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Investigation and Comparison of Spatial–Temporal Characteristics of Farmland Fragmentation in the Beijing–Tianjin–Hebei Region, China, and Bavaria, Germany

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Abstract: Farmland fragmentation has emerged as the primary manifestation of global land use changes during the last century. Following the economic reform and opening up in China from the 1980s, the Beijing–Tianjin–Hebei (BTH) region has witnessed continuous farmland fragmentation. Understanding the spatial–temporal dynamics of farmland fragmentation is crucial for formulating sustainable land use management strategies. However, the specific causes and locations of farmland fragmentation remain unclear, as do potential significant differences or similarities across different countries. Given this quandary, this study empirically analyzes the spatial–temporal characteristics of farmland fragmentation in two different contexts: the BTH region in China and Bavaria in Germany. The study utilizes multiple theoretical models for temporal and spatial farmland fragmentation, applying the comprehensive index method, landscape pattern analysis, and the magic cube model. The results indicate that the farmland fragmentation index (FFI) value in BTH and Bavaria first increased or remained stable, but afterwards, both decreased and increased again. Moreover, the spatial analysis demonstrated high significance values for the FFI in the northern and western BTH region and in northern and southern Bavaria. There are, furthermore, significant differences in the FFI in different macro landforms. The FFI in the mountain regions is significantly higher than that of the plains. Finally, the results also demonstrate that a decreasing FFI relates to the overall low values within an FFI region. The theoretical framework in this study appears to align with empirical results, and thus provides a reference for future policy measures to protect farmland.

Keywords: farmland fragmentation; spatial–temporal characteristics; Beijing–Tianjin–Hebei region; Bavaria

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1. Introduction

Farmland is a fundamental resource for food production [1]. Its size, volume, and availability are critical factors in calculating a country or region's carrying and sustainable development capacity [2]. A mismatch between land supply and demand becomes increasingly acute with rapid socio-economic and spatial development (such as in China). The consequence of a growing population, decreasing arable land, degrading soil fertility, inefficient and fragmented arable land, and other problems in agricultural production threaten national food security [3,4]. Farmland fragmentation (FF) is a manifestation of these problems. While FF may have some benefits, such as enabling more households to engage in farming [5], it often leads to wastage of production materials and decreased agricultural productivity [6,7]. It further prevents the application of new farming technologies and hinders the large-scale development of agriculture [8]. As arable land resources become increasingly limited, there is a need to maximize the provision of products and services for the growing food demand [3].

Farmland fragmentation occurs in many transition economies and developing countries [1,9], yet it is the complex result of multiple factors [10]. The effect is, however, significant for food security and land resource sustainability in East Asia [4]. China's per capita arable land is only 0.09 hectares, far below the global average of 0.20 hectares per capita [11]. FF enriches the diversification of agricultural production and reduces the risk of agricultural production. However, it also causes many negative impacts, such as declining agricultural production efficiency and increased production costs [9], which have become an essential obstacle to China's agricultural modernization and large-scale development [12]. In order to reverse the negative impacts of FF, the Chinese government has been committed to controlling and managing farmland fragmentation in recent years. Among the land management methods, land consolidation effectively solves fragmentation problems and promotes agricultural modernization in many countries worldwide [13,14].

The practice of land consolidation contradicts, however, the theory behind it. Although land interventions, such as land consolidation, were implemented, FF has risen [15]. This calls for alternative methods to monitor FF's dynamics and create land policy interventions to minimize fragmentation [16]. This requires frameworks to detect spatial and temporal trends in the evolution of landscape fragmentation [17]. Recent empirical and methodological literature provides various spatial statistical methods to detect FF. However, relatively few studies still focus on the temporal and spatial dynamics of FF [15]. Given this, an in-depth analysis of farmland fragmentation's evolutionary characteristics can provide better theoretical insight into how and where land consolidation contributes to the development of modern agriculture and the implementation of rural revitalization strategies. As this phenomenon of fragmentation is occurring in different countries, it is furthermore relevant to rely on comparative studies in order to detect both generic and idiosyncratic aspects. For this reason, we compare two specific study areas, which differ in historical and institutional contexts, namely Germany and China. Such a comparison is relevant because one would expect several similarities and patterns that may determine how, where, when, and why FF occurs.

As the capital city group of China, the Beijing–Tianjin–Hebei (BTH) region has an important national and regional development strategic position. It connects the poor mountainous areas of Yanshan–Taihang to the more developed socio-economy of the Beijing–Tianjin area. The BTH region is a flat region of plains, hills, and mountains. The terrain is undulating and uneven. It is not easy to concentrate and contiguously distribute farmland. The varying topography in this area is the main reason why FF continues to exist. At the same time, FF is being addressed by national policies. China is in a period of rapid economic development, with the accelerated expansion of urban construction land and the rapid development of road transportation networks. While much farmland has been converted into construction land, the degree of FF has surprisingly increased [18]. Especially in the BTH region, there is still a severe degree of fragmentation of regional farmland [19]. Additionally, farmland located in the urban fringes has begun to show fragmentation characteristics [20]. The expansion of urban construction land occupying farmland is serious [21]. At present, FF is one of the main problems in the BTH region. Resource integration and cross-regional governance are prerequisites for the coordinated development of the BTH region. As one of the most critical resources in this region, the research on FF can provide scientific support for the optimal layout of regional land use and contribute to the realization of regional coordinated development and rural revitalization strategies.

In order to make a comparison, the Bavaria region in Germany (referred to as "Bavaria") was selected. The region has urban and rural areas, and land consolidation is an instrument to reduce farmland fragmentation and stimulate rural development. The Bavarian government has made a point of diminishing the spatial inequities between the rural and urban areas and increasingly uses land consolidation to stimulate effective land use. A comparison between the rate and trends of fragmentation describes different choices and spatio-temporal changes within local regions and can reveal specific endogenous trends and the influence of external factors in fragmentation. Hence, comparing the two can explore the similarities and differences in FF's dynamics between developed and developing countries and guide the development of FF in the BTH region.

The structure of this paper is as follows: The next section presents the theoretical models and introduces the study areas, data, and methods used in the research. Section 3 describes the results and the temporal–spatial analysis of FF variation in the case areas. These results enable a comparison of the two study areas in terms of FF values and variations. Section 4 discusses the findings in order to derive generic and idiosyncratic characteristics. Finally, Section 5 concludes and presents recommendations for further research.

2. Materials and Methods

2.1. Theoretical Models and Hypotheses

Land serves both as a physical resource and a basis for various concepts and definitions of property and ownership. Given the multi-dimensionality of land, scholars categorize fragmentation into three types: physical fragmentation, ownership fragmentation, and operational fragmentation [22,23]. In contrast to tenure or other social perspectives, physical land use fragmentation can reveal the compliance of physical land cover dynamics with some land use planning systems [15]. Therefore, we chose physical farmland fragmentation at the regional level to capture landscape configuration and study the distribution of FF [24].

From the regional or spatial perspective, the concept of physical farmland fragmentation manifests itself as the existence of many spatially separated (discontinuous) patches of farmland within a region, typically scattered across a broad area [25,26]. Small scales, irregular shapes, and discontinuous distribution dominate land fragmentation [27,28]. It is more difficult—or impossible—for agricultural machines to work on small-scale parcels and at low efficiency on more parcels than expected, especially in corners and along boundaries [29]. Moreover, irregular shapes prevent the proper cultivation of some crops that need to be cultivated in rows or series [27]. Furthermore, discontinuous distribution involves a complicated boundary network among parcels; hence, parts of a holding (especially the tiny parcels) will remain uncultivated at the margins of the parcels [25].

In stage I, society is primarily agricultural, transportation is limited, and the level of agricultural machinery production is low. The evolution of FF is often influenced by individual farmer behavior. Different plots have varying soil quality and slope, so farmers use FF as an environmental risk management strategy. By selecting suitable plots and planting different crops under varying conditions, they can mitigate the risk of crop failure and protect against total harvest loss due to various natural disasters [30]. As farming experience accumulates in this stage, farmers gradually recognize the positive impacts of FF, leading to a slow but steady increase in the degree of FF.

In stage II, society begins transforming from an agricultural to an industrial society. As industrialization develops, the degree of FF increases due to land abandonment for artificial uses such as infrastructure construction and rural industrial land [31,32]. During this stage, urbanization-induced farmland loss contributes to an increase in the degree of FF [33,34].

In stage III, due to urban expansion and sprawl, more farmland is consumed at urban fringes to meet housing demands [35]. The principal objectives of land consolidation projects include maintaining the viability of farming [36]. They can result in significant changes to farmland parcel size, shape regularity, and distribution, and the degree of FF decreases.

In stage IV, with the effect of urban expansion and urban sprawl, more farmland is consumed at urban fringes because of the demands for land for housing [37,38]. Farmland fragmentation intensifies, particularly in metropolitan areas and cities experiencing urban development [15,39], leading to another increase in the degree of FF.

H1. *Generally, with the advancement of socio-economic factors and implementation of land policies, the degree of FF initially undergoes a gradual deepening, then a sharp increase, followed by a decrease, but with the potential to rise again.*

The rate of evolution and spatial distribution of FF differ across various landform areas [18]. Farmlands are easier to merge, swap, or consolidate in plain or flat areas, resulting in relatively low FF. Consequently, land management interventions tend to be more effective for farmlands in flat areas [3]. In mountainous areas, cultivated land is divided into irregularly shaped and generally smaller plots due to the topographic and geomorphological conditions and the intervening water system. The unevenness of these plots can lead to a higher FF and limit the feasibility of land leveling.

H2. *Observed FF values are typically lower in flat regions than their mountainous counterparts. Moreover, the decrease in these values, brought about by land management interventions, exhibits a faster rate in plain terrains than in mountainous ones.*

2.2. Study Area

Two study areas were selected: the BTH region and Bavaria. The BTH region includes China's capital city (Beijing), municipal city (Tianjin), and 11 cities in Hebei Province, which has an important strategic position in national and regional development as the capital circle of China. The terrain of the BTH region is characterized by "high in the northwest and low in the southeast" (Figure 1a). The BTH region belongs to the warm temperate, semi-humid monsoon climate region. The superior geographical location and suitable climatic conditions make this region one of China's primary agricultural product-producing areas. Most farmlands are allocated in the North China Plain, the central and southern areas of this region, with grain and cash crop production based in Hebei.

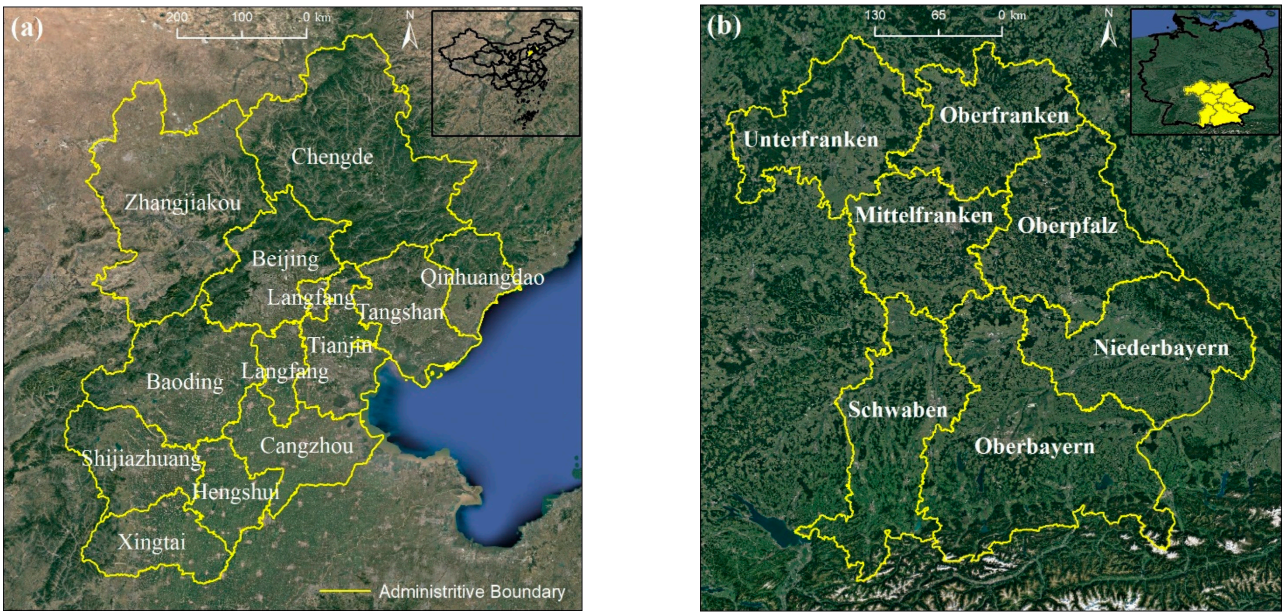

Figure 1. Study areas. (**a**): Beijing–Tianjin–Hebei region, China; (**b**) Bavaria, Germany.

The second study area is Bavaria, in Germany (Figure 1b). The Free State of Bavaria lies in the southeast of Germany. It has seven administrative regions, referred to as Regierungsbezirke. The southern part of Bavaria is hilly and mountainous (the Alps), and agricultural landscapes still dominate their surrounding areas. As a strong agricultural state, Bavaria has a nearly 500-year history of land consolidation [40], and after World War II, it launched several policies to improve and extend land consolidation beyond its agricultural optimization [41]. Similar policies were adopted in other parts of Europe, modeled after the German example.

The choice of BTH in China and Bavaria in Germany as the focus of this study, aiming to investigate and compare the spatio-temporal characteristics of FF, is based on two key considerations: Primarily, both regions are recognized as significant economic hubs within their respective countries, each undergoing accelerated urbanization processes over the previous decades. Consequently, assessing the intensity of FF in these regions enhances our comprehension of farmland spatial transformation patterns in the context of globally rapid urbanization. Secondly, considerable variations exist among these regions regarding policy environments, natural conditions, and agricultural paradigms. The diversity of these research contexts aids in verifying the external validity of the theoretical constructs with respect to FF, as outlined in this study.

2.3. Data

These spatial research units for the BTH region are the formal county-level administrative districts. The acquisition of farmland data at a resolution of 30 m in the BTH region in 1980, 1990, 2000, 2010, and 2020 relied on China's National Land Use and Cover Change (CNLUCC) dataset provided by the Resource and Environment Science Data Centre of the Chinese Academy of Sciences (http://www.resdc.cn, accessed on 12 July 2020). This dataset has been validated to have high accuracy [42]. The digital elevation model employs the Shuttle Radar Topography Mission dataset [43].

The spatial research units for Bavaria are the municipal boundaries provided by the Bayern Atlas. The acquisition of farmland data in Bavaria relied on interpreting 1992, 1995, 2000, 2005, 2010, 2015, and 2020 land cover images [44] with a spatial resolution of 300 m derived from the European Space Agency (https://www.esa-landcover-cci.org/, accessed on 12 July 2020). This dataset contains a time series of annual global land cover classifications from 1992 to 2020, generated from multiple satellite images to gain a higher classification accuracy.

2.4. Methods

2.4.1. Multi-Dimensional Evaluation of FF

In contrast to current theoretical analyses of FF, our study proposes a new conceptual index system for FF assessment at the regional scale, with the following three dimensions: patch scale (PS), shape regularity (SR), and spatial distribution (SD). Referring to the existing literature [10,15,27], the definitions and quantitative methods of the selected indexes are shown in Table 1.

Table 1. Indicators for assessing farmland fragmentation.

Target Level	Standard Level	Index Level	Quantitative Method	Index Definition	Index Direction
Farmland Fragmentation	Patch scale (0.21)	Number of patches (0.667)	$\mathrm{NP} = N$	The number of farmland patches in a certain area	+
		Largest patch index (0.333)	$\mathrm{LPI} = \frac{max(LA_1, LA_2, \ldots, LA_i)}{A} \times 100\%$	The percentage of the maximum area patch in total farmland area in a certain area	−
	Shape regularity (0.24)	Landscape shape index (0.333)	$\mathrm{LSI} = \frac{0.25P}{A}$	The complexity of the shape of farmland in a certain area	+
		Area–weight mean shape index (0.667)	$\mathrm{AWMSI} = \sum_i^N \left[\left(\frac{0.25P_i}{\sqrt{LA_i}} \right) \times \left(\frac{LA_i}{LA} \right) \right]$	The regularity of patch shape of farmland in a certain area	+
	Spatial distribution (0.55)	Patch density (0.167)	$\mathrm{PA} = N/A$	The number of farmland patches per unit area	+
		Aggregation index (0.833)	$\mathrm{AI} = \left[1 + \sum_i^N \frac{P_i \ln(P_i)}{2\ln(N)} \right] \times 100$	The spatial aggregation degree of cultivated land in a certain area	−

Notes: A is the total area of farmland; N is the total number of patches; LA_i is the area of patch i; P_i is the circumference of patch i; P is the total circumferences of patches.

This study uses a farmland fragmentation index (FFI), which ranges between 0 and 1. The larger the value, the higher the farmland fragmentation degree. The formula for the FFI is as follows:

$$FFI = \sum_{i=1}^{n} \left(\sum_{j=1}^{m} x_{ij} w_{ij} \right) w_i \tag{1}$$

In this expression, *FFI* is the farmland fragmentation index; *n* represents the number of dimensions—in this paper, $n = 3$; x_{ij} and w_{ij}, respectively, indicate the standardized value and weight of the *j*-th indicator in dimension *i*; and w_i and *m* denote the weight of dimension *i* and the number of indicators, respectively.

In order to compare the different sets of variables and improve data integrity, we standardized the data using the min–max method, one of the most widely used data standardization measures.

An analytic hierarchy process (AHP) was used to assign the FF indicators weights. Eight experts from related fields were invited to participate in the determination of the weights of each indicator.

2.4.2. Magic Cube Model

The magic cube model was used to qualify the multi-dimensional spatial characteristics of FF. More concretely, the three sides of the magic cube represent the patch scale (x), shape regularity (y), and spatial distribution (z) of farmland fragmentation, respectively. We further divide x, y, and z into two grades (i.e., lower and higher, with numbers 0, 1, respectively) by using "Mean $\pm$ 0.5 $\times$ Standard Deviation" [45]. On this basis, eight combinations are merged by consulting relevant experts to minimize within-group variability and maximize its homogeneity, and the study area can be divided into several categories (Figure 2 and Table 2).

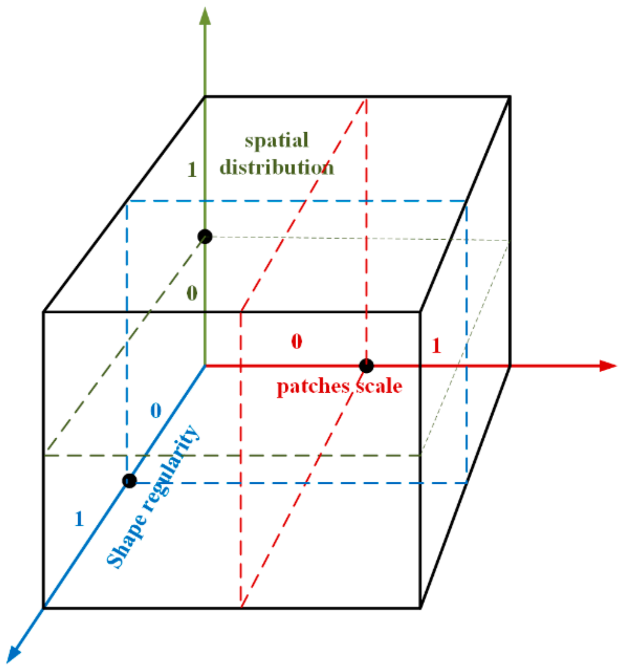

Figure 2. The magic cube model of farmland fragmentation.

Table 2. The classification standards and characteristics of farmland fragmentation based on spatial differences.

Zoning	Magic Cube Coordinate	Characteristics
Comprehensive improvement zone	(1,1,1)	Patch scale, shape regularity, and spatial distribution of farmland are poor. The phenomenon of FF is the most serious.
Key improvement zone	(0,1,1) (1,0,1) (1,1,0)	Two of the three dimensions are poor and need to be improved.
Target improvement zone	(1,0,0) (0,1,0) (0,0,1)	One of the three dimensions is poor and needs to be improved.
Comprehensive development zone	(0,0,0)	Modern agriculture development is endowed with superior patch scale, shape regularity, and spatial distribution of farmland.

3. Results

3.1. Characteristics and Patterns of FF in the Beijing–Tianjin–Hebei Region, China

3.1.1. Temporal–Spatial Patterns of FF in the BTH Region, China

At the regional level, the FFIs in different time nodes were calculated using Equation (1). When comparing the overall values displayed in Figure 3, FF in the BTH region displays patterns that are similar to the theoretical model, and thus confirms Hypothesis 1. The overall FFI in the Beijing–Tianjin–Hebei region decreased slightly from 0.292 in 1980 to 0.275 in 1990. In contrast, the FFI kept increasing from 1990 to 2000. From 2000 to 2005, the FFI decreased sharply, yet went up again after 2005.

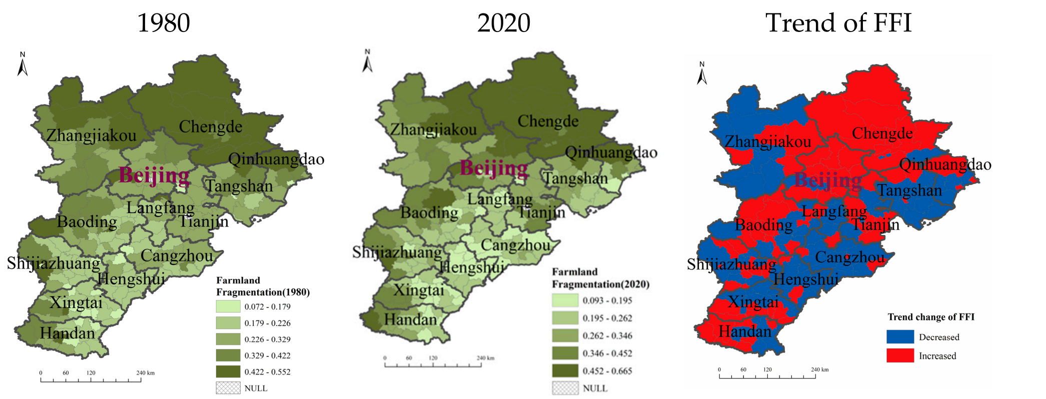

Figure 3. Spatial distribution maps of the farmland fragmentation index in the BTH region.

Regarding the three dimensions of FF, the SR and SD indicators exhibit trends that are similar to the FFI. The SR value remained the lowest, meaning that the shapes of farmland in the BTH region are relatively regular. The PS value remained stable from 1980 to 2020 and is the highest, implying that many parcels and smaller parcel areas in the BTH region are the main reason for the resulting FF.

Figure 3 shows the spatial distribution maps at the county level in the BTH region from 1980 to 2020. The high-value areas of FF in 1980 were distributed in strips along the Taihang mountains of Hebei and Zhangbei grassland (the vast grasslands in northern Zhang-jiakou), while the low-value areas were more geographically continuous, and mainly distributed in the southeastern BTH region. In 2020, the high-value areas of the FFI were still mainly distributed in the northern and western BTH region, while low-value areas were still similar to those from 1980. According to the trajectory change over the past 40 years, the districts and counties in the increased region are mainly distributed in the

Yanshan Mountains in northern Hebei, the Baishi Mountains in northern Baoding, and the Taihang Mountains in the southwestern Hebei region. The districts and counties in the decreased region are mainly distributed in the northwestern, northeastern, and middle of the southern BTH region. Moreover, the decreased regions are coupled with a low-value FFI, and the increased regions are coupled with a high-value FFI (Figure 3).

3.1.2. Spatial Differentiation and Characteristics of FF in the BTH Region

The spatial–temporal change results derived from the FF indicators in the BTH region are the basis for evaluating the differences between cities with different geomorphologies. The DEM data, accessed through the Geospatial Data Cloud, enabled the classification of macro geomorphological types under the basic geomorphological types (plains, terraces, hills, and mountains) in the BTH region for research purposes. Based on the study of Zhao et al., 2015, this paper adopts the division method of the proportion of plains and mountains in cities and divides cities in the BTH region into four macro landforms: plain region, plain–mountain region, mountain–plain region, and mountain region (Figure 4).

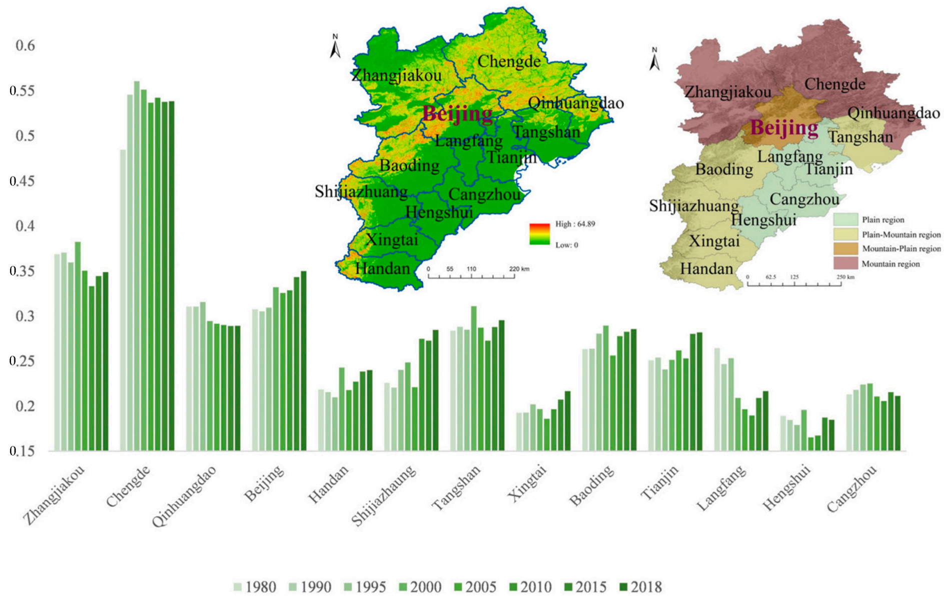

Figure 4. Spatial differentiation of farmland fragmentation under different macro landforms in the BTH region.

Almost all of the FFI trends in the BTH region's cities confirm both Hypothesis 1 and 2. As the proportion of mountains is higher in the spatial unit, the FFI is also higher. Cities in the mountain region (such as Zhangjiakou, Chengde, and Qinhuangdao), located in the northern BTH region, have a relatively high-value FFI. From 1980 to 1995, the FFI in Chengde and Qinhuangdao first rose and then went down from 1995 to 2000, while the FFI in Zhangjiakou rose until 2000. The FFI in these three cities was stable from 2005 to 2020, which suggests that they are still in stage III of the theoretical model. The FFI exhibits an increasing trend in the mountain–plain region, especially from 1995 to 2000. The FFI also decreased in Beijing from 2000 to 2005 because of the implementation of land consolidation policies [46]. It rose sharply again after 2005. The values of the FFI in the plain and plain–mountainous regions are lower than those in the mountainous and mountain–plain regions.

3.2. Characteristics and Patterns of FF in the Bavaria Region, Germany

3.2.1. Temporal–Spatial Patterns of FF in Bavaria, Germany

Compared to the BTH region, the FFI variation in Bavaria has different characteristics. The FFI was stable from 1992 to 1995 at around 0.320 and decreased to 0.293 in 2000. After

2000, the FFI rose slowly and reached 0.305 in 2020. The overall trend of the FFI in Bavaria showed how the FFI changed in stages III and IV, which is consistent with Hypothesis 1. The FF, PS, and SD dimensions showed a similar trend with the FFI.

Figure 5 displays the spatial distribution of FF from 1992 to 2020 for Bavaria. The high-value areas of FF in 1992 were distributed in strips along the Bavarian Alps, and in clusters in Oberfranken and Oberpfalz, where the Franconian Jura, Altmühl Valley Nature Park, and Bavarian Forest are located, while the low-value areas were more geographically continuous in central Bavaria, especially in the metropolitan regions. In 2020, the FFI showed a similar distribution to that in 1992. The change in the FFI over the past 30 years is relatively consistent and coherent. The FFI values in the rural districts consistently decreased, whereas the FFI in the metropolitan or nearby districts of the capital (such as Munich, Augsburg, Landshut, and Würzburg) increased. This pattern is in line with urban sprawl and rural–urban conversions. There are decreased FFI values in northern Bavaria and in the middle of southern Bavaria, in particular.

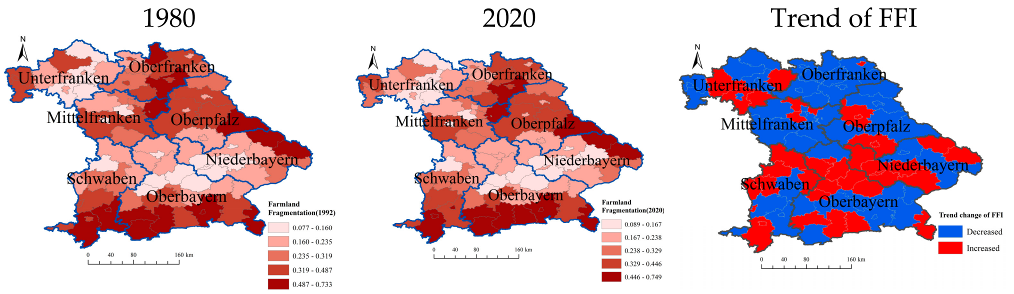

Figure 5. Spatial distribution maps of the farmland fragmentation index in Bavaria.

3.2.2. Spatial Differentiation and Characteristics of FF in the BTH Region

Almost all the trends of the FFI in Bavaria's administrative regions confirm Hypothesis 1 and 2 (Figure 6). The FFI in the mountainous region is much higher than in the mountain–plain region. The regions of Oberfranken, Oberpfalz, Oberbayern, and Scha-waben, located in northern and southern Bavaria, belong to the mountainous region. They exhibit relatively high FFI values. From 1992 to 2000, the FFI values in Oberpfalz, Schwaben, and Oberfranken declined sharply, while the FFI in Oberbayern gradually declined, in line with the transforming of natural areas into farmland [47]. The FFI in all these four regions slowly increased from 2000 to 2020, which means that they are in stage IV of the theoretical model and are affected by urban development. Afforestation and abandonment of farmland are prevalent in this stage.

3.3. Comparison of FF in the BTH Region and Bavaria

3.3.1. Time Evolution of FF in Two Study Areas

The overall FFI trends from 1992 to 2020, displayed in Figure 7, show that the FFI variation in Bavaria is similar to that of the BTH region from 2000 to 2020. In both areas, FFI values were stable, went down, and rose again. These trends are consistent with the theoretical model for temporal change with respect to FF, which suggests that Hypothesis 1 is valid. Meanwhile, the absolute FFI in Bavaria is higher than that of the BTH region. An explanation could be that Bavaria is a more mountainous region; i.e., the proportion of mountain and mountain–plain regions is much higher than that of the BTH region. Therefore, the FFI in Bavaria is also much higher than in the BTH region, which verifies Hypothesis 2.

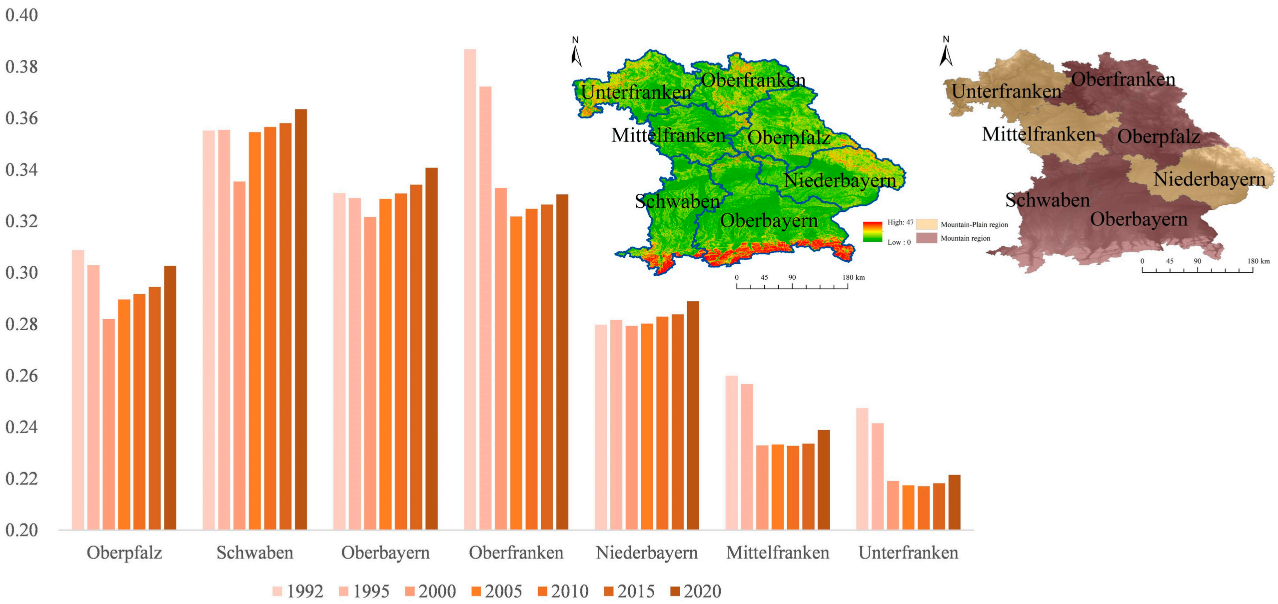

Figure 6. Spatial differentiation of farmland fragmentation under different macro landforms in Bavaria.

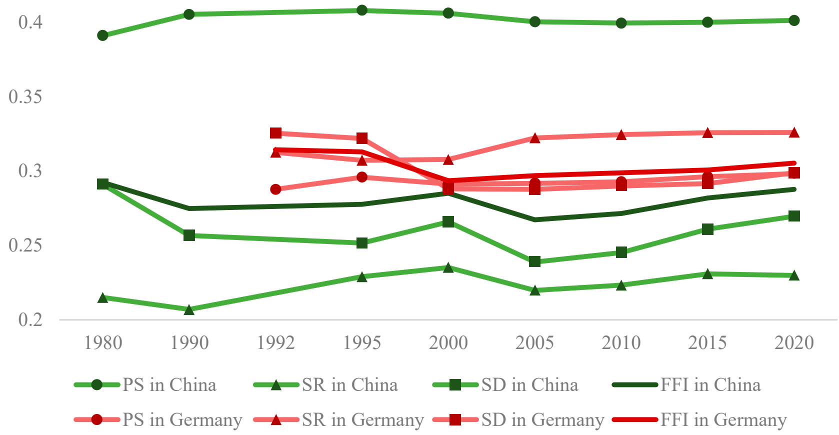

Figure 7. The trend of the farmland fragmentation index and its three dimensions in the two study areas.

In terms of the three dimensions of FF, the values of the three dimensions of FF in Bavaria are not very different from each other, and the trends of their changes are close to that of the overall FFI value, while the three values of the BTH region are significantly different, with only the trend of SD consistent with the overall FFI trend. Therefore, FF in the BTH region should be addressed comprehensively, especially concerning improving the patch scale.

3.3.2. Division of FF Zones and Implications for Future Land Consolidation

Based on the quantitative detection of temporal changes with respect to FF in the BTH region and Bavaria, we divided the study areas into four categories (Figure 8 and Table 3).

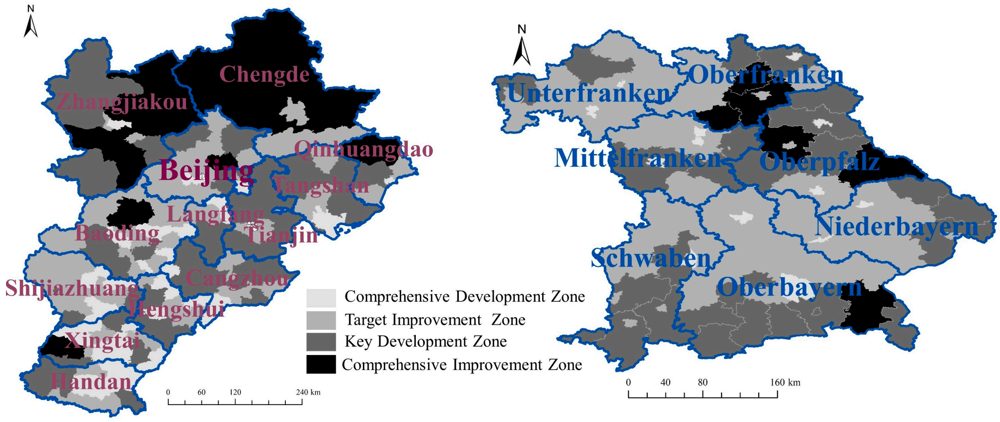

Figure 8. Division of farmland fragmentation zones in the two study areas.

Table 3. The percentage of each zone in the two study areas.

Zone		BTH Region	Bavaria
Comprehensive development zone		25.93%	13.68%
Target improvement zone	target for patch scale (PS)	5.29%	3.16%
	target for shape regularity (SR)	10.05%	36.84%
	target for spatial distribution (SD)	21.16%	10.53%
Key improvement zone	key improvement for PS and SR	20.63%	10.53%
	key improvement for PS and SD	2.65%	18.95%
	key improvement for SR and SD	5.82%	0.00%
Comprehensive improvement zone		8.47%	6.32%

Comprehensive development zone: The magic cube coordinate of this zone is (0, 0, 0), which means that the values of the three dimensions of FF are under average. Defragmentation is a critical phenomenon in this zone. The percentages for this zone in the BTH and Bavaria regions are 25.93% and 13.68%, respectively. The percentage for the BTH region is double that of Bavaria. This is because the BTH region has more plains, which provide better conditions for implementing land consolidation. This cluster is mainly concentrated in the core areas of capital cities with high socio-economic growth. Therefore, the consolidation of farmland in these areas is a priority of projects in order to make room for the expansion of construction land.

Target improvement zone: The magic cube coordinate of this zone is (1,0,0) or (0,1,0) or (0,0,1), which means that one of the values of FF's dimensions is over average and needs a targeted improvement to deal with fragmentation. This zone always surrounds a comprehensive development zone, which means that with the spillover effect of land consolidation in core capital areas, the surrounding areas can improve. Regarding the three target zones, the percentages of the targets in the patch scale zone in the two study areas are below 6%. As for the target in the shape regularity zone, the percentage in Bavaria is 36.84%, which is triple that of the BTH region (10.05%). Therefore, Bavaria should pay more attention to consolidating irregular shapes. As for the target in the spatial distribution zone, the percentage in the BTH region (21.16%) is double that of Bavaria (10.53%), which means that in the future, the BTH region should take more action to improve continuous farmland.

Key improvement zone: The magic cube coordinate of this zone is (1,1,0) or (0,1,1) or (1,0,1), which means that two of the values of FF's dimensions are over average and need fundamental improvement. These regions are far from core urban areas and receive little effort and attention from land consolidation. The BTH region should pay more attention to the critical improvement of PS and SR in some areas as the percentage reaches 20.63%, while some areas in Bavaria should focus on PS and SD (18.95%).

Comprehensive improvement zone: The magic cube coordinate of this zone is (1,1,1), which means that all the values of FF's three dimensions are over average and need comprehensive improvement. These areas are mainly mountainous, forest areas, and national parks. This zone is mainly in the northern BTH region, accounting for 8.47%, and in northern Bavaria, accounting for 6.32%. Both percentages in the study areas are relatively low, showing that land consolidation projects are successful in the two regions.

4. Discussion

Following the results of Section 4, one could question the extent to which these results are significant and generic beyond the single case areas. In other words, what is similar and different when comparing the two case areas, and to what extent can these differences and similarities be attributed to the landscape, institutional, and operational contexts only? Alternatively, are these a direct result of fragmentation trends and methods of fragmentation calculation? Although there are some common features, different areas show different patterns due to their different backgrounds and developmental stages [48].

4.1. Similarities between the Characteristics of FF in the BTH Region and Bavaria

The FFI in both case studies are in line with Hypothesis 1 and 2. Regarding the temporal pattern, with the reform and opening up in 1978, China has transformed from an agricultural society to an industrial society. At this stage, urban expansion is the most significant influencing factor for FF [49], which results in a gradual increase in the FFI between 1980 to 2000. This corresponds to existing studies on converting farmland to artificial land for urban use [32,50]. Land consolidation has effectively reduced the degree of FF in the 2000–2005 period, both in the BTH region and in Bavaria. Currently, urban sprawl continues to occur, which is the prime reason for the continuation of increasing FF [46] in both the BTH region after 2005 and in Bavaria after 2000. The results of the temporal changes thus support Hypothesis 1.

Regarding spatial distribution, Marraccini et al. [47] state that FF relates to the distance from core areas of capital cities. When applying a gradient analysis from urban to rural, Weng [51] found that landscape fragmentation correlates positively with the degree of urbanization, consistent with our results. For our case areas, we find lower FFI values are mainly distributed in the capital districts in the BTH region and in flat and flat–mountain regions, i.e., the central areas of Cangzhou, Hengshui, Langfang, Xingtai, Handan, Shijiazhuang, and Tangshan. In contrast, the degree of FF increases along the gradient from urban to rural. Bavaria has similar characteristics. Low FFI values exist in the regional capital cities, such as Munich, Landshut, Nuremberg, and Würzburg.

In terms of the FFI for the four landform categories, the results confirm Hypothesis 2. Natural condition plays a vital role in physical fragmentation distribution (Jiang et al., 2019). Topographic and landform features are essential [3,52]. The FFI values in the northern and western BTH region's mountain regions (such as the Yanshan Mountains and Taihang Mountains) are much higher than in the plain regions. Similarly, the FFI values in southern and northern Bavaria (where the Alps and the Bavarian Forest are located) are also higher. The terrain is undulating in mountainous areas, the farming conditions are harsh, and the farmland is often scattered. In grassland or forest areas, farmland development is often neglected and lags because of woodland conservation [53], resulting in a higher degree of FF.

4.2. Differences between the Characteristics of FF in the BTH Region and Bavaria

According to the theoretical model constructed in this study, from 1980 to 2020, the FFI in the BTH region experienced stage II–IV, while the FFI in Bavaria experienced stage III-IV, which shows that the development stage of FF in Germany is ahead of China. It entered stage III in 1992, while FF in China did not enter stage III until around 2000. Land use patterns are consistent with development stages [31]. As a developed country, Germany is in a higher stage of economic development, and the development stage of FF is also higher. In Bavaria, the FFI rose again in 2000, while it rose from 2005 in the BTH region. FF is affected by post-urbanization, especially with better social conditions. Therefore, FF in Germany is in an advanced stage.

As for spatial distribution, the FF patterns in Bavaria have formed concentric circles, with the capital cities in each administrative region as the center and the core areas of capital cities mostly low-value FFI and comprehensive development zones. With the gradient from capital cities to their surrounding cities in the district, the value of FF is increased, and the zone transforms into a comprehensive improvement zone. The results in Bavaria are consistent with the conclusion of other studies. Wadduwage et al. [54] used gradient analysis and landscape metrics and identified that the FFI decreased with the distance to core areas.

Analysis of socio-economic and natural condition variances between the two research areas enhances our understanding of FF transitions across diverse societal stages. In the BTH region, industrialization and urbanization have exacerbated FF, primarily driven by the competition between construction land and farmland. Conversely, Bavaria has mitigated FF by improving social conditions, potentially facilitated by advancements in agricultural technology and financial investments. This comparison illustrates that achieving intensive farmland during economic development is feasible yet remains a formidable challenge for developing countries. As a result, sustainable agricultural development targeting FF reduction requires extensive cross-sectoral and inter-regional collaboration for substantial progress. Moreover, we should extend our focus beyond topography to the effects of other natural conditions on farmland fragmentation. For instance, factors such as temperature and precipitation may impact crop ripening, subsequently altering farming patterns and FF.

4.3. Generic Aspects concerning Fragmentation Calculation Methods

4.3.1. Key Factors Affecting Spatio-Temporal Changes in FF

The temporal analysis in Sections 3.1.1 and 3.2.1 reveals visible differences in the temporal changes in FF between Germany and China. The results indicate that the FFI is inversely related to the development of society. With the development of society, under the influence of urbanization and industrialization, the contradiction between people and land is becoming increasingly severe, and the problem of low-efficiency utilization of farmland is becoming more and more prominent. In order to use farmland intensively and economically, the government has introduced a series of measures, such as land consolidation projects. One of the most important objectives of the consolidation projects is to decrease land parcel fragmentation and improve parcel shape to use the farmland more efficiently and make machine farming more comfortable [55]. After the implementation of the revised "land management law" in 1998, China launched the "national land development and consolidation plan (2001–2010)", which defined the core task of farmland consolidation regulation and explored the model of "merging small fields into large blocks" of farmland consolidation. Especially from 2000 to 2005, after the farmland consolidation, the FFI in the BTH region decreased significantly, the number of farmland patches decreased, the patch area increased, the patch boundary was smooth, and the spatial aggregation degree increased. From 2010 to 2020, the FFI of the BTH region rose again, among which the shape distribution (SD) index increased significantly. The patch density of farmland increased, and the aggregation degree decreased. This shows that the primary goal of farmland consolidation is to expand the amount of farmland and compensate for the farmland occupied by non-agricultural construction land, resulting in the segmentation and fragmentation of the farmland landscape [56].

The spatial analysis in Sections 3.1.2 and 3.2.2 suggests that landscape characteristics are driving factors with respect to the changes in FF. In particular, the spatial differentiation analysis of FF under different macro landforms in the BTH region varied widely. The FFI in the western mountainous area is significantly higher than in the eastern plain area of the BTH region, which implies that the FFI positively correlates with the proportion of the mountainous area. This indicates that FF has a synergistic relationship with the landscape. These findings are consistent with the work of Qian et al. [18], highlighting that the spatial distribution characteristics of FF matched the landforms. The enhanced areas are mainly distributed in the northwestern hilly area, while the weakened areas are mainly in the eastern plain area. Meanwhile, the research scale of this study area is also applicable to other regions, which encourages the use of county boundaries based on the landform characteristics of each city to help managers and decision-makers to manage farmland resources and implement differentiated measures to improve or utilize the farmland fragmentation in different landforms.

4.3.2. Contribution of the Analytical Framework and the Index of Farmland Fragmentation

Human activity is an essential factor affecting change with respect to farmland, and human intervention has a direct or indirect impact on the distribution of farmland [57]. With the development of industrialization and rapid urbanization, the scope of construction land continues to expand, resulting in an increased frequency of farmland conversion [58] and the FF problem becoming increasingly severe. Farmland fragmentation is caused by the long-term effects of socio-economic systems and the natural environment, and it must be assessed via a long time series and under different landforms [18,30,59]. Understanding the changing FF growth pattern in urbanization processes is vital in rural development planning and sustainable growth management. This requires stakeholders to have a sound knowledge of the characteristics of farmland in the multi-dimensional aspects of patch scale, shape regularity, and spatial distribution, and then make the most realistic decision-making for farmland utilization and agricultural development planning in different regions. Therefore, expanding the characteristics of FF under different landforms and exploring its long-term changes will be conducive to human well-being. However, improving the quality and efficiency of farmland has become an important part of farmland protection, but its ways and measures are still being explored. The analytical framework presented in this study has the potential to make an essential contribution to the existing literature as it enriches the spatio-temporal change model of FF to a certain extent and makes a comparison of FF in developed and developing countries. In terms of practical application, based on scientifically measuring the spatio-temporal characteristics of FF, this study brings forth the complex idea of considering patch scale, shape regularity, and spatial distribution of FF when guiding the practice, planning, and management of regional land consolidation projects, which is of great significance in terms of improving the utilization efficiency of farmland resources.

4.3.3. Policy Suggestions for Farmland Fragmentation Based on the Magic Cube Zone

Based on the spatial differentiation of farmland fragmentation, this paper proposes policies to optimize the farmland pattern in the BTH region.

(1) The comprehensive improvement zone mainly includes Zhangjiakou City and Chengde City, northwest of Hebei Province. The three-dimensional indexes of FF in this zone are higher than the average value. This zone belongs to the region with the highest degree of FF in the BTH region and needs to be comprehensively improved. This zone is a mountainous area with a poor environment. It should be combined with construction related to the "return of farmland to forest and grassland" and Three-North Shelterbelt. Policies such as strengthening the compensation of relevant policies and encouraging farmland consolidation should also be proposed.

(2) The critical improvement zone mainly includes some counties in the northwest mountainous and coastal areas. In this zone, two dimensions of the three-dimensional index are higher than the average value. Under the premise of protecting and improving the ecological environment, this zone should actively develop saline–alkali land and wasteland and supplement the effective farmland area.

(3) Only one aspect of FF in the target improvement zone needs targeted remediation. The construction of high-standard basic farmland should be strengthened in this area to

guide the centralized connection of farmland, regulate the shape of farmland plots, and improve the landscape value of farmland.

(4) The comprehensive development zone mainly includes counties in the central and southern plains of Hebei Province. The three-dimensional index of FF in this area is lower than the average value, which means the overall degree of fragmentation is low and the farmland is in relatively good condition. The zone should strengthen law enforcement of the ecological red line and permanent basic farmland, prevent further fragmentation of farmland, control land regulation standards, and take the green road of sustainable development.

5. Conclusions

Based on the proposed theoretical framework of farmland fragmentation, this study quantitatively measures the temporal–spatial variations of FF in the Beijing–Tianjin–Hebei region from 1980 to 2020 and in Bavaria from 1992 to 2020. The main conclusions are:

(1) The FF values in the BTH region are undulating, which is consistent with stages II–IV of the proposed theoretical framework. The FF values in Bavaria show a different and less consistent pattern, characterized by both stable and increasing and decreasing values. This pattern is more consistent with stages III–IV of the theoretical framework. Both results confirm Hypothesis 1 of this study.
(2) The FFI is mainly high in the mountain and the mountain–plain regions of the northern and western BTH regions and in northern and southern Bavaria. The FFI is mainly low in the flat regions of the southeastern BTH region, in the middle of Bavaria, and in the district capitals of both study areas.
(3) The decreased trend regions are mainly distributed in low-value FFI regions, while the increased trend regions are mainly distributed in high-value FFI regions.
(4) This study applied the magic cube model to describe and predict the variation in FF values. It turned out that the FF values within the three dimensions are not close to each other in the BTH region. The patch scale reached the highest, while shape regularity was the lowest among them. The values of the three dimensions of FF are close to each other in Bavaria. Among them, shape regularity was relatively high, whereas spatial distribution was relatively low.

These findings enhance our understanding of FF and aid in realizing sustainable agricultural development. Firstly, we underscore the importance of employing comprehensive approaches and long time series remote sensing data to assess FF thoroughly. Secondly, we advocate for tailoring land use policies to the specific circumstances of areas at different stages of farmland fragmentation to achieve improvements. As food security remains a globally pertinent issue, we still need to optimize the spatial layout of farmland, through means such as basic farmland protection, even in areas with lower degrees of FF.

This research constructed a comprehensive theoretical framework to identify and describe temporal and spatial variations in FF. A longitudinal empirical data collection and analysis of FF dynamics (spatially and temporally) confirmed the validity of the theoretical framework for this type of analysis. The applied model appeared to work for cases in both developing and developed countries, which suggests that it is valid for multiple locations. Therefore, the results of this research can support land management practitioners and spatial decision-makers using the FF analysis in their daily work.

Despite the results we have achieved, more analyses need to be conducted. Further research can focus on analyzing the FF variations for different distances to urban core areas. Additionally, one can test other methods to find the driving factors for FF variation in different regions or counties.

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