



# OPEN Spatial–temporal distribution of farmland occupation and compensation and its impact on ecological service value in China from 1990 to 2021

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Land transformation during global urbanization has led to a sharp decrease in farmland, causing not only food security issues but also ecological problems. To address this issue, the Chinese government has implemented the Requisition–Compensation Balance Policy for Farmland (RCBF) in 1997. This policy effectively curbed the reduction of farmland, but the compensated land often comes from mountainous and desert areas, leading to fragmentation of farmland and subsequent ecological security issues. The balance between farmland requisition and compensation is closely related to ecological security. However, current research on farmland occupation and compensation is mostly based on farmland area. The area occupied and compensated for by farmland in different regions is inconsistent, and using only net increase or decrease in area to represent farmland occupation and compensation cannot accurately and fairly compare the degree of farmland occupation and compensation between regions. Therefore, this study has proposed a novel index to measure the balance of farmland requisition and compensation—the Farmland Requisition and Compensation Index (FOCI). FOCI can transform dimensional expressions that represent the area of farmland occupation and compensation into dimensionless expressions, namely scalars, which makes it possible to visually and fairly compare the degree of farmland occupation in each region. Then, this new index has been used to investigate the spatiotemporal evolution of farmland requisition and compensation in China at the national and provincial levels over the past 30 years (1990–2021), as well as the impact of this change on the fragmentation of farmland landscape and ecological service value. The results indicate that (1) FOCI shows a trend of first decreasing and then increasing at both national and provincial scales; (2) Provinces with increasing FOCI are mainly concentrated in the southeast and northwest regions, while significant decreases in FOCI are observed in the southwest region, indicating a shift of the FOCI center of gravity towards the southeast; (3) FOCI and farmland landscape fragmentation are significantly positively correlated spatially, suggesting that provinces with higher levels of farmland requisition and compensation also exhibit higher levels of farmland landscape fragmentation; (4) FOCI and ecological service value are significantly negatively correlated spatially, indicating that provinces with higher levels of farmland requisition and compensation have lower ecological service values, with these areas mainly concentrated in the northwest region of China. In general, FOCI has the advantage of eliminating the dimensional influence in different regions and could be a reliable alternative for evaluating the balance of farmland requisition and compensation between regions.

**Keywords** Farmland occupation compensation index, Dynamic equilibrium of farmland occupation compensation, Farmland landscape, Ecological service value

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Farmland is a crucial resource for human survival, and it is essential for maintaining national food security<sup>1</sup> and ecological security<sup>2,3</sup>. However, farmland space is undergoing transformation on a global scale. In 2019, half of the globally added farmland area replaced natural woody and herbaceous plants<sup>4</sup>, severely impacting the sustainable development function of ecosystems. At the same time, the spatial–temporal pattern of farmland in China has undergone profound reshaping, with the area of farmland being converted out gradually exceeding the area being converted in<sup>5</sup>. Population growth<sup>6</sup>, urban expansion<sup>7</sup>, and economic development have resulted in overexploitation of natural resources, leading to a continuous reduction in the area of farmland in many regions<sup>8,9</sup> and a continuous decline in farmland quality<sup>10,11</sup>. To compensate for the loss of farmland due to occupation, the cultivation of natural resources such as forests, grasslands, and wetlands into farmland<sup>12,13</sup> is considered a solution, and these measures can solve the problem of farmland scarcity in the short term. However, these compensatory measures pose a serious threat to the ecological environment, leading to increased fragmentation of farmland landscapes<sup>14</sup>, a decline in ecosystem service value, and damage to biodiversity and biological habitats<sup>15–17</sup>. Farmland security and ecological security are crucial to human well-being. At present, farmland resources and the ecological environment are facing huge risks and challenges, and the loss of farmland resources and the deterioration of the ecological environment have caused people to worry about the survival of the future.

In order to maintain the national food security, the Chinese government implemented the Requisition–Compensation Balance Policy for Farmland (RCBF) in 1997, implementing the dynamic balance system of farmland and the strategy of basic farmland<sup>18</sup>. The RCBF policy requires a long-term balance between the occupation and compensation of farmland, which to some extent alleviates the pressure of farmland reduction. However, due to misunderstandings by some local governments, issues such as “occupation before compensation”, “more occupation than compensation”, and “occupation superiority, compensation inferiority” have arisen<sup>19</sup>. Furthermore, the compensated farmland not only moves towards the periphery of the region<sup>20</sup>, but also shifts from low-altitude gentle slope areas to high-altitude steep slope areas<sup>21</sup>. The development of high-altitude farmland leads to ecological land loss, farmland landscape fragmentation, and impacts on biodiversity<sup>22</sup>. With the intensification of urbanization and human activities, this phenomenon will further enhance the destruction of farmland landscape and ecology<sup>23</sup>. For policy makers, understanding the extent of farmland occupation and compensation in various regions, and how it affects the pattern of farmland landscape and the value of ecological services, is crucial to improving sustainable RCBF strategies. However, there is currently scarce reporting on the spatial and temporal patterns of farmland occupation and compensation at the national and provincial levels in China. It is also unclear whether the impact of farmland occupation and compensation on farmland landscape and ecological service value at the national and provincial levels is positive or negative.

In the context of farmland occupation and compensation, factors such as climate, precipitation, soil, and terrain often interact and affect the quantity and quality of compensated farmland through various processes and reactions<sup>24</sup>. Many studies indicate that the quantity and quality of compensated farmland tend to decrease, due to urbanization occupying high-quality farmland, while the compensated farmland often comes from mountainous and desert areas, leading to a sharp decline in the quantity and quality of farmland<sup>25</sup>, which is the main cause of the imbalance in farmland occupation and compensation<sup>26,27</sup>. Additionally, the quantity and quality of farmland are closely related to the farmland landscape and ecological service value<sup>28–30</sup>. Farmland can provide high-quality habitats for organisms, with significant value in protecting biodiversity and ecosystem service functions<sup>31,32</sup>. However, as the farmland occupation and compensation lead to changes in farmland space, the fragmentation of the farmland landscape hinders communication and interaction between species, resulting in a sharp decline in biodiversity<sup>33,34</sup>. Compensated farmland often has poor quality and productivity (Jiang et al. 2020, Li, Wang et al. 2020, and it occupies forest land, grassland, and wetland with high ecological service value, leading to a rapid decline in their ecological service value<sup>35,36</sup>. Past studies have mainly focused on analyzing the area and quality of farmland, as well as independently studying the landscape pattern and ecological service value of farmland. It should be noted that although most studies measure the balance of farmland occupation and compensation using farmland area, they only focus on the balance of changes in farmland area<sup>37</sup>. Due to regional differences in urbanization and natural resources<sup>38</sup>, statistical analysis based on farmland area is influenced by dimensional factors and cannot fairly reflect or compare the spatiotemporal distribution of farmland occupation and compensation between regions, which may lead to result inaccuracies. At the same time, existing research on the impact of farmland occupation and compensation on food security is more abundant<sup>39,40</sup>, while there are few reports on the landscape and ecological service value of farmland. The farmland use conversion brought about by land occupation and compensation will have a certain impact on the farmland landscape and ecological service value<sup>41</sup>. Currently, the research on farmland landscape and ecological service value mainly focuses on local regions for analysis and evaluation<sup>42,43</sup>. The impact of land occupation and compensation on the farmland landscape and ecological service value among various provinces in China, and the spatiotemporal patterns and differences in the impact of farmland occupation and compensation on the farmland landscape and ecological service value, are still unknown.

There have been numerous reports on the quantity and quality of farmland occupation and compensation, as well as the research on farmland occupation and compensation, on the landscape and ecological service value of farmland. However, due to the influence of the dimension of farmland quantity, there is little research on the spatial and temporal changes of farmland occupation and compensation between regions, as well as the impact of farmland occupation and compensation on the landscape and ecological service value of farmland. Therefore, this study has constructed a novel index to measure the balance of farmland occupation and compensation—the Farmland Occupation and Compensation Index (FOCI). FOCI can transform dimensional expressions into dimensionless expressions and scalars, which makes it possible to visually and fairly compare the degree of farmland occupation in each region. Based on FOCI, this paper analyzes the dynamic changes in the balance of farmland occupation and compensation in China at the national and provincial levels from 1990 to 2021 and

explores the spatial impact of farmland occupation and compensation on farmland fragmentation and ecological service value. The main objectives of this study are as follows: (1) to propose a new index for dynamically measuring the balance of farmland occupation and compensation—FOCI; (2) to analyze the changes and gravity shift of the FOCI at the national and provincial levels over the past 30 years; (3) to explore the spatial and temporal impact of the FOCI on farmland fragmentation; (4) to determine the regularity of the impact of the FOCI on ecological service value.

### The proposed new index

The Farmland Occupation and Compensation Index (FOCI) was proposed in this work based on the characteristic analysis of land occupation and compensation in different years, to measure the new index of farmland occupation and compensation balance. Under the current policy framework for farmland occupation-compensation balance management, the "Notice of the Ministry of Natural Resources and the Ministry of Agriculture and Rural Affairs on Reforming and Improving the Management of Farmland Occupation-Compensation Balance" (2024) clearly stipulates strict control of cross-regional supplementary farmland and adherence to the principle of primarily achieving self-balance at the county level, with provincial adjustments serving as a supplementary means for implementing supplementary cultivated land. Additionally, it improves the management mechanism for implementing the balance of occupation and compensation when converting farmland to construction land, and for maintaining the balance of conversion when farmland is turned into other types of agricultural land and integrates all types of farmland occupation activities, including non-agricultural construction, afforestation, fruit and tea planting, into the unified farmland occupation-compensation balance management. Given that data involving cross-provincial supplementary cultivated land is confidential and not yet publicly available, in this study, when calculating FOCI, we limit our scope to discussions on farmland occupation-compensation balance within the provincial level and fully incorporate the occupation of farmland by other agricultural lands (such as forest land, orchard land, etc.). The previous research on farmland occupation and compensation mostly used quantitative analysis of farmland area<sup>44,45</sup>. However, the natural resources and economic development levels of each province in China vary<sup>46</sup>, so using only farmland area to measure occupation and compensation cannot form a fair statistical and comparative analysis at the provincial level. Therefore, this paper specifically constructs the Farmland Occupation and Compensation Index (FOCI) to quantitatively analyze the spatiotemporal changes of farmland occupation and compensation at the national and provincial scales. Its value not only reflects the balance of farmland occupation and compensation, but also can be used to measure changes in farmland, explore the spatiotemporal laws and trends of farmland occupation and compensation, etc. The formula for calculating FOCI is as follows:

$$FOCI = \frac{\sum_{i=1}^n X_i}{\sum_{i=1}^n Y_i} \quad (1)$$

here FOCI is the Index of Farmland Occupation and Compensation.  $x_i$  represents the area converted from non-agricultural land to farmland in that year, and  $y_i$  represents the area converted from farmland to non-agricultural land in the same year. When  $FOCI < 1$ , it indicates an imbalance in the occupation and compensation of farmland, resulting in a net decrease in farmland; when  $FOCI \geq 1$ , it signifies a balance in the occupation and compensation of farmland.

## Materials and methods

### Data and preprocessing

China ranks third in the world in terms of farmland area, following only the United States and India, making it a major agricultural powerhouse globally. Securing the safety of China's farmland is crucial for food security and national development. This study utilizes the China Land Cover Data (CLCD)<sup>47</sup> from 1990 to 2022, with a spatial resolution of 30 m, derived by Yang and Huang using Landsat data from Google Earth Engine, combined with random forest classification and post-processing. Through visual interpretation of samples, CLCD achieved an overall accuracy of 79.31%. The ecosystem services value data is obtained from the Earth Resources Data Cloud Platform (<http://www.gis5g.com/>, accessed on February 18, 2024), and utilizing the static ecosystem services equivalence factor table proposed by Xie<sup>48</sup>, five variables were chosen for calculation: net primary productivity, precipitation, biological migration resistance, soil erosion, and road density. These were used to compute the total ecosystem services value for 341 prefecture-level administrative units in China for the years 2000, 2010, and 2020 (ESSV). This paper uses the ZonalStatistics tool in ArcMap 10.8 to process the social service value of prefectural-level administrative units, and thereby obtains the ESSV at the provincial level. China's national and provincial vector boundaries data are from Geospatial Data Cloud (<http://www.gscloud.cn/>). All image data processing in this study was conducted using ArcMap 10.8 (URL: <http://www.esri.com/>). All data are detailed in Table 1.

### Methods

#### Land use transfer matrix

The land use transfer matrix is the application of the Markov model in land use change<sup>49</sup>, and the direction, area, rate, and intensity of land use change can be derived through the matrix. In this study, the land use transfer matrix is used to calculate the area of farmland transferred in and out at 7 time nodes in 1990, 1995, 2000, 2005, 2010, 2015, and 2021 (every two consecutive years, such as 1990–1991). The calculation formula is as follows:

Data name	Resolution	Data sources	Data site
Net Primary Productivity (NPP)	1 km	Geographic Data Sharing Infrastructure, global resources data cloud	<a href="http://www.gis5g.com/">http://www.gis5g.com/</a>
Precipitation	1 km	Geographic Data Sharing Infrastructure, global resources data cloud	<a href="http://www.gis5g.com/">http://www.gis5g.com/</a>
Biological Migration Resistance	1 km	Geographic Data Sharing Infrastructure, global resources data cloud	<a href="http://www.gis5g.com/">http://www.gis5g.com/</a>
Soil Erosion Rate	1 km	Geographic Data Sharing Infrastructure, global resources data cloud	<a href="http://www.gis5g.com/">http://www.gis5g.com/</a>
Road Density	1 km	Geographic Data Sharing Infrastructure, global resources data cloud	<a href="http://www.gis5g.com/">http://www.gis5g.com/</a>
Landuse	30 m	Zenodo	<a href="https://zenodo.org/records/4417810">https://zenodo.org/records/4417810</a>
Vector boundaries	-	Geospatial Data Cloud	<a href="https://www.gscloud.cn/">https://www.gscloud.cn/</a>

**Table 1.** Data information and sources.

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \dots & S_{1n} \\ S_{21} & S_{22} & \dots & S_{2n} \\ \dots & \dots & \dots & \dots \\ S_{n1} & S_{n2} & \dots & S_{nn} \end{bmatrix}, D_i = \sum_{j=1}^n S_{ij} - S_{ij}, D_j = \sum_{i=1}^n S_{ij} - S_{jj} \quad (2)$$

In the formula,  $S_{ij}$  represents the area converted from land use type  $i$  to type  $j$ ;  $D_i$  and  $D_j$  represent the decrease in area of land use type  $i$  and the increase in area of type  $j$  during the study period.

*Coupled landscape fragmentation index*

Under the background of land occupation compensation, the transfer of farmland space has brought about serious farmland landscape fragmentation and ecological security issues. In order to comprehensively analyze the degree of farmland fragmentation in China, this paper adopts the Coupled Landscape Fragmentation Index (CLFI)<sup>50</sup>. CLFI is a comprehensive index coupling PD (Patch Density) and LSI (Landscape Shape Index), which can reflect both the density of farmland patches within a certain area and explain the shape of the patches. Its calculation formula is as follows:

$$CLFI_i = \sqrt{\left(\frac{PD_i \times LSI_i}{PD_i + LSI_i}\right)^{0.5} \times (0.5 \times (PD_i + LSI_i))} \quad (3)$$

$$PD_i = \frac{PD_{i,actual} - \min(PD_{i,actual})}{\max(PD_{i,actual}) - \min(PD_{i,actual})} \quad (4)$$

$$LSI_i = \frac{LSI_{i,actual} - \min(LSI_{i,actual})}{\max(LSI_{i,actual}) - \min(LSI_{i,actual})} \quad (5)$$

where  $CLFI_i$  refers to the coupled land fragmentation index of PD and LSI in the  $i$  province. The higher the value of CLFI, the higher the degree of coupling, and the greater the values of PD and LSI, thus the higher the degree of land fragmentation in the agricultural landscape.  $PD_i$  and  $LSI_i$  are the standard scores of PD and LSI for the  $i$  province, which can be obtained using formulas (4)–(5), where  $PD_i$ , actual and  $LSI_i$ , actual refer to the PD and LSI of the  $i$  province.

*Barycenter model*

The centroid model is used to identify the transfer path and distance to the centroid of the target object. This model has been widely applied in urban planning, land use, and ecosystem services value<sup>51,52</sup>, etc. In this study, the centroid model is adopted to estimate the land occupation and compensation index of each province in China from 1990 to 2021 and analyze its transfer path. The equation for the centroid of land occupation and compensation is as follows:

$$X_t = \frac{\sum_{i=1}^n (C_{ti} \times X_i)}{\sum_{i=1}^n C_{ti}} \quad (6)$$

$$Y_t = \frac{\sum_{i=1}^n (C_{ti} \times Y_i)}{\sum_{i=1}^n C_{ti}} \quad (7)$$

In the formula,  $X_t$  and  $Y_t$  represent the latitude and longitude coordinates of the centroid of farmland balance in year  $t$ .  $C_{ti}$  represents the magnitude of the land balance index in the  $i$ -th provincial region, and  $X_i$  and  $Y_i$  represent the latitude and longitude coordinates of the geometric center of the  $i$ -th provincial region.

The centroid migration distance refers to the straight-line distance between the centroid of 1 year and the centroids of the following years. The calculation formula is as follows:

$$L = \sqrt{(X_{t+n} - X_t)^2 + (Y_{t+n} - Y_t)^2} \quad (8)$$

where  $L$  represents the distance of centroid migration.  $X_{t+n}$  and  $Y_{t+n}$  respectively represent the latitude and longitude coordinates after  $n$  years from the  $t$  year.  $X_t$  and  $Y_t$  represent the latitude and longitude coordinates of the centroid of farmland in the  $t$  th year.

### Spatial correlation analysis

Spatial autocorrelation is a fundamental concept in geography, primarily measured by Moran's I. It describes the potential interdependence between observed data within the same geographical distribution area and is an important tool for evaluating the spatial aggregation degree of the variables of interest<sup>53</sup>. The bivariate local Moran's I employed in this study is an improvement upon the traditional Moran's I, revealing the correlation between one element in space and another nearby element<sup>54</sup>. It is used to explore the spatial relationships between the Farmland Occupation and Compensation Index (FOCI) and the Coupling Landscape Fragmentation Index (CLFI), as well as the total value of ecosystem services (ESSV). The calculation formula is as follows:

$$I_L = \frac{n(x_i - \bar{x}) \sum_{j=1}^n W_{ij} (y_j - \bar{y})}{\sum_{i=1}^n (x_i - \bar{x})^2} \quad (9)$$

where  $I_L$  represents the bivariate local Moran index.  $x_i$  represents the farmland occupation index, and  $y_j$  represents either the coupled landscape fragmentation index or the total amount of ecosystem service value and per capita ecosystem service value.

## Result and discussion

### The spatiotemporal variation of FOCI

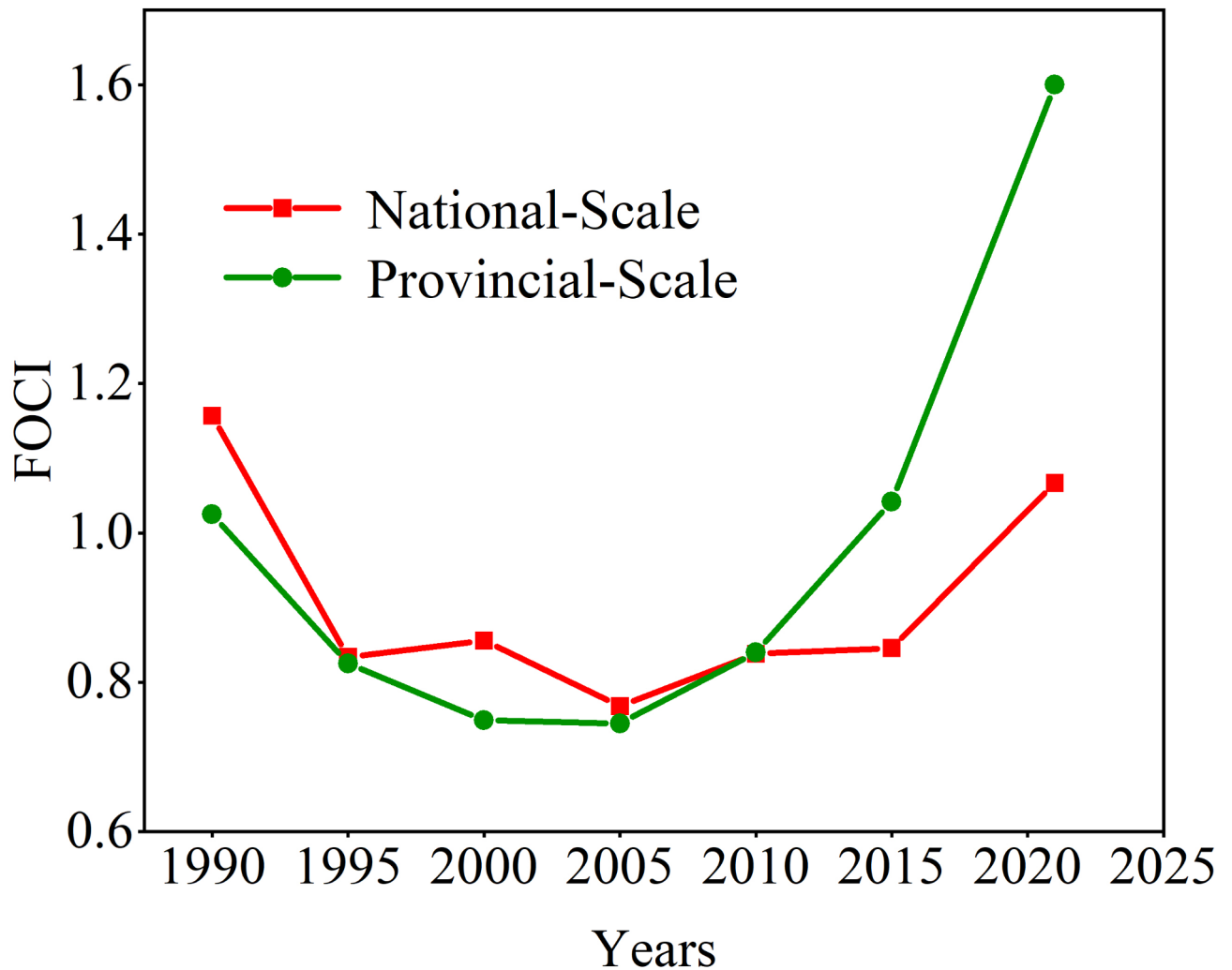
From 1990 to 2005, the situation of farmland occupation and compensation in China showed a declining trend, reaching its lowest point in 2005. After 2005, the situation of farmland occupation and compensation displayed a positive trend. In 1990, the provinces with balanced land occupation and compensation accounted for about 44.1% of the national total, mainly concentrated in the Qinghai-Tibet Plateau, Yunnan-Guizhou Plateau, Inner Mongolia Plateau, and the Northeast Plain. The provinces with imbalanced land occupation and compensation accounted for about 55.9%, widely distributed in coastal and northwestern regions. Compared to 1990, the form of farmland occupation and compensation in China deteriorated significantly by 2005, with less than 25% of the provincial areas having balanced farmland occupation and compensation, while the provinces with imbalanced farmland occupation and compensation expanded to around 76%, due to the difference between occupied farmland area and compensated area. From 1990 to 2005, the farmland area in China reduced by nearly 53,000 square kilometers, while urban area increased by nearly 65,000 square kilometers. Approximately 88.6% of the new urban areas came from converted farmland, indicating that the timely replacement of farmland occupied by urbanization development, especially in regions with a decline in farmland occupation and compensation index, is challenging, and there is a significant disparity between farmland occupation and compensation.

In 2021, the FOCI was the highest since 2005 (Fig. 1); and 52.9% of the provinces in China achieved a balance between farmland occupation and compensation, the highest in history, with approximately 55.6% of these provinces located in the southeastern coastal region (Fig. 2). From 2005 to 2021, the urban area of China increased by 81,400 square kilometers, while the farmland area decreased by 32,000 square kilometers, representing a 60% reduction in the rate of farmland reduction compared to the period of 1990–2005. This reduced rate of difference is attributed to China's introduction in 2006 of the legally binding constraint of the “red line” for 1.8 billion mu of farmland, which has promoted the implementation of the policy on farmland occupation and compensation. This is a direct cause of the continuous improvement in China's farmland occupation and compensation since 2005. During this period, the situation of farmland occupation and compensation has improved in some regions, particularly in the southeastern coastal area, leading to an increase in FOCI. The regions with low FOCI are mainly distributed in China's southwestern and northern areas, and some provinces such as Beijing, Tianjin, Liaoning, Shanghai, Hebei, Shandong, and Taiwan all have FOCI values less than 1, indicating an imbalance in farmland occupation and compensation. The rapid urbanization has led to the occupation of farmland area exceeding the compensation area, which is the main reason for the decrease in FOCI and the imbalance in farmland occupation and compensation in these areas.

### Changes in provincial-level FOCI features and center of gravity

The occupation of farmland is influenced by objective factors such as farmland conditions and regional development. The provincial description of the occupation of farmland in China can clearly illustrate the occupation of farmland in space, reflecting the temporal and spatial evolution of the occupation of farmland. Therefore, the linear regression slope of the occupation of farmland in each province in China from 1990 to 2021 is used to describe the trend of the occupation of farmland in China (Fig. 3). The trend of the occupation of farmland in China, denoted as  $k$  ranges from  $-0.254$  to  $2.167$ , with Macau showing the most significant increase in the occupation of farmland. Provinces with an increasing trend are concentrated in the southeast and northwest regions, including Hong Kong, Fujian, Xinjiang, Zhejiang, Jiangsu, Jiangxi, Shanxi, and Guangdong, with  $k$  values ranging from  $0.124$  to  $0.469$ . The occupation of farmland in the northeast region is moderately increasing, with  $k$  values ranging from  $0.028$  to  $0.090$ . The occupation of farmland in the southwest region is decreasing, with Heilongjiang showing the highest decline rate of  $-0.254$ .

This article uses the gravity center model to study the spatial distribution and gravity center of FOCI at the provincial level in China from 1990 to 2021. As shown in Fig. 4, the center of gravity of FOCI in 1990 was at  $110.5^\circ$  E,  $33.3^\circ$  N in Shaanxi Province. The gravity center of FOCI moved in two phases from 1990 to 2021. The first phase was from 1990 to 2005, during which the center of FOCI moved approximately 317.7 km northwestward, from coordinates  $110.5^\circ$  E,  $33.3^\circ$  N in 1990 to  $107.1^\circ$  E,  $33.5^\circ$  N in 2005. The second phase was from 2005 to 2021, during which the FOCI gravity center significantly moved approximately 746.2 km southeastward, from coordinates  $107.1^\circ$  E,  $33.5^\circ$  N in 2005 to  $112.4^\circ$  E,  $28.7^\circ$  N in 2021.



**Fig. 1.** The changing trend of FOCI in China from 1990 to 2021.

The FOCI in Chinese provinces mainly experienced a slow-then-rapid evolution from northwest to southeast. This phenomenon can be attributed to the Chinese government's first proposal in 2006 that 1.8 billion mu of farmland is a legally binding constraint and an insurmountable red line. Since then, adhering to the farmland red line has gradually become one of the rigid requirements for various national development and construction activities. In addition, China has continuously improved its farmland protection policies and land occupation compensation policies, making provinces in the rapidly developing southeast increasingly focus on farmland protection and compensation, intensifying the efforts of farmland compensation. These actions are closely related to the eastward movement of the FOCI center in China.

#### The spatial correlation between FOCI and CLFI in China

This study used the bivariate local Moran's I index method to analyze the spatial correlation between the land occupation and compensation index and land fragmentation in China at the provincial and county levels in 2000, 2010, and 2020. The bivariate Moran's I index of land occupation and compensation and land fragmentation in China from 2000 to 2020 at the provincial and county levels were both positive, with a p-value less than 0.05. The significance test indicated a significant positive spatial correlation between adjacent provincial and county levels in terms of land occupation and compensation and land fragmentation. The bivariate FOCI-CLFI (Fig. 5) shows four types of spatial correlation between land occupation and compensation and land fragmentation: high FOCI, high CLFI (HH); high FOCI, low CLFI (HL); low FOCI, high CLFI (LH); low FOCI, low CLFI (LL).

The local spatial correlation between farmland occupation and compensation and farmland fragmentation at the provincial and county levels in 2000, 2010, and 2020 was similar. In 2000, there were more regions in the HH and LL categories at the provincial and county levels, with LH regions at the county level. In 2010, there were more regions in the LL and HL categories, with HH scattered in the northeast region. In 2020, there were more regions in the HL category, mainly concentrated in the northern region, with LL regions at the county level. From the perspective of regional distribution and the types of spatial correlation, the HH regions in China from 2000 to 2020 moved from west to east, indicating that in the eastern regions, where land occupation and

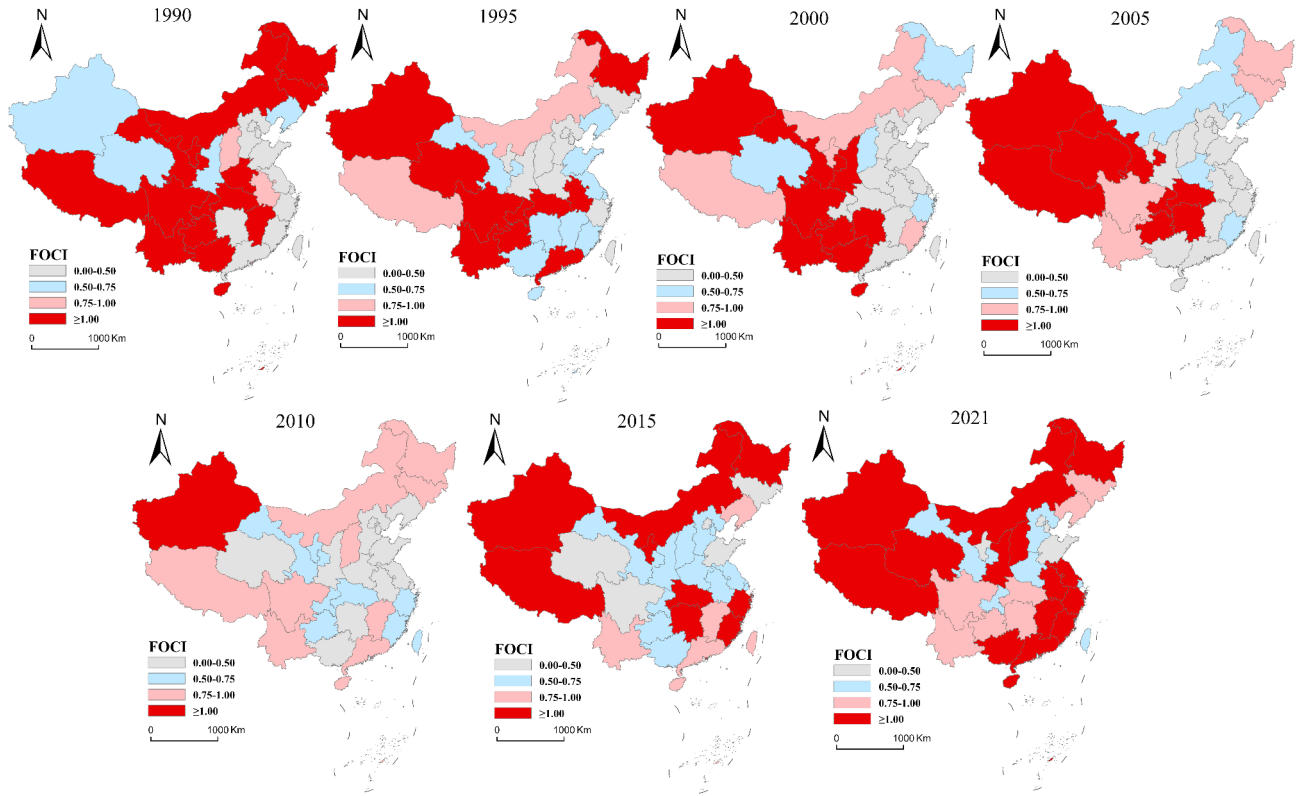


Fig. 2. Temporal and Spatial Changes of FOCI in China from 1990 to 2021.

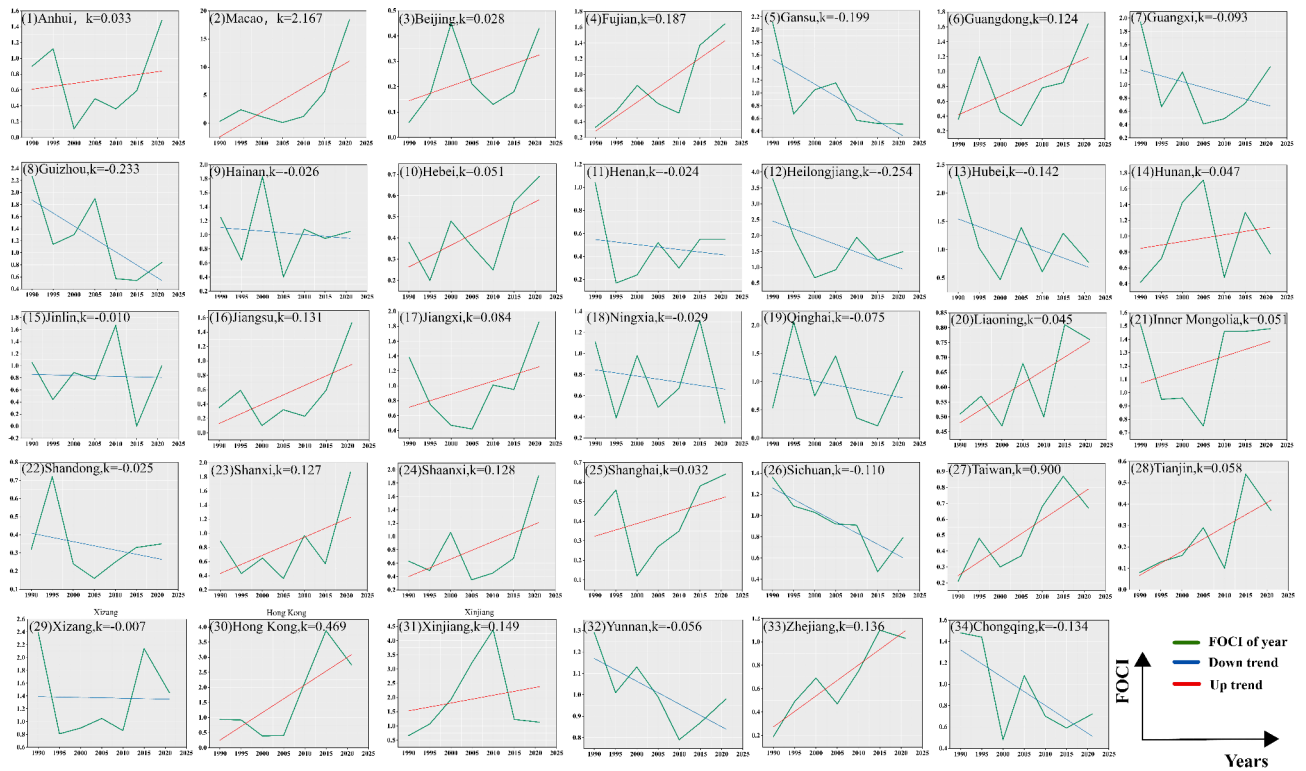
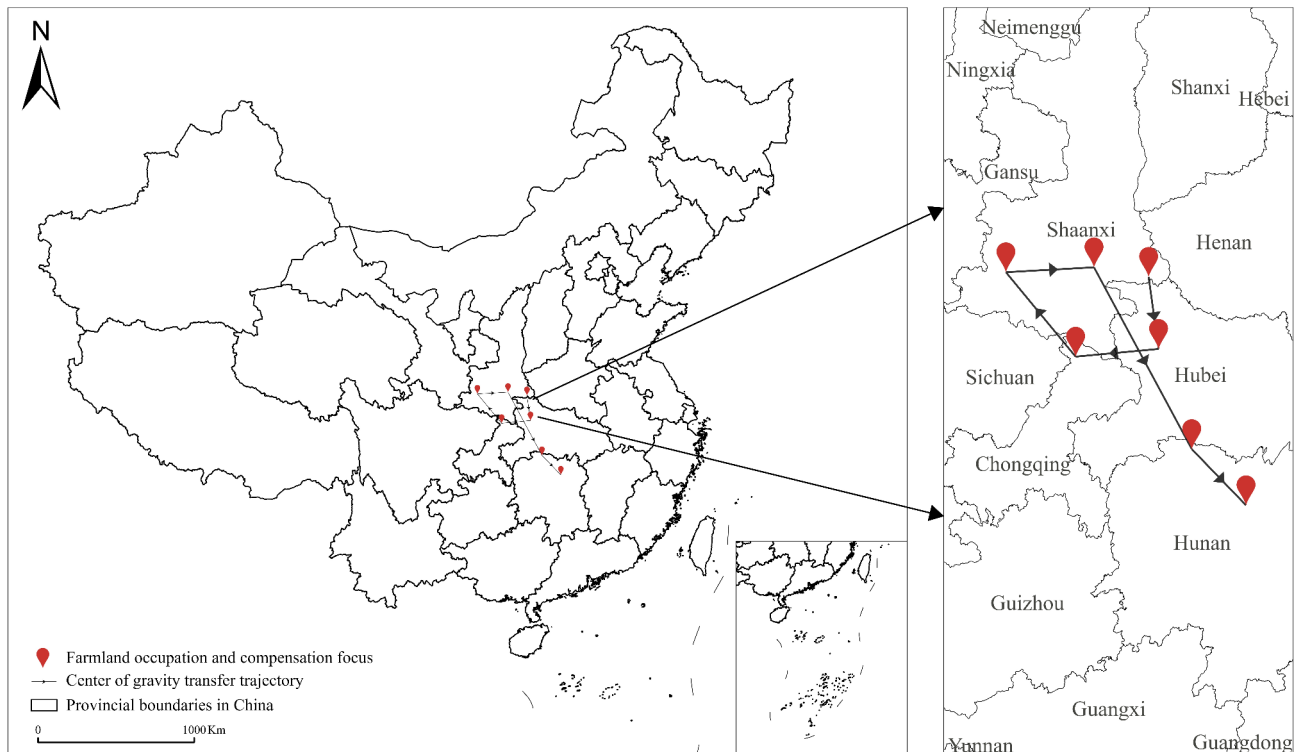


Fig. 3. Trend of FOCI changes in various provinces of China.



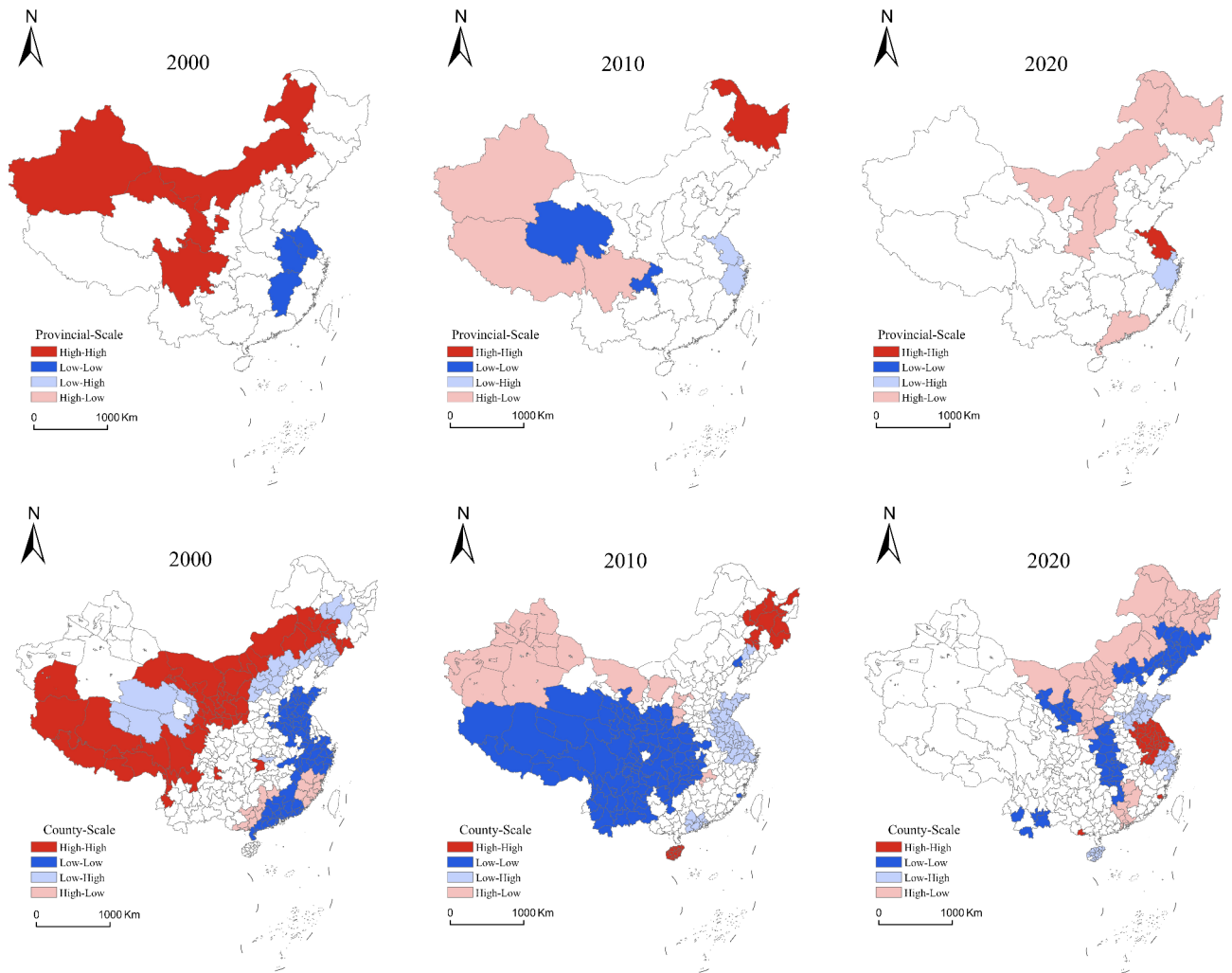
**Fig. 4.** Changes in FOCI Center of Gravity in China from 1990 to 2021.

compensation are high, land fragmentation is severe due to urbanization development increasing farmland occupation and scattered supplementary farmland, leading to aggravated land fragmentation. The HL regions moved from west to northeast, and Tibet, Xinjiang, and Inner Mongolia have vast farmland areas where urbanization development occupies enough concentrated land for supplementing, resulting in high farmland occupation and compensation but low farmland fragmentation in these regions. The LL regions mainly appeared in the southwestern region at the county level in 2010, indicating low farmland occupation and compensation, meaning fewer farmland needs supplementing and thus low farmland fragmentation in that region.

#### The spatial correlation between FOCI and ESSV

From 2000 to 2020, the Moran's *I* index for the local bivariate of farmland occupation and ecological service value in provincial and county-level areas of China were both negative, with *p*-values less than 0.05. The significant testing indicates a significant negative spatial correlation between the total amount of farmland occupation and ecological service value in adjacent provincial and county-level areas. Similarly, the bivariate FOCI-ESSV (Fig. 6) shows four types of spatial correlation between the degree of farmland occupation and the total ecological service value: high FOCI and high ESSV (HH); high FOCI and low ESSV (HL); low FOCI and ESSV (LH); and low FOCI and low ESSV (LL).

From the temporal dimension, during the period from 2000 to 2010, most regions in China were in a stage of accelerated urbanization and industrialization. At this time, a large amount of farmland was converted into construction land to meet the needs of urban expansion and industrial development, resulting in a significant downward trend in the FOCI values in many provinces and aggravating the imbalance between farmland occupation and compensation. For example, in the developed provinces along the eastern coast such as Guangdong and Jiangsu, with the development of urbanization, a large amount of high-quality farmland was occupied, and the compensated farmland often failed to reach the quality and ecological function level of the occupied farmland in a short time. Such drastic changes in farmland resources directly affected the value of ecosystem services. Since the functions provided by the farmland ecosystem, such as soil conservation, water source conservation, and maintenance of biological habitats, were damaged to some extent, the growth of the total value of ecosystem services was limited or even declined locally. During 2010–2020, with the strengthened implementation of the national farmland protection policy, especially the strict control of the 1.8-billion-mu farmland red line and the enhanced enforcement of the land occupation-compensation balance policy, the FOCI in some regions began to rise. In provinces such as Heilongjiang and Jilin in the Northeast region, through the implementation of land remediation projects and the promotion of high-standard farmland construction, the effective farmland area was increased and the farmland quality was improved, making the FOCI gradually approach or exceed 1, and the farmland occupation and compensation tended to be balanced. In terms of ecological service value, with the stabilization of the quantity and quality of farmland, the ecosystem service functions were restored and enhanced to a certain extent, such as the reduction of soil erosion and the restoration of biodiversity in the farmland ecosystem, thus promoting the increase in the value of ecosystem services.



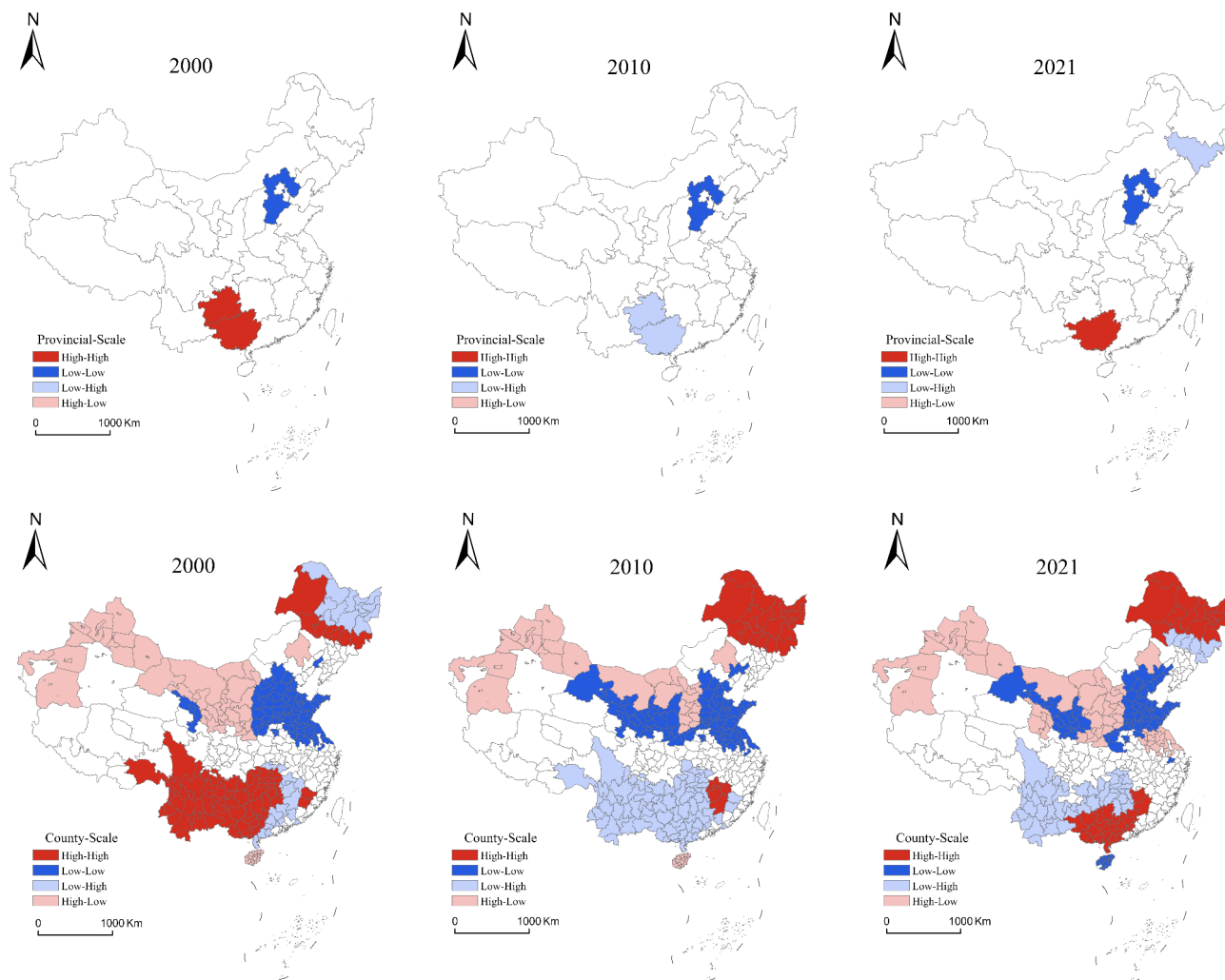
**Fig. 5.** Spatial correlation analysis between FOCI and CLFI.

From the spatial dimension analysis, at the provincial level, the northern and northwestern regions showed a relatively obvious spatial correlation characteristic of high FOCI—low ESSV (HL). Taking Xinjiang as an example, although it achieved a balance or even a slight surplus in farmland occupation and compensation by reclaiming some wasteland, the FOCI value was relatively high. However, since the newly reclaimed farmland was mostly located in ecologically fragile areas, such as the edge of oases or desert areas, the original stability of the ecosystem was poor, and the reclamation process further damaged the original vegetation and ecological environment, resulting in a decrease in the value of ecosystem services. In the southwestern region, it mainly showed a spatial correlation pattern of low FOCI—high ESSV (LH). In regions such as Yunnan and Guizhou, the terrain was complex and mountainous, urban expansion was relatively slow, the scale of farmland occupation was small, and the FOCI remained at a low level. At the same time, the rich forest resources and unique ecosystems in this region were well preserved, and the forest ecosystem service value accounted for a relatively high proportion in the total value of ecosystem services, making the overall value of ecosystem services at a relatively high level.

## Discussion

### Significant advantages of FOCI

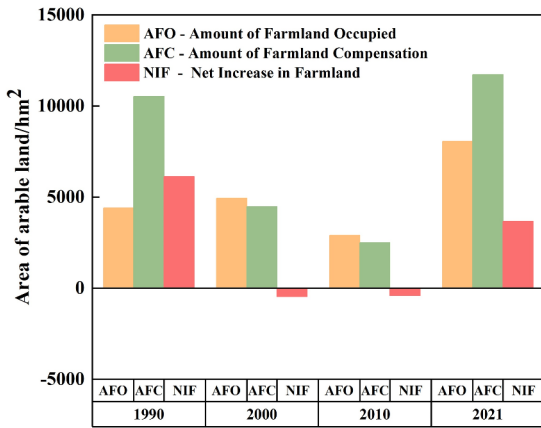
Different provincial units have different economic development and natural resources, which may lead to the use of farmland occupied area, farmland compensation area and farmland net increase. When studying the problem of farmland occupied area, farmland compensation area and farmland net increase at provincial scale, the farmland occupied area, farmland compensation area and farmland net increase amount are inconsistent, so that the farmland occupied area and compensation situation of each province cannot be equitably measured. In this paper, FOCI is adopted to measure the balance change between farmland occupation and compensation, eliminating the dimension between farmland area, making it more fair and reasonable to compare and analyze farmland occupation and compensation among provincial scales, and to study the spatial relationship between farmland occupation and compensation on farmland fragmentation and ecological service value. To further illustrate the advantages and complementarities of using FOCI to study the comparison and analysis



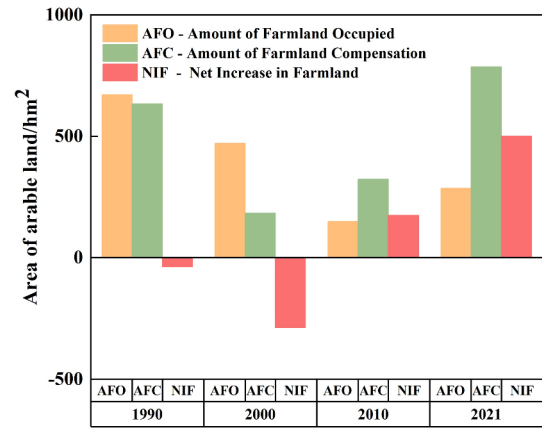
**Fig. 6.** Spatial correlation analysis between FOCI and ESSV.

of farmland use and compensation at the provincial scale, this paper selects three typical Chinese provinces and special administrative regions with different levels of development and natural resources: Xizang (low level of economic development, high natural resource content), Jiangsu (high level of economic development, high natural resource content) and Hong Kong Special Administrative Region (high level of economic development, low natural resource content). By using FOCI, the amount of agricultural land occupied (AFC), the amount of agricultural land compensated (AFO) and the net increase of agricultural land (NIF), the degree of agricultural land occupied and compensated in the three regions was comprehensively evaluated and compared.

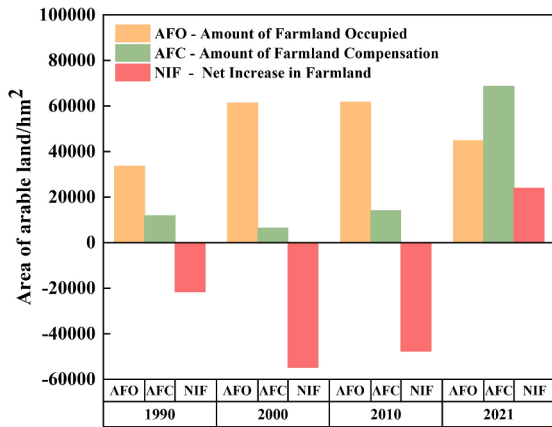
In Fig. 7, figures (a), (b), (c) and (d) respectively show the AFC, AFO, NIF and FOCI of Xizang, Hong Kong and Jiangsu from 1990 to 2021. First, in figure (d), the FOCI of Xizang and Jiangsu in 2021 is 1.45 and 1.53, respectively. (a) The figure shows that Xizang will have an AFC of 8,056.17  $\text{hm}^2$ , an AFO of 11,718.81  $\text{hm}^2$  and an NIF of 3,662.64  $\text{hm}^2$  in 2021. At the same time, Figure (c) shows that Jiangsu's AFC in 2021 is 44,729.00  $\text{hm}^2$ , AFO is 68,565.00  $\text{hm}^2$ , and NIF is 23,836.00  $\text{hm}^2$ . The ratio of farmland occupation to compensation, FOCI, is very close in Xizang and Jiangsu provinces despite the huge difference in farmland occupied area, compensated area and net increment of farmland. It provides a significant and effective reference index for the comparison of farmland occupation and compensation balance between Xizang and Jiangsu. Secondly, (d) As shown in the figure, the FOCI of Hong Kong and Xizang in 2010 were 2.17 and 0.86 respectively. (a) The figure shows that Xizang had an AFC of 2895.12  $\text{hm}^2$ , an AFO of 2488.86  $\text{hm}^2$  and an NIF of -406.26  $\text{hm}^2$  in 2010. Meanwhile, Figure (b) shows that Hong Kong will have an AFC of 148.41  $\text{hm}^2$ , an AFO of 322.74  $\text{hm}^2$  and an NIF of 174.33  $\text{hm}^2$  in 2021. FOCI shows that the farmland occupation and compensation level of Hong Kong in 2010 is greater than that of Xizang. However, according to AFC, AFO and NIF, although the farmland occupation and compensation in Xizang in 2010 did not reach a balance, the farmland compensation in Xizang Province was very strong. In summary, FOCI not only has a significant advantage in measuring the balance between farmland occupation and compensation among provincial scales, but also plays a significant role in measuring the balance between farmland occupation and compensation together with multiple indicators as a supplementary index.



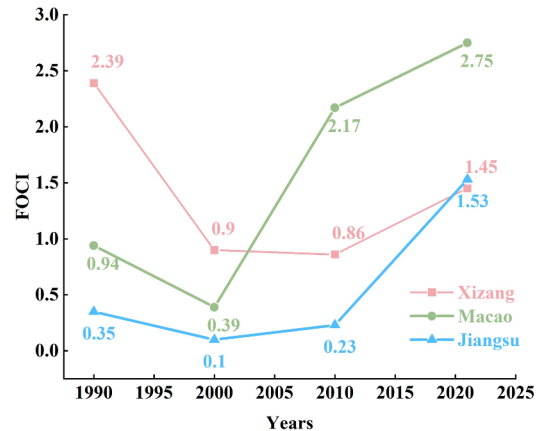
(a) Comparison of AFO, AFC and NIF in Xizang



(b) Comparison of AFO, AFC and NIF in Hong Kong



(c) Comparison of AFO, AFC and NIF in Jiangsu



(d) The trend of FOCI changes in three provincial administrative regions

Fig. 7. Comprehensive analysis of farmland occupation and compensation.

### Farmland quantity and FOCI

Overall, the farmland occupation and compensation situation in China from 1990 to 2021 has significantly improved. The increase in farmland quantity is the main driving factor for the rise in the farmland occupation and compensation index. In 2022, China's farmland saw a net increase of 1.3 million hectares, marking the second consecutive year of net increase in total farmland after 2021, which greatly improved the country's farmland occupation and compensation index. From 2005 to 2021, although China's compensation index showed an upward trend, with  $FOCI < 1$ , China's farmland was still in a negative growth state until 2021 when  $FOCI > 1$ , achieving the net increase in farmland for the first time in over a decade. At the provincial level, from 2009 to 2019, only five provinces including Inner Mongolia, Xinjiang, Heilongjiang, Jilin, and Liaoning witnessed an increase in farmland area, while the remaining 26 provinces experienced a decrease, with Sichuan seeing the largest reduction. In 2021, the farmland compensation index in the northern region was generally higher than that in the southern region; the farmland compensation index in the southeast region was generally higher than in the southwest region. This is mainly due to the vast and flat land and sufficient compensation for farmland in the northern region; the southeast region is located in the third tier of China's topography with flat terrain and abundant natural resources<sup>55</sup>, coupled with the implementation of farmland occupation and compensation policies, leading to a certain compensation for the quantity and quality of farmland in these areas; while the complex terrain and variable climate in the southwest region make it difficult to compensate for farmland. The regional differences have resulted in a heterogeneous distribution of China's farmland occupation and compensation spatiotemporal pattern.

### FOCI and fragmentation of farmland landscape

In the past 20 years, the total CLFI of farmland in China has continued to increase, and the fragmentation of farmland has become more serious. Economic development has led low-efficiency farmland to be converted into construction land with high economic output, while urban expansion has encroached on surrounding farmland<sup>56</sup>, exacerbating the fragmentation of farmland and sacrificing the ecological functions of ecological landscapes<sup>57</sup>. Overall, the changes in FOCI and CLFI show a basic consistency, exhibiting a significant positive

correlation. This means that the changes in the farmland balance index have a positive effect on the overall fragmentation of farmland in the region. Looking at local changes, FOCI and CLFI are mainly positively correlated. In regions with high farmland balance index, the degree of farmland fragmentation is high, and the distribution of additional compensated land is scattered. An increase in the number of farmland patches and their complex shapes are the primary causes of this phenomenon. In some regions, such as Xinjiang, Inner Mongolia, and Heilongjiang, FOCI and CLFI are negatively correlated, meaning that in these areas, a high farmland balance index corresponds to a low degree of farmland fragmentation. This is because Xinjiang, Inner Mongolia, and Heilongjiang are sparsely populated, and after urbanization occupies farmland, the distribution of additional compensated farmland is contiguous with large patch areas, which to some extent promotes the scaled production of farmland<sup>58</sup>. Therefore, in these areas, while maintaining a high farmland balance index, the degree of farmland fragmentation decreases. The results indicate that an overall increase in the farmland balance index will significantly affect the exacerbation of farmland fragmentation. However, in local areas, an increase in the farmland balance index will lead to a reduction in the degree of farmland fragmentation. The differences in natural factors are the main reason for the heterogeneity of the spatial expression of the farmland balance index and the fragmentation of farmland in local areas.

### FOCI and total value of ecological services

The overall trend of Ecosystem Service Value (ESSV) in 341 cities in China shows an increase from 29.26 billion yuan in 2000 to 30.26 billion yuan in 2020, especially with a more significant growth from 2010 to 2020 compared to 2000 to 2010. The changes in land use types have a significant impact on the total value of ecosystem services, with forest ecosystem service value being the highest, followed by water ecosystem service value. Land use types contribute around 37–47% of the total ecosystem service value<sup>30,59</sup>. Under the background of farmland balance, China's forest area has increased by approximately 53,000 square kilometers from 2000 to 2020, with 97% of the new forest land coming from farmland. The conversion of farmland to forest land outweighs the conversion of forest land to farmland, which is the main reason for the increase in ESSV in China. However, in some regions such as Inner Mongolia, Shaanxi, and Fujian, the total value of ecosystem services has been continuously decreasing over the past 20 years, while the FOCI (Farmland Occupation and Conversion Intensity) has been on the rise. This is due to the rapid reduction in farmland quantity caused by urban expansion, leading to a shift from farmland to forest and grassland in order to ensure that the red line of 1.8 billion mu of farmland is not exceeded<sup>60</sup>. The decrease in ESSV in these areas is attributed to the fact that the ecological service value generated by farmland is less than that generated by forest and grassland. It is crucial to pay special attention to these regions. If the declining trend in ecosystem service value is not controlled, ecological security issues will worsen.

Compared with existing studies, the application of FOCI endows this research with significant advantages in exploring the relationship between farmland occupation and compensation and ESSV. Previous research methods usually evaluated the impact on the ecological environment by using the area of farmland occupation and compensation<sup>61,62</sup>. However, due to the dimensional differences in farmland area, it was difficult to fairly measure the actual balance of farmland occupation and compensation among different regions. They only analyzed the impact of farmland on the ecological environment in small areas and might have biases when analyzing the impact of farmland occupation and compensation on the ecological service value at the provincial scale<sup>63–65</sup>. In contrast, FOCI successfully transformed the dimensional expression representing the area of farmland occupation and compensation into a dimensionless scalar form, cleverly eliminating the interference caused by the differences in area dimensions among regions. It enables an intuitive and fair comparison of the degree of farmland occupation and compensation in various regions. In this paper, by exploring the spatiotemporal changes of the bivariate spatial autocorrelation between FOCI and ESSV at the provincial and county levels from 2000 to 2021, the long-term spatiotemporal dynamic changes of the balance of farmland occupation and compensation and the total value of ecological services are presented more fairly and reasonably. We clearly found that there is a close negative correlation between FOCI and ESSV in the spatiotemporal dimension. That is, an increase in the intensity of farmland occupation and compensation will significantly reduce the value of ecosystem services. This provides a new and more accurate perspective for deeply understanding the ecological effects of farmland occupation and compensation balance, strongly supports the scientific formulation and implementation of ecological compensation policies, and lays a solid theoretical foundation for protecting ecological security and promoting sustainable development.

### Impact, application, and prospects

The study proposed a new index for measuring the balance of farmland occupation and compensation (FOCI) and studied its consistent impact on farmland landscape fragmentation and ecosystem service value with existing research results<sup>66–68</sup>, demonstrating the feasibility of using FOCI to measure the balance of farmland occupation and compensation, and to study farmland landscape fragmentation and ecosystem service value.

In summary, although FOCI demonstrates superiority in the study of farmland occupation and compensation at the provincial scale, providing a fairer indicator for the comparison and analysis of farmland occupation and compensation at this scale, its result only focuses on the ratio of farmland occupation area to compensation area, thus neglecting the individual roles of the farmland occupation area and the compensation area. The farmland occupation area and compensation area can fully reflect the quantitative characteristics of farmland transfer, yet they are not suitable for comparing farmland occupation and compensation at the provincial scale. Therefore, FOCI, the farmland occupation area, and the farmland compensation area should be used together as indicators to study and analyze farmland occupation and compensation to more comprehensively and fully reflect the situation of farmland occupation and compensation.

In future research, we will further optimize and expand the functions of FOCl. Besides considering the farmland occupation area and compensation area, we will incorporate farmland quality data. For example, the proportional changes of different grades of farmland during the occupation and compensation processes, which can help to more comprehensively reflect the quality of farmland occupation and compensation balance. Moreover, FOCl will be integrated with other relevant socioeconomic and eco—environmental indicators to construct a comprehensive evaluation model. For instance, socio-economic factors such as population growth, urbanization process, and adjustment of agricultural industrial structure, as well as eco-environmental factors like land use change, water resource conditions, and climate change will be included. Through multivariate statistical analysis methods (such as principal component analysis and regression analysis), the quantitative relationships between these factors and FOCl will be determined, enabling a more comprehensive and in-depth understanding of the influencing mechanisms and driving factors of farmland occupation and compensation balance.

## Conclusion

The introduced Farmland Occupation and Compensation Index (FOCl) in this study can eliminate the problem of farmland quantity being affected by dimensional influences, making the statistical and comparative analysis of farmland occupation and compensation between regions fairer and more intuitive. Through the FOCl, this research explores the spatiotemporal changes in the occupation and compensation of farmland at the national and provincial scales in China from 1990 to 2021, as well as the spatiotemporal variations in the impact of farmland occupation and compensation on farmland landscape and ecological service value. The results indicate:

- (1) From 1990 to 2005, the index of farmland occupation and compensation in China decreased, and the overall imbalance of farmland occupation and compensation decreased as well. The amount of farmland decreased, and by 2005, FOCl reached its minimum value. The areas with imbalanced farmland occupation and compensation are mainly located in the eastern and northern parts of China. After 2005, the national index of farmland occupation and compensation increased, but due to FOCl being less than 0, the amount of farmland continued to decrease, although at a slower pace. By 2021, FOCl was greater than 0, achieving a balance of farmland occupation and compensation nationwide. Over the past 30 years, the provinces with rising FOCl were mainly concentrated in the southeast and northwest regions, while the southwestern region showed a clear downward trend in FOCl. The center of FOCl is shifting towards the southeast.
- (2) From 2000 to 2020, there exists a significant positive spatial correlation between the farmland requisition—compensation index (FOCl) and the comprehensive fragmentation index of farmland landscape (CLFI). The degree of farmland requisition will significantly affect the fragmentation of farmland landscape. With the increase of FOCl, most areas experience an increase in CLFI, leading to aggravated farmland fragmentation. In a few regions such as Xinjiang, Inner Mongolia, and Heilongjiang, the increase in FOCl leads to a decrease in CLFI due to the natural factors, representing a phenomenon caused by the contiguous compensation of farmland.
- (3) Meanwhile, from 2000 to 2020, the conversion index of farmland showed a significant negative correlation with the total value of ecosystem services in both time and space. The increase in farmland conversion index will generate a large amount of compensatory farmland, which mainly comes from forests, grasslands, and wetlands, thereby compromising the ecological services value of these areas. As a result, the farmland conversion index in some regions has increased while the ecological service value has decreased.

## Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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## Author contributions

Yuhao Li: conceptualization, visualization, methodology, writing. Shuhui Shangguan: methodology, investigation, writing. Shuang Liu: resources, funding acquisition, and editing. Wenyu Li: methodology, validation, writing. Yijin Li: conceptualization, resources, writing. Han Rui: methodology, validation. Jingwen Xu: supervision, resources, validation, funding acquisition, writing-review and editing.

## Declarations

### Competing interests

The authors declare no competing interests.

### Additional information

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