table 2 Driving variables in the multiple linear regression model and their definitions

Criterion	Indicators	Data description	Unit
Geographic factors	Temperature (TEMP)	Average annual air temperature	℃
	Precipitation (PRE)	Average annual precipitation	mm
Demographic factors	Proportion of rural population (PRP)	$\frac{\text{Rural population}}{\text{Total population}}$	
	County's population density (CPD)	1 km × 1 km raster	people/km^2
	Average farmland area per household (FAH)	$\frac{\text{Area of farmland}}{\text{Number of rural households}}$	ha/household
Socio-economic factors	The proportion of primary industry in GDP (PPI)	$\frac{\text{GDP in primary industry}}{\text{GDP}}$	
	Proportion of artificial land area (PAL)	$\frac{\text{Artificial surfaces in county } i}{\text{Area of county } i}$	
	Per capita disposable income of rural residents (PIR)	China Statistical Yearbook (county level)	yuan
	Farmland production efficiency (FPE)	$\frac{\text{GDP in the primary industry in county } i}{\text{Area of farmland in county } i}$	10^4 yuan/ha
Administrative level factor	Administrative divisions	Dummy variables: Municipal districts, county-level city, county, 1 or 0	

Geographical conditions restrict farmers' utilization of limited farmland resources, and the heterogeneous geographic factors within HHHP make the farmland infrastructure and utilization modes distinctly different. To avoid endogeneity of variables, we did not introduce topographic factors that directly relate to the formation of fragmentation. Finally, the annual average precipitation and annual average temperature were selected as the main geographic driving factors.

Rural residents are the subjects of farmland utilization, and farmland ownership and agricultural management are mainly based on farm households. Household population is usually the basis for the adjustment and division of farmland tenure (Tan *et al*., 2006). Therefore, variables related to the population size have become essential factors affecting the utilization of farmland and landscape evolution. Accordingly, proportion of the rural population, county's population density, and the average farmland area per household were selected to depict the demographic impacts.

Socio-economic factors are the crucial foundation for rural development and farmland management. Urban development profoundly affects the allocation of urban and rural land resources and the pattern of farmland use, which has an inevitable impact on the farmland landscape pattern. We adopted the indicator of proportion of artificial land to characterize the development of urbanization. The industrial structure and consumption transformations also trigger the further transition of rural livelihoods and agricultural production. Therefore, we took the proportion of primary industry in GDP to indicate the socio-economic transition. Per capita disposable income of rural residents and farmland production efficiency were selected as well. The production efficiency may reflect the economic output of farmland, which together with the rural residents' income could influence the landscape pattern of farmland through various paths, such as changing the method of land use, economic operations, and household decision-making.

Finally, considering the differences in policy implementation and administrative effectiveness, dummy variables 0 and 1 were introduced to represent different administrative units of the municipal districts, county-level cities, and counties in the administration hierarchy system. These units can also reflect the urban-rural dual structure system in China to a certain extent, which would impact urban and rural land allocation and farmland utilization.

Based on socio-economic and geographical panel data of four periods (2000, 2005, 2010, and 2015) at the county level, multiple linear regression was used to quantify the driving forces affecting the landscape pattern of farmland in HHHP. The FFI is the dependent variable, while the indicators in Table 2 are the independent variables. The general form of the multivariable linear regression equation established for HHHP is as follows:

$$FFI = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \cdots + \beta_m x_m + \mu \quad (3)$$

where β_0 is constant, m is the number of the independent variables, β_m represents the regression coefficient, and μ is a random error perturbation term.

3 Results

3.1 Spatio-temporal analysis of index of farmland fragmentation variations in the Huang-Huai-Hai Plain

Overall, the FFI in HHHP was at a medium level and showed relatively distinct regional heterogeneity (Figure 2). The average FFI values of HHHP in 2000, 2005, 2010, and 2015 were 0.55, 0.51, 0.47, and 0.45, reduced by 6.34%, 7.99%, and 5.85%, respectively, which represents gradually intensifying fragmentation. The FFI in Hebei and Henan were initially at a relatively higher level (0.60) in 2000. Afterwards, the FFI declined by 26.67% and 18.33%. The fragmentation trend in Hebei intensified annually, while the change in Henan appeared more steady. The FFI values in Beijing and Jiangsu were below the average level of HHHP, and fragmentation was relatively severe. The evaluation indexes declined from 0.43 and 0.41 in 2000 to 0.31 and 0.34 in 2015, respectively. However, in terms of the temporal variation, it appears that a rapid and dramatic decrease in Jiangsu occurred from 2000–2005, then slightly improved from 2010 to 2015. In contrast, the period of conspicuous reduction in other provinces mainly appeared around 2005 to 2010, which may be related to the stage of the transition and structure adjustment of agriculture in each area. The FFI in Anhui exhibited the largest decline (0.48 to 030). In comparison, the FFI in Shandong only slightly declined, from 0.51 to 0.48, during 2000–2015.

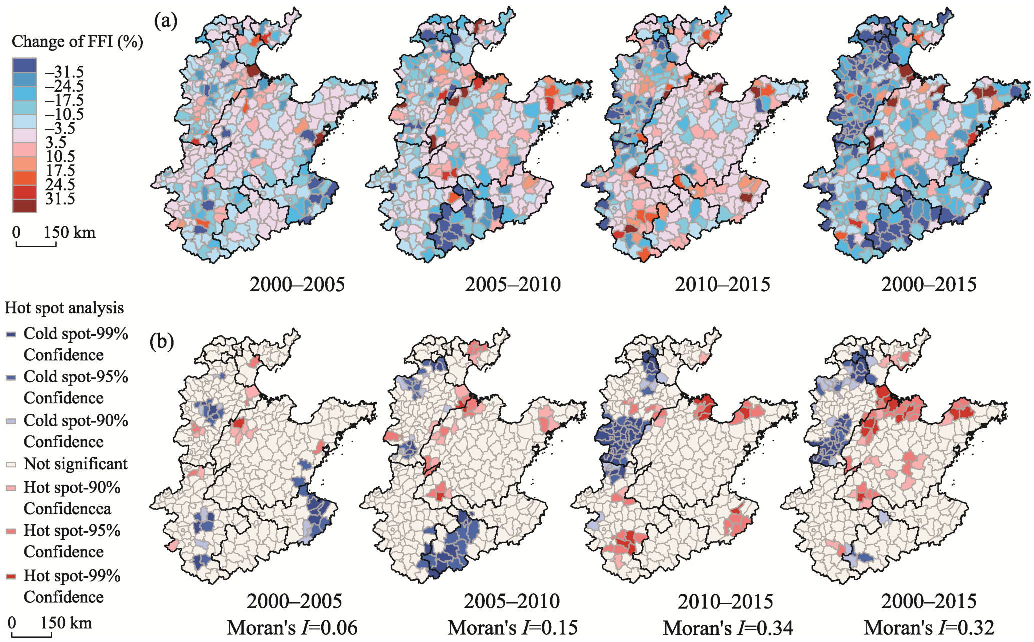

Figure 2 Distribution and hot spot analysis of the interannual variation of index of farmland fragmentation in the Huang-Huai-Hai Plain

The spatial variations of FFI in HHHP are shown in Figure 2b. Relatively substantial farmland fragmentation first emerged in the counties along eastern Jiangsu around 2000–2005. The areas with a significant FFI decline gradually spread to adjacent counties in Anhui and appeared in the North China Plain and Beijing-Tianjin-Hebei Metropolitan Circle. The decline eventually evolved into two distinct fragmented zones centered on Shijiazhuang (the provincial capital of Hebei) and Langfang (a city located between Beijing and Tianjin). The spatial trajectory of farmland fragmentation was influenced by urbanization from the southeastern coast to the inland regions to some extent, consistent with the pattern of economic development in HHHP. The counties that experienced less farmland fragmentation were mainly concentrated around the central areas of Shandong and the borders between

Shandong, Hebei, and Henan. Meanwhile, counties with elevated FFI were significantly aggregated in the areas around the Bohai Bay and central Shandong. The counties in Yancheng and Huai'an, Jiangsu, gradually transformed from cold spots to hot spots after 2010, which means a significant change in FFI from low to high (Figure 2b).

3.2 Divergent characteristics of farmland landscapes

The index of farmland dominance, integrity, aggregation, and regularity all demonstrated different degrees of apparent decline: from 0.75, 0.63, 0.32, and 0.79 in 2000 to 0.53, 0.39, 0.23, 0.71, respectively, in 2015 (i.e., decreases of 29.21%, 39.02%, 26.80%, and 9.52%, respectively). Meanwhile, the farmland connection index improved from 0.25 to 0.39.

Regarding the spatial heterogeneity, farmland dominance index in Jiangsu showed the earliest decline, where the average decrease was about 27% due to the early initiation of economic transformation and agriculture adjustment. The downward trend occurred most sharply in Beijing and counties located adjacent to Henan in Anhui. From 2005 to 2015, the index declined by about 71% and 65% in Beijing and Anhui, respectively. The considerable decline of dominance index in Hebei began around 2010 and dropped by about 38% by 2015. Meanwhile, dominance index of the counties in central Jiangsu and the borders of Henan and Anhui somewhat improved after 2010. In contrast, the indexes showed less severe degradation in most of Shandong and Henan (Figure 3a).

The variation of farmland integrity index exhibited relatively similar spatial and temporal divergence to dominance index (Figure 3b). During 2000–2005, the integrity index in Jiangsu showed an overall widespread decrease. Moreover, counties with increasing and decreasing index were interspersed throughout Anhui, Henan, and Hebei, revealing a sophisticated land use pattern in this period. Anhui and Beijing showed a drastic decline with a magnitude of more than 70% and 40%, respectively. After 2010, the region with severely decreasing index shifted to most areas of Hebei, Henan, and Tianjin. Shandong, Anhui, and Jiangsu experienced a slight decline or even a slight rebound.

Most counties in HHHP are located in the plain with low and flat terrain where the farmland has been subject to long-term artificial management that results in regularly shaped patches. From 2000 to 2015, the overall decline of farmland regularity index was about 10%. The most severe reduction was observed in Henan, exceeding 16% in southern counties. The irregular trend began to emerge in farmlands of southern Henan, northern Jiangsu, and Tianjin from 2000 to 2005. The regularity index of most counties in central Hebei and Shandong showed increases, as well as improved in northern Jiangsu and western Anhui. However, the scope of the degraded index had expanded since 2010 and mainly included the counties of Shandong and Hebei, but the magnitude was relatively modest (Figure 3c).

Farmland aggregation index experienced a vigorous decrease, especially in Anhui and North China, where the most intense reduction of over 60% occurred. Similarly, starting in 2000, a decline emerged in Jiangsu and gradually moved into Anhui and the counties around Beijing. Counties in Shandong and Henan presented a relatively modest decline of about 8% and 15%, respectively. During 2010–2015, the scattered trend was gradually mitigated and the index increased in counties of Huai'an in Jiangsu and Dezhou, Qingdao, and Yantai in Shandong (Figure 3d).

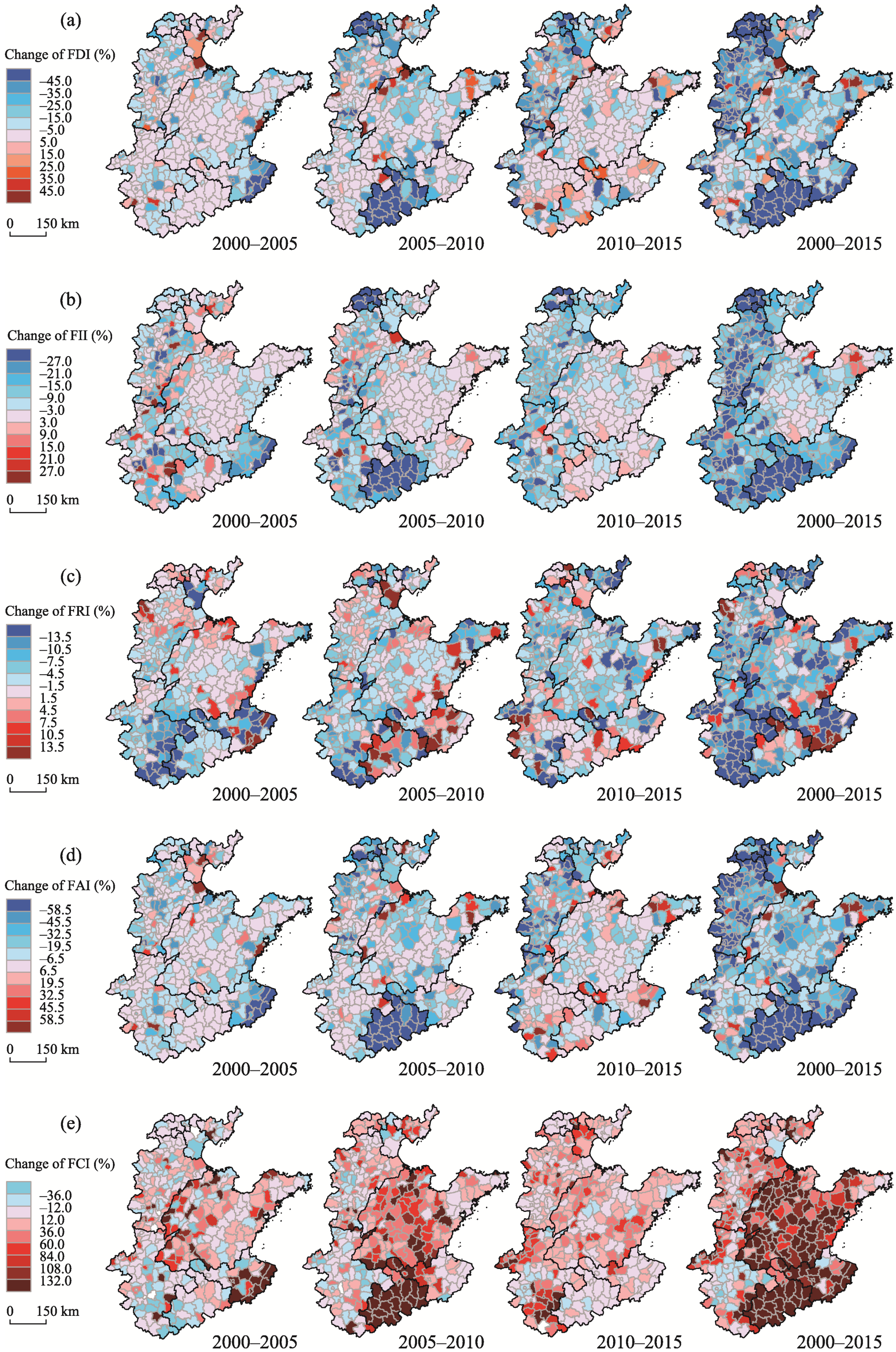

Figure 3 Distribution of interannual variation of multidimensional evaluation indexes in the Huang-Huai-Hai Plain

Farmland connection index, however, mainly manifested an improvement (Figure 3e). The index of the central HHHP, southern Jiangsu, and most counties in Anhui, Shandong, and Hebei gradually increased. Overall, there were relatively limited counties with the connection index decreases: Tianjin, Xingtai, and Shangqiu and their neighboring counties.

3.3 Analysis based on administrative division

In 2000, FFI values of municipal districts, county-level cities, and counties were 0.482, 0.559, and 0.573, respectively, compared to 0.384, 0.451, and 0.468 in 2015. While the most striking decreases were found in the index of aggregation, dominance, and integrity, with average decreases of 40%, 30%, and 20%, respectively (Figures 4b and 4e). Farmland dominance index and aggregation index of the municipal districts greatly declined (40.14% and 46.81%, respectively). The prominent reductions in the index of integrity (29.64%) and regularity (11.23%) also occurred in counties (Figures 4c and 4d). Farmland integrity index of all types of administrative divisions showed substantial increases; the index in counties increased by 63.25%, higher than in municipal districts and county-level cities (Figure 4f). Considering the temporal changes, the evolution within the municipal districts was generally earlier than the other types, in which the period of intense deterioration occurred around 2005 to 2010, after which the trend slowed down. Instead, the apparent fragmentation trends within county-level cities and counties occurred around 2010.

The diverse changes in different types of administrative divisions could somewhat reflect the farmland endowment and utilization patterns under the influence of the administration and regulations. Usually, urban residents comprise the bulk of the population in municipal

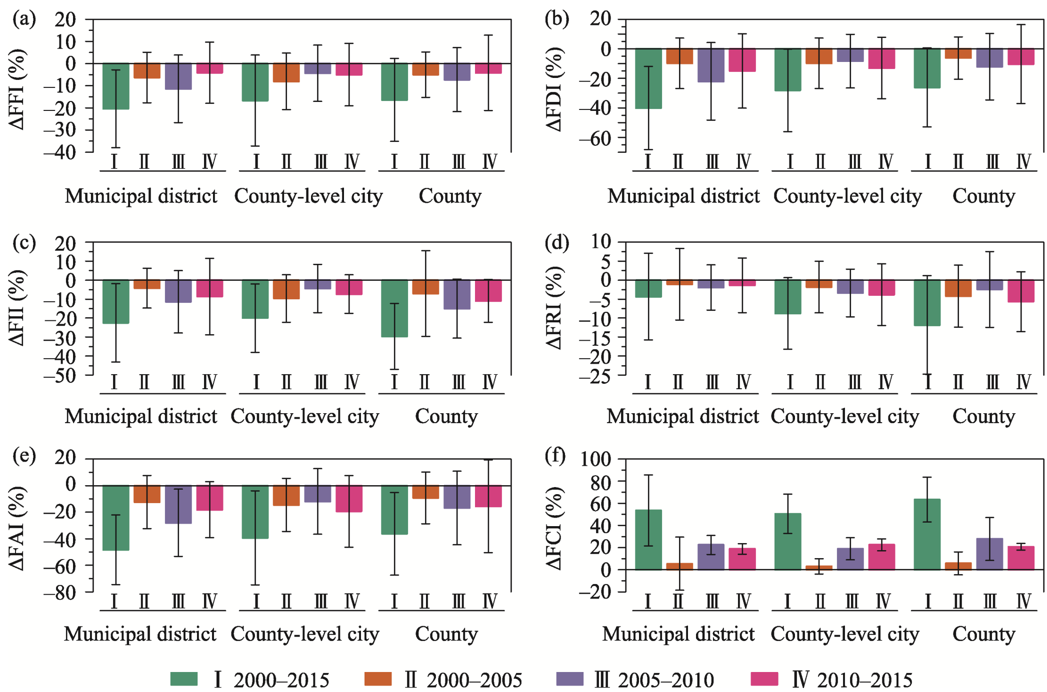

Figure 4 Statistics on interannual variations of evaluation indexes in municipal districts, county-level cities, and counties in the Huang-Huai-Hai Plain

districts, where the regional development, livelihood styles, and administration patterns are characterized by the urban mode. The non-agricultural industry is dominant in the gross economics, and the farmland resources are limited or sporadically distributed in the suburbs. Urban construction, industry development, and industrial restructuring have encroached on and crowded out farmland space. Therefore, the fragmentation in municipal district is principally manifested in the decreases in dominance and aggregation index.

In contrast, the demographic composition of a county is dominated by rural residents. The farmland carries and maintains the production and livelihood of the majority of the rural population. County-level cities, which are situated on the middle development stage between urban and counties, have the relatively weak foundation of modernized industry but with faster development. With the rapid population growth in counties, limited farmland resources have been continuously segmented and reorganized to satisfy the demand for rural livelihood. Meanwhile, due to urbanization, more farmers' out-migration and off-farm employment have resulted in the accelerated abandonment and shelving of farmland (Zhang *et al*., 2020). Consequently, farmland patches have been highly fragmented with irregular edges, and the patterns tend to be disordered and decentralized.

3.4 The influencing factors on the dynamics of farmland landscape patterns

The multiple linear regression results based on panel data from 359 counties from 2000–2015 are listed in Table 3. Compared to the significant association of the factors from demographic, socio-economic, and natural aspects, macro-administrative factors may not directly contribute to the changes of landscapes or utilization patterns. Therefore, the impact of the type of administrative division was not significant.

All demographic drivers had a strong impact on changes in the farmland landscape indexes. PRP and FAH presented significant positive correlations with FFI, index of dominance, integrity, and aggregation at a significance level of 1% but negative correlations with the connection index. CPD had a strong, negative correlation with FFI, dominance, integrity, aggregation, and connection index. As for socio-economic drivers, PPI significantly and positively correlated to FFI, dominance, integrity, regularity, and aggregation index but negatively correlated to the connection index. In contrast, PIR showed a strong, positive correlation with connection index and a negative correlation with FFI, dominance, integrity, regularity, and aggregation index. As a direct representation and indicator of land urbanization, the growth of the proportion of artificial surfaces exacerbates the loss of farmland, i.e., PAL was negatively correlated to FFI, dominance, and aggregation index. However, farmland regularity index had a positive correlation with PAL. Meanwhile, FPE only significantly and positively correlated with connectivity and composite index.

Theoretically, precipitation and temperature are generally perceived to be conducive to farming and agricultural operations, and the PRE did have a significant positive correlation with most indexes such as FFI, dominance, integrity, regularity, and aggregation index. However, the TEMP showed negative impacts on FFI, dominance, integrity, and aggregation index and no significant correlation with regularity and connection index. This finding may indicate that in the north, precipitation factors were more dominant and restrictive to agricultural development. Moreover, with the north–south span of HHHP, the annual average temperature increased from north to south. Although the high temperatures of Jiangsu and

Table 3 The estimation results of multiple regression on farmland landscape evolution and the driving factors in the Huang-Huai-Hai Plain from 2000 to 2015

	Farmland fragmentation index, FFI	Farmland dominance index	Farmland integrity index	Farmland regularity index	Farmland aggregation index	Farmland connection index
PRP	0.0933***	0.1310***	0.0771***	0.0769***	0.2035***	–0.0505
	(–3.54)	(–2.66)	(–3.29)	(–3.78)	(–3.9)	(–1.37)
PPI	0.0739***	0.1746***	0.1244***	0.0697***	0.2272***	–0.2007***
	(–2.64)	(–3.34)	(–5.00)	(–3.23)	(–4.1)	(–5.12)
PAL	–0.8169***	–1.8754***	–0.0358	0.3770***	–1.3329***	0.0398
	(–4.90)	(–6.02)	(–0.24)	(–2.93)	(–4.04)	(–0.17)
TEMP	–0.0287***	–0.0483***	–0.0228***	0.0047	–0.0459***	–0.0064
	(–4.56)	(–4.12)	(–4.08)	(–0.97)	(–3.69)	(–0.73)
In(*PRE*)	0.0328**	0.0500*	0.0535***	0.0615***	0.0737***	–0.0452**
	(–2.38)	(–1.95)	(–4.37)	(–5.78)	(–2.7)	(–2.35)
In(*CPD*)	–0.0573***	–0.0765***	–0.0213*	0.009	–0.0972***	–0.0329*
	(–4.34)	(–3.10)	(–1.81)	(–0.88)	(–3.71)	(–1.78)
FAH	0.1538***	0.3046***	0.1772***	0.0921***	0.3976***	–0.2352***
	(–4.13)	(–4.38)	(–5.36)	(–3.2)	(–5.39)	(–4.52)
PIR	–0.0726***	–0.1855***	–0.0660***	–0.0967***	–0.2119***	0.1926***
	(–5.06)	(–6.92)	(–5.17)	(–8.72)	(–7.45)	(–9.59)
FPE	0.0007*	0.0002	–0.0002	–0.0001	0.0007	0.0017***
	(–1.8)	(–0.26)	(–0.56)	(–0.46)	(–0.97)	(–3.19)
Constant	0.9624***	1.3737***	0.2404*	0.1226	1.0533***	1.0205***
	(–5.89)	(–4.5)	(–1.65)	(–0.97)	(–3.25)	(–4.46)
Observations	1436	1436	1436	1436	1436	1436
R-squared	0.288	0.348	0.287	0.269	0.367	0.322

Notes: *, **, and *** represent 10%, 5%, and 1% significance levels, respectively; t values are in parentheses. PRP: Proportion of rural population. PPI: the proportion of primary industry in GDP. PAL: Proportion of artificial land area. TEMP: Temperature. PRE: Precipitation. CPD: County's population density, FAH: Average farmland area per household, PIR: Per capita disposable income of rural residents, FPE: Farmland production efficiency.

Anhui are suitable for crop growth and agricultural business, the industry and urban-oriented development weakened the agriculture conditions, as revealed by the changes and regression results of the indexes.

4 Discussion

4.1 Processes of farmland fragmentation and its driving mechanism

Farmland landscapes are manifested as the spatial distribution status of farmland, which is gradually differentiated by its size, shape, type, structure, distribution, and other attributes through long-term natural or external human interference. Farmland fragmentation is the effect of the interactions between natural ecosystem and socio-economic system (Figure 5).

Globally, it is estimated that approximately 60% of irrigated farmland is located around urban areas (d'Amour *et al.*, 2017). Given the ideal topographical conditions and relatively low price of farmland, combined with the important role of local governments involved in the land transfer, it is inevitable that farmland has become the main source of construction supplies (Tu *et al*., 2021). Boosted by a series of policy reforms and implementation since the 1980s (Tu *et al*., 2020), massive expansion of urban planning has occurred from large metropolises to small- and medium-sized cities and towns in China (Deng *et al*., 2015). The Chinese government has monopolistic control over the land market, where land finance is regarded as an important policy approach to promote regional economic growth (Huang *et al*., 2019). Political tournament has motivated local governments to accelerate the pace of cultivated land conversion (Chen *et al*., 2020). Driven by the implementation of projects in urban real estate, industrial areas, and development zones, coupled with disorder and interspersed sprawl of rural homesteads, the farmland in rural areas is increasingly emerging as fragmented with complex, and unstable land use forms. Our findings confirmed that the periphery of large cities and the counties neighboring municipal districts suffered relatively severe fragmentation and degradation during the urbanization process.

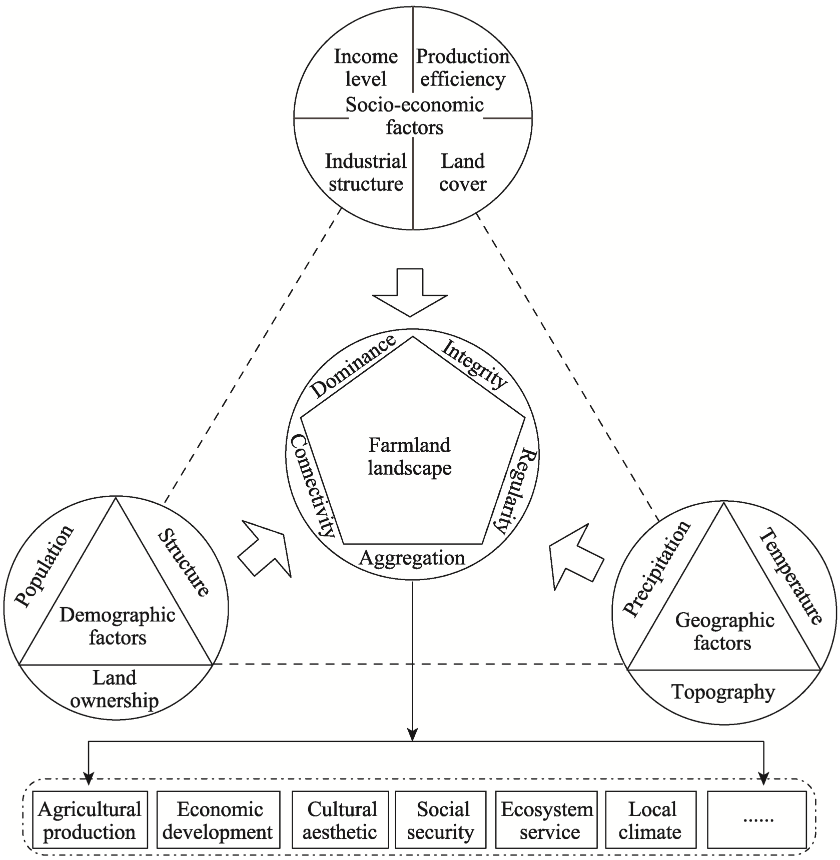

Figure 5 The conceptual framework of the driving mechanism

Our study also identified the demographic and urban expansion changes on farmland patterns. Population density is a significant negative driver. The growth of the population stimulates the pursuit of living or production space. A greater population pressure on farmland increases the liklihood it will be converted into residential land, building land, or further subdivided for the additional population. The structure of the population also has significant impacts on farmland patterns. A decline of the rural proportion of the population manifests a coupled evolution–transition process of the livelihood changes, economic transformation, and regional development which remolds the farmland pattern and triggers fragmentation both indirectly and directly. For instance, when farmers' income increases significantly through non-farming means, i.e., much higher than the net income from engaging in farming, non-agriculture in rural areas is stimulated, which exacerbates the abandonment and conversion of the farmland. This outcome potentially contributes to the risk of instability and fragmentation of farmland (Jiang *et al*., 2012; Paudel *et al*., 2020). Our findings confirmed that rising incomes led to the fragmentation, while farmland landscapes in counties dominated by rural residents and agriculture tended to have more stable and sustainable characteristics.

On the other hand, urbanization also provides more possibilities to convert traditional farming to ecological agriculture, modernized agriculture, and other business modes with higher efficiency and comparative advantages (Long *et al*., 2009). These new types of agricultural systems present opportunities to increase income. When portions of the surplus labor force transfer to the cities, the involution of agriculture decreases, and people engaged in agriculture occupy an expanded area of farmland. This trend increases the enthusiasm of farmers and the possibility of large-scale intensive and efficient utilization of farmland (Zhang *et al*., 2018; Li and Li, 2019). The operators therefore pay more attention to technology, machinery inputs, and the protection of farmland. For example, farmers may smooth the channel and field roads between farmland areas, as well as use the consolidated land to develop facility agriculture and urban agriculture (Long *et al*., 2010), which is beneficial to the improvement and enhancement of farmland fragmentation.

4.2 Policy implications

Households are the basic business units in rural China. Under the egalitarian principle of "in the family" land distribution and reallocation (Kung, 1994; Lu *et al*., 2011), existing farmland plots are periodically divided according to changes in village population (Tan *et al*., 2006). The frequency and magnitude of allocation and the scarcity of farmland resources may impact the level of fragmentation of farmland. Our findings showed the close relationship between FPE and farmland landscape conditions, especially in terms of regularity and integrity of plots as shown in a previous study (Sklenicka, 2016). A larger average parcel area owned by a household corresponds to more favorable and prolificacy of family-oriented production and intensive management. Conversely, fragmented plots and depletion of farmland that occur during farmland subdivision and ownership reallocation further hamper the use and function of farmland. In the long run, the risk of abandonment and transfer of farmland will continue to increase (Sikor *et al*., 2009; Ntihinyurwa and de Vries, 2021). Therefore, addressing farmland fragmentation has become a primary issue in promoting agricultural modernization and rural revitalization in China.

However, the spontaneous and small-scale intra-farm transfer method does not easily change the fragmented and scattered operation of farmland. Therefore, at the county level, it is important for governments to improve the tenure and governance regulations (Zhang *et al*., 2019; Gao *et al*., 2020). Additionally, the government should scientifically promote the transfer of rural land management rights and ecological spatial protection and restoration through the tenure adjustments and reformations as well as land engineering projects. These actions will centralize and integrate contracted farmland and reduce the farmland fragmentation of land property rights and the natural landscape (Long *et al.*, 2020; Ge and Lu, 2021). It is also necessary to reasonably formulate the spatial planning of rural land use, improving space utilization, to optimize the layout of villages and revitalize low-utility land through the planning and integration of rural settlements and other built-up land (Liang *et al.*, 2020a; Lyu *et al.*, 2021). Further, there should be a thorough trade-off between changes in the landscape pattern of farmland and avoiding the adverse disturbance of the farmland landscape during rapid urbanization. The government needs to reasonably control the development of construction land, as well as alleviate the encroachment of farmland by urban expansion and other demands (Nguyen and Kim, 2020; Zhu *et al.*, 2020). Finally, it may be best to cultivate industries with local advantages and optimize the organization of agricultural production and industrial structure to reduce reliance on economic development driven by land development (Liu *et al.*, 2019; Xu *et al.*, 2021).

Our findings suggest that the indicators of farmland landscape patterns may be a potential predictive method of diagnosing the prospective intensity of agricultural development, characterizing the evolution of farmland use patterns, and determining changes in rural human–land relations. Based on our study, we suggest the following. First, there is an urgent need to move toward reform aimed at separating ownership rights, contract rights, and the right to use contracted rural land; these actions will empower and improve the functions of farmland to provide the legal and policy grounds for the market-based allocation of farmland resources. Second, we should encourage the development of diverse forms and subjects of land transfer, as well as foster new types of agricultural businesses. The result is a gradual mitigation of farmland fragmentation by supporting the development of diversified and large-scale farming. Third, we should accelerate the comprehensive improvement and consolidation of rural land. Given the regional differences in farmland patterns and fragmentation severity, their characteristics and scale will influence the consolidation methods to an extent; improvement in the cultivation conditions of farmland should consider different engineering measures and promote the scale and quality of regional land consolidation following local conditions. At the same time, it is necessary to balance the temporal relationship between land ownership determination and land consolidation in a scientific way. Note that land consolidation may be difficult to obtain when land ownership has been determined and certified; this situation may further aggravate the fragmentation of farmland and trigger land-use conflicts.

Finally, we should share a dialectical view of farmland fragmentation. The fragmented farmland pattern has caused inefficiency of farmland utilization and limited intensive and large-scale farming. However, to some extent, it is also a production management measure for farmers to disperse their risks and enrich their cropping structure in agricultural production (Ntihinyurwa *et al.*, 2019).

5 Conclusions

To investigate the spatio-temporal evolution of farmland fragmentation in a traditional agricultural region during rapid urbanization, we established a comprehensive index system. The results suggested that the evolution of farmland fragmentation is accelerating: initially fast and then slower. The fragmentation trend was spatio-temporally synchronized with urbanization. Sharp decreases in FFI gradually moved from counties in Jiangsu to areas around Beijing-Tianjin. FFI in central Shandong experienced a slight decline and remained more favorable, consistent with the development pattern of land transition. The indexes of dominance, integrity, and aggregation of the farmland decreased evidently. The change of the regularity index was small, while the connectivity index increased. Moreover, the fragmentation trend emerged earlier in municipal districts than in county-level cities and counties, and the decline of FFI was most noticeable. Farmland dominance and aggregation index decreased most severely in municipal districts, while the most apparent decline in farmland integrity and regularity index occurred in counties.

The farmland fragmentation was driven by the coupling of demographics and socio-economic factors. The proportion of artificial land, population density, the proportion of primary industry, and income were the most significant factors. These factors had significant negative effects on FFI, dominance, integrity, regularity, and aggregation index. Moreover, the connection index also showed significant positive correlations with income and farmland production efficiency.

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