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Spatiotemporal Evolution and Driving Forces of Production-Living-Ecological Space in Arid Ecological Transition Zone Based on Functional and Structural Perspectives: A Case Study of the Hexi Corridor

Xianglong Tang, Leshan Cai * and Pengzhen Du

School of Architecture and Urban Planning, Lanzhou Jiaotong University, Lanzhou 730070, China; tangxl@mail.lzjtu.cn (X.T.); dupz@lzu.edu.cn (P.D.)
* Correspondence: 12231858@stu.lzjtu.edu.cn

Abstract: The rational allocation of land resources is crucial to ensuring human well-being, livelihood, and survival. The study of Production-Living-Ecological Space (PLES) provides new perspectives on land resource allocation. However, few studies have assessed the feasibility of PLES optimization in ecological transition zones. For this study, using the composite functional space classification method, a classification and functional utility scoring system were constructed. Various methods, including dynamic attitude, transfer matrix, and spatial autocorrelation, were employed to characterize the evolution of the quantity and quality of PLES in the Hexi Corridor. Moreover, the mechanisms driving these changes were explored using a geodetector. Our findings revealed that: (1) The distribution of Production-Ecological Space (PES) is higher in the west and south and lower in the east and north. Production-Living Space (PLS) is scattered. Ecological-Production Space (EPS) is mostly distributed in the south or west, whereas Ecological Space (ES) is mainly located in the north and west of the Hexi Corridor. (2) From 1980 to 2020, the area of PES and PLS increased by 2037.84 km^2 and 673 km^2, respectively; the area of EPS was relatively stable, and the area of ES decreased by 2523.06 km^2. (3) The evolution of PLES quality indicated that the high functional utility area of PES and PLS was roughly the same as the expanded functional utility area, whereas the expanded functional utility area of EPS and ES is similar to the median functional utility area. (4) The spatiotemporal evolution of PLES is closely linked to natural, economic, and social factors.

Keywords: ecological transition zone; multifunctional land use; production-living-ecological space; driving forces; Hexi Corridor

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1. Introduction

Space is a crucial resource for all human activities. With the progress of science and technology and the rapid increase in the global population, human activities have given rise to various new forms of land use, resulting in substantial changes in global land utilization [1]. For instance, the expansion of cultivated land in Southeast Asia has led to deforestation [2], whereas extensive afforestation efforts in East Asia have positively impacted vegetation conditions [3]. Anthropogenic pressures have caused severe eutrophication in water bodies [4] and the loss of wetlands in some continental European watersheds [5]. Profound shifts in land use significantly influence biodiversity, global climate change, and ecosystem resilience [6–8]. Given that the rational allocation of land resources is closely tied to human well-being, health, livelihood, and survival [9,10], the multifunctional use and spatiotemporal evolution of land have recently garnered increasing attention [7,11,12].

Since China's reform and opening up, rapid urbanization and industrialization have propelled social and economic development [13,14]. However, this progress has given rise to increasingly severe problems, including significant soil erosion, declining biodiversity, heightened conflicts between humans and land, and a looming crisis in sustainable land allocation [3,15]. In 2012, the Chinese government specifically put forward the overall goal of "intensive and efficient production space, livable and moderate living space, and clear and beautiful ecological space", emphasizing "overall planning of territorial spatial development, scientific layout of production space, living space, and ecological space, and leaving more space for nature" [16]. The comprehensive spatial zoning method known as Production-Living-Ecological Space (PLES) classifies space based on the production, living, and ecological functions of the land, encompassing all human activities [17]. PLES is one of the thematic research elements of territorial spatial planning, as well as a zoning approach to territorial spatial planning [18]. This approach provides a novel perspective for evaluating spatial development suitability and maximizing spatial functions in the process of territorial space development and protection, gaining favor from the Chinese government and researchers [19,20]. PLES has now become a pivotal basis for optimizing land allocation in China, with significant implications for managing land use conflicts and regulating land allocation based on social and economic factors [21,22]. The concept of PLES is based on the functional perspective of land use. According to the theoretical viewpoint of "element-structure-function" in system theory, the system structure is the basis for the realization of system function. Therefore, if land use is regarded as a system, the structure of land use is the basis for the realization of land use functions. Based on the structure of land-use types and the establishment of a logical connection and classification system between land-use types and land-use functions, a scientific spatial classification and evaluation system for PLES can be constructed.

Understanding the characteristics of PLES classification and its spatiotemporal evolution forms the foundation of PLES-related research. PLES classification methods primarily fall into two categories: the land class merging method and the index system method [21]. The land class merging method identifies the evolutionary characteristics of PLES quantity but struggles to describe the differences in PLES quality [23]. In contrast, the index system method assesses the functional strength of PLES using natural, social, and economic data [17]. While this method can identify the evolution characteristics of PLES quality, its evaluation of functional strength relies on a series of indicators, all considering the administrative unit as the evaluation unit, making it challenging to fully and accurately reflect spatial function. Another approach that is sometimes used is PLES identification through point-of-interest (POI) data and social behavior activities [24]. With economic and social development, human demand for land increases. The functions played by each of the PLES show a diversified trend, and the identification of PLES in a fixed scale range should be based on the dominant function of land use. The results of existing studies do not sufficiently take into account the multifunctionality of land use [21]. Therefore, we propose a model for dividing the composite functional space. The model of composite functional space is based on the characteristics of spatial functional composability, which analyzes functions for the three types of single spaces, namely, ecological, production, and living spaces, as well as composite spaces such as Production-Living Space, Production-Ecological Space, and Ecological-Production Space [25]. Currently, driven by the demand for multifunctional space utilization and coordinated development, the composite functional space classification method has gained widespread acceptance in China [25,26]. Therefore, we employed this method to characterize the study area and established a function evaluation system to score the spatial function of PLES in the Hexi Corridor. This approach only requires land use data from different periods, enabling precise identification of the quality and quantity evolution characteristics of PLES [19,27]. When exploring the driving mechanisms of the evolution of PLES, common methods include geographically weighted regression [28], correlation coefficient [29], and geodetector [28]. The advantage of geodetector is that it permits the analysis of both numerical and qualitative data, as well as the interaction of two factors on the dependent variable [30]. For the purposes of our study, we are also considering our case as an example of an ecological transition zone. Ecological transition zones are characterized by a large environmental gradient [31]. Further characteristics include evident changes for various landscape elements, with a strong edge effect. The regional climate of such zones is typically more sensitive to global climate change [31,32]. Land cover types in the ecological transition zone are complex and diverse [33], and conflicts between different land use types are more intense [34]. The Hexi Corridor is a highly representative ecological transition zone, characterized by a harsh climate and a fragile ecological environment. This transition zone features diverse landforms such as snow-capped mountains, forests, grasslands, deserts, rivers, and oases [35,36]. Overall, the Hexi Corridor exhibits relatively slow social and economic development and a low level of urbanization. Nevertheless, the arid zone contains several oases that represent higher concentrations of human activity, noticeable land-use conflicts, and detrimental impacts of human activity on the environment [37]. The PLES evolution model and driving mechanisms in the Hexi Corridor differ significantly from those in other regions. With the introduction of the Western Development Strategy and the Belt and Road Initiative. Initiative, the importance of the Hexi Corridor is becoming increasingly significant as an important corridor for international land transportation connecting Eurasia and as a key region for the implementation of the Belt and Road initiative [4,38]. With the expansion of oasis towns, pressure on water resource supply increases, rendering the distribution of PLES more complex [39]. Agricultural and industrial activities place additional pressure on water resources. The functional integrity of PLES within the Hexi Corridor therefore holds considerable ecological, economic, and cultural value for promoting regional sustainable development and enhancing the well-being of the populations of the surrounding areas.

Previous studies on PLES identification and evolution have focused on urbanized areas due to the personal backgrounds of the researchers, the availability of data, and the more intense conflicts over production, living, and ecological spaces within highly urbanized areas [40]. Comparatively few studies have to date assessed and classified patterns in ecological transition zones within arid areas. Moreover, most relevant studies have focused on either the quality evolution [41] or quantity changes [31,42] of PLES, making it challenging to accurately pinpoint the temporal and spatial evolution characteristics. Analysis of driving factors in previous studies primarily revolved around social, economic, and demographic factors, with limited attention to natural factors.

Therefore, this study sought to construct a PLES classification and function scoring system from the novel perspective of land use compound function. This approach aims to unveil the temporal and spatial evolution of PLES in the Hexi Corridor, both in terms of quality and quantity. Additionally, geodetector is employed to assess the influence of different factors on the temporal and spatial evolution of PLES in the Hexi Corridor and elucidate the mechanisms driving these changes. Furthermore, by integrating research findings and related studies, we sought to propose a scientific and rational strategy for the sustainable development and spatial management of the Hexi Corridor. Collectively, the strategies proposed herein aim to facilitate the rational allocation and sustainable development of land space in the areas surrounding the Belt and Road Initiative.

2. Materials and Methods

2.1. Study Area and Data Sources

2.1.1. Study Area

The Hexi Corridor is located in northwest China, west of the Yellow River, north of the Qilian Mountains, and south of the Beishan Mountains. The Hexi Corridor includes five prefecture-level cities (Wuwei, Jinchang, Zhangye, Jiuquan, and Jiayuguan), with a total of 20 county-level administrative units, covering an area of 27.74×10^4 km^2 (Figure 1). The Hexi Corridor has an average annual temperature of 4–10 °C and annual precipitation of approximately 200 mm, with sunshine and annual total solar radiation up to 5700–6400 MJ/m^2. Its landforms mainly include snow-capped mountains, oases, grasslands, deserts, and rivers. Both regions as a whole exhibit typical characteristics of ecological transition zones [38]. The Hexi Corridor hosts three major river basins—the

Yanghe River, Heihe River, and Leshuhe River—constituting the primary distribution areas of oases in the region. Settlements are predominantly located within or on the periphery of oases [36,39,43], which account for approximately 10% of the total area of the Hexi Corridor but contribute approximately 90% of the region's GDP [44]. In recent years, the development of land resources in the Hexi Corridor has become increasingly active, and a large amount of unused land has been transformed into construction land, arable land, and grassland [45], leading to increasingly rapid and far-reaching changes in PLES. Given its unique characteristics, the Hexi Corridor serves as an ideal location for studying the temporal and spatial evolution, as well as the driving mechanisms, of ecological transition zone PLES in arid regions.

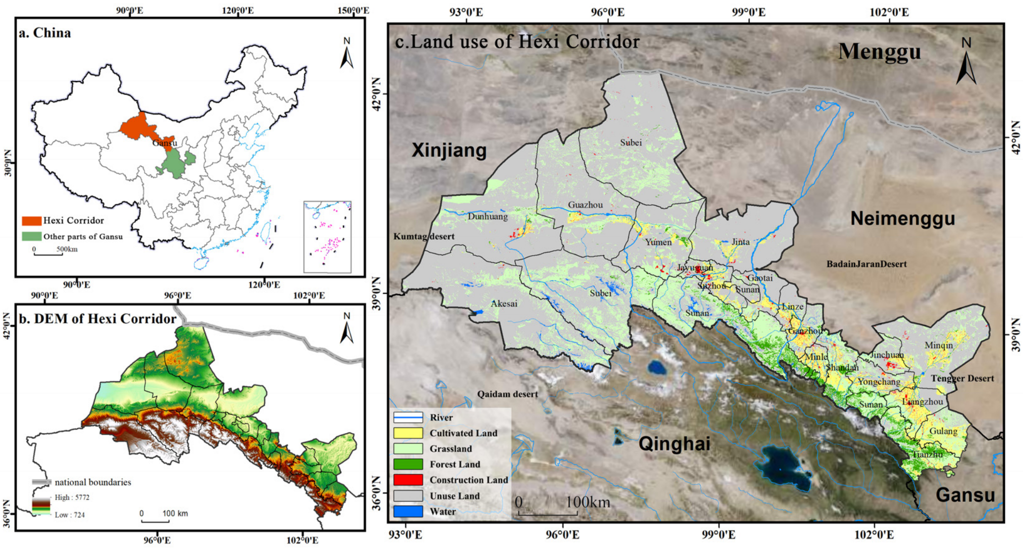

Figure 1. Map of the Hexi Corridor in the year 2020. (**a**) is the map of China; (**b**) is the DEM of the Hexi Corridor; and (**c**) shows the land use of the Hexi Corridor. (Land use data from CNLUCC, DEM data from the European Space Agency, administrative boundaries from the National Geomatics Center of China).

2.1.2. Sources and Processing of Land Use Data

The study selected the "China Land Cover" (CNLUCC) data provided by the National Resources and Environment Database of the Chinese Academy of Sciences (https://www.resdc.cn/ (accessed on 15 April 2024)). Several studies have shown that this data are one of the most suitable datasets for regional-scale studies in China [32,46]. The land use classification of this dataset is shown in Table 1, which has a raw precision of 30 m × 30 m. This study uses land use data from this dataset for the years 1980, 1990, 2000, 2010, and 2020.

Table 1. Classification system of CNLUCC.

Class I Land Use Type		Class II Land Use Type	
Code	**Type**	**Sub Code**	**Name**
1	Cultivated land	11 12	Paddy field Dry land
2	Forest land	21 22 23 24	Woodland Shrub wood Open woodland Other forest land
3	Grassland	31 32 33	High coverage grassland Medium coverage grassland Low coverage grassland

Table 1. *Cont.*

Class I Land Use Type		Class II Land Use Type	
Code	**Type**	**Sub Code**	**Name**
4	Water	41 42 43 44 45	Canal Lake Permanent glacier and snow Beach land Reservoir pit
5	Construction land	51 52 53	Urban construction land Rural construction land Other construction land
6	Unused land	61 62 63 64 65 66 67	Sand Gobi Saline alkali land Swamp Bare land Bare rock gravel ground Other unused land

2.1.3. Sources and Processing of Other Data

The other data types, sources, and accuracy of this study are summarized in Table 2. The study standardized the spatial accuracy of all data to 1 km × 1 km when using geodetector.

Table 2. Other data sources.

Data Name	Source	Accuracy
Average annual precipitation, temperature, evaporation, sunshine hours, NDVI, population density, and per capita GDP	Resources and Environmental Science and Data Center, Chinese Academy of Sciences http://www.resdc.cn (accessed on 15 April 2024)	1 km × 1 km
Administrative divisions of the Hexi Corridor area	National Center for Basic Geographic Information https://www.ngcc.cn/ (accessed on 15 April 2024)	-
COP-DEM	European Space Agency https://panda.copernicus.eu/panda (accessed on 15 April 2024)	30 m × 30 m
Other social and economic development data	China County Statistical Yearbook, National Economic and Social Development bulletins	Interpolating the data as 1 km × 1 km

2.2. Methods

2.2.1. Classification System and Spatial Scoring Standard System of PLES in Hexi Corridor

This study focuses on the classification of land use types, function identification, and scoring, aiming to explore the relationship between changes in PLES types and function scores. The objective of this study was to establish a scientific basis for spatial planning and management by assessing the spatial evolution of PLES from both a qualitative and quantitative perspective. The most significant advantage of this method lies in its more systematic and comprehensive assessment of the temporal and spatial evolution of PLES. This holistic approach not only considers the quantitative evolution trend of land use types but also incorporates the qualitative evolution trend of land use functions. Moreover, the proposed approach integrates the multifunctional utility of a single land type (e.g., cultivated land serves both productive and ecological functions) into quantitative data, emphasizing the crucial role of land in coordinating and balancing production, life, and ecology. Liu et al. constructed a functional evaluation system for PLES in China based on CNLUCC, according to the field research method and expert scoring method [47]. Given the growing emphasis on the multifunctional use of land and its diverse social and ecological contributions, this study integrates existing classification methods and functional evaluation frameworks of PLES, national standards, and pertinent research [16,19,48–50]. Drawing on methodologies applied in these prior studies [26,51,52], we constructed a PLES functional scoring system applicable to the Hexi Corridor based on the characteristics of land use in the Hexi Corridor using field survey methods (Table 1).

The land use types in the Hexi Corridor underwent meticulous classification, with each assigned function score drawing on the methodology proposed by Liu et al. [47]. We have further categorized PLES into Production-Ecological Space (PES), Production-Living Space (PLS), Ecological Production Space (EPS), and Ecological Space (ES). In turn, its functional utility is divided into a Production-Ecological Functional Score (PEFS), a Production-Living Functional Score (PLFS), an Ecological Production Functional Score (EPFS), and an Ecological Functional Score (ESFS)—comprising four functional scores. To express the primary and secondary relationships of the four spatial functions, we used a six-grade scale from 0 to 5. For example, cultivated land (paddy fields and dryland) primarily serves agricultural production but also has an ecological function. Its PEFS, EPFS, and ESFS scores are 4, 2, and 4, respectively.

The PLES classification system (Table 3) corresponds to CNLUCC [26,29,51,53]. On the other hand, we score the function of land use types in CNLUCC according to the actual situation of the Hexi Corridor and the research of Liu et al. [47]. The scoring standards are derived from the study of Liu et al. [47]. The scoring results are shown in Table 4. We combine Tables 3 and 4 to get the classification system and spatial scoring standard system of PLES in the Hexi Corridor (Table 5).

Table 3. Classification system of PLES in the Hexi Corridor. The Class II land use types here correspond to the CNLUCC (shown in Table 1 above).

PLES	Class II Land Use Type	Basis of Categorization
Production-Ecological space (PES)	Paddy field Dry land	Cultivated land has the function of providing ecosystem supply services for food and other biological products, as well as ecosystem support functions such as climate regulation, atmospheric regulation, nutrient cycling, and soil and water regulation. It is also an important land for agricultural production.
	Reservoir pit	The reservoir pit has an important ecological service function and is an important water conservation land, as well as a fishery production function.
Production-Living Space (PLS)	Urban construction land Rural construction land Other construction land	Construction land is the main land for human production and living.
Ecological-Production Space (EPS)	Woodland Shrub wood Open woodland Other forest land High coverage grassland Medium coverage grassland Low-coverage grassland	Forest land has the functions of climate regulation, atmospheric regulation, water and soil regulation and other ecosystem regulation, and plays an important role in biodiversity, and is known as the "lungs of the earth", which is an important ecological land. Grassland has the functions of providing biological products, atmospheric regulation, climate regulation, water conservation, soil conservation, ecological landscape and recreation, and is an important ecological land. At the same time, woodlands can provide some products for human use, such as the fruits of some trees. Human livestock are grazing on grassland. Therefore, woodlands and grasslands have a partially productive function.

Table 3. *Cont.*

PLES	Class II Land Use Type	Basis of Categorization
Ecological Space (ES)	Canal Lake Permanent glaciers and snow Beach land Sand Gobi Saline alkali land Swamp Bare land Bare rock gravel ground Other unused land	Canals and Lakes play an important role in regulating regional air temperature and stabilizing local climate; permanent glaciers and snow have the functions of water conservation and climate regulation, and are important ecological land. Unused land has important landscape ecological functions, and sandy, bare, and saline land are the natural land cover types and are important ecological sites.

Table 4. Spatial scoring standard system of CNLUCC in the Hexi Corridor. The Class II land use types here correspond to the CNLUCC (shown in Table 1 above).

Class II Land Use Type		Production-Ecological Functional Score (PEFS)	Production-Living Functional Score (PLFS)	Ecological-Production Functional Score (EPFS)	Ecological Functional Score (EFS)
Sub Code	Name				
11	Paddy field	4	0	2	4
12	Dry land	3	0	1	3
21	Woodland	0	0	1	5
22	Shrub wood	0	0	1	4
23	Open woodland	0	0	2	3
24	Other forest land	2	1	3	3
31	High coverage grassland	3	0	3	5
32	Medium coverage grassland	2	0	2	4
33	Low coverage grassland	1	0	1	3
41	Canal	2	0	0	5
42	Lake	2	0	0	5
43	Permanent glacier and snow	4	0	0	3
44	Beach land	0	0	0	5
46	Reservoir pit	1	0	2	5
51	Urban construction land	3	5	0	0
52	Rural construction land	3	5	0	0
53	Other construction land	1	3	0	0
61	Sand	0	0	0	1
62	Gobi	0	0	0	1
63	Saline alkali land	0	0	0	2
64	Swamp	0	0	0	4
65	Bare land	0	0	0	1
66	Bare rock gravel ground	0	0	0	1
67	Other unused land	0	0	0	1

Table 5. Classification system and spatial scoring standard system of PLES in the Hexi Corridor.

PLES	Class II Land Use Type	Production-Ecological Functional Score (PEFS)	Production-Living Functional Score (PLFS)	Ecological-Production Functional Score (EPFS)	Ecological Functional Score (EFS)
Production-Ecological Space (PES)	Paddy field	4	0	2	4
	Dry land	3	0	1	3
	Reservoir pit	4	0	0	3
Production-Living Space (PLS)	Urban construction land	3	5	0	0
	Rural construction land	3	5	0	0
	Other construction land	1	3	0	0
Ecological-Production Space (EPS)	Woodland	0	0	1	5
	Shrub wood	0	0	1	4
	Open woodland	0	0	2	3
	Other forest land	2	1	3	3
	High coverage grassland	3	0	3	5
	Medium coverage grassland	2	0	2	4
	Low coverage grassland	1	0	1	3
Ecological Space (ES)	Canal	2	0	0	5
	Lake	2	0	0	5
	Permanent glacier and snow	0	0	0	5
	Beach land	1	0	2	5
	Sand	0	0	0	1
	Gobi	0	0	0	1
	Saline alkali land	0	0	0	2
	Swamp	0	0	0	4
	Bare land	0	0	0	1
	Bare rock gravel ground	0	0	0	1
	Other unused land	0	0	0	1

2.2.2. Dynamic Degree of PLES Change

In this study, a single dynamic index was used to describe the change of a single space in the Hexi Corridor [29]. The formula for calculating single dynamic attitude is as follows:

$$K = (Ub - Ua)/Ua/T \times 100\% \quad (1)$$

where K represents the dynamic patterns of a certain type of space in the region within a certain period of time. Ua is the area of a certain type of space at the beginning of the study period, Ub is the area of the space at the end of the study period, and T is the research period.

A single comprehensive dynamic index was used to describe the overall change severity of the Hexi Corridor PLES. This comprehensive dynamic index was calculated as follows:

$$KC = \frac{\Sigma_{i=1}^{n} \Delta LU_{i-j}}{2\Sigma_{i=1}^{n} LU_i} \times \frac{1}{T} \times 100\% \quad (2)$$

where KC is the comprehensive dynamic pattern; T is the study period; ΔLU_{i-j} represents the absolute area transformed from space i to space j; LU_i is the area of space i at the beginning of the study period.

2.2.3. Transition Matrix of PLES

The transition matrix was used to characterize the change of PLES structure [54]. The land use transfer matrix can be used to quantitatively explore the change of PLES and reveal the direction and overall effect of PLES transfer in different periods. The calculation formula is as follows:

$$S_{ij} = \begin{Bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{Bmatrix} \quad (3)$$

where S_{ij} is the area of space i transformed into space j; n indicates the number of types of PLES.

2.2.4. Geodetector

Geodetector is a statistical method to detect the spatial differentiation of geographical phenomena and identify the main driving forces, including a factor detector, risk detector, ecological detector, and interactive detector [29,55]. Factors and interactive detectors were used in this study. These factors were calculated as follows:

$$q = 1 - \sum_{h=1}^{L} N_h \sigma_h{}^2 / N\sigma^2 \quad (4)$$

In the formula, q is an explanatory index that affects the function score of PLES, ranging from 0 to 1. Larger values indicate a greater influence of driving factors on the function score of PLES and vice versa; L is the classified number of influencing factors; N_h and N are the number of units in layer h and the study area. $\sigma_h{}^2$ and σ^2 are the variances of the function score of PLES for layer h and the study area, respectively.

3. Results

3.1. Spatiotemporal Variation Characteristics of PLES

The PLES distribution in the Hexi Corridor exhibits distinct characteristics based on location and topography. In the Gobi and desert hinterland, changes in PLES are relatively steady, while the variations in various oases and their peripheral regions are more pronounced (Figure 2), though still constrained within a specific regional range. The overall pattern of PLES over the past 40 years can be summarized as follows: (1) PES is characterized by high levels in the west and south and low levels in the east and north. PES is predominantly distributed along the rivers and alluvial plains of the Hexi Corridor and is mainly concentrated in Liangzhou, Minqin, Minle, Ganzhou, Linze, Suzhou, and Jiayuguan. (2) PLS accounts for a relatively small number of towns and villages of varying sizes; PLS is scattered across major oasis areas in the Hexi Corridor. These areas are mostly surrounded by production ecological space. (3) EPS is mostly distributed in the south or west of the Hexi Corridor and is composed of an alpine meadow formed after the melting of the Qilian Mountains glacier. They are mainly concentrated in the north and west of the Hexi Corridor, particularly in the Gobi and desert regions. Concentrated mainly in Minqin, Jinta, Subei Mongolian Autonomous County (Beishan area), Dunhuang, Guazhou, Yumen, and Aksai.

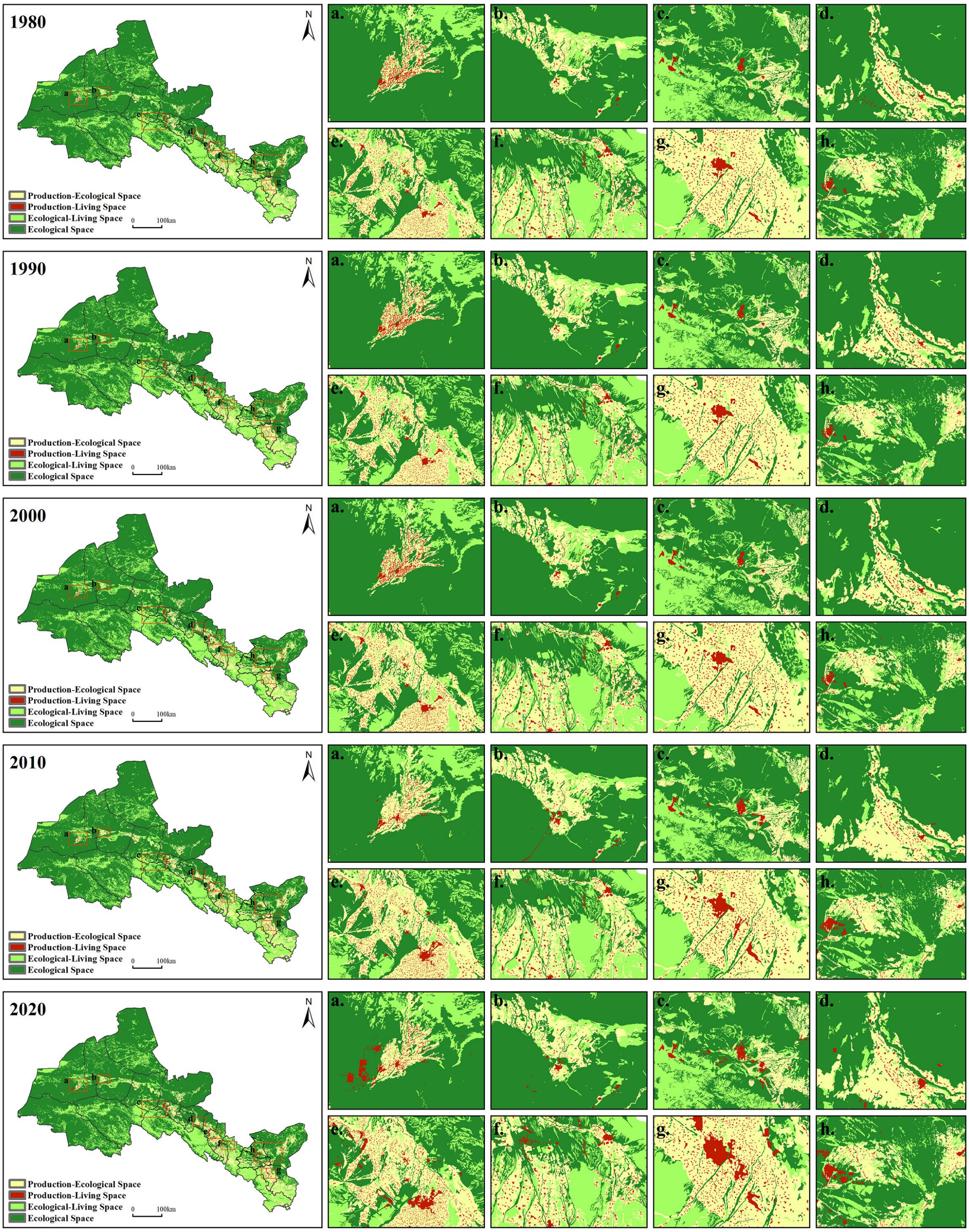

Figure 2. Spatial pattern of PLES from 1980 to 2020. Figures (**a**,**b**) represent Dunhuang and Yumen, respectively, located in the north of the Hexi Corridor; Figures (**c**–**f**) are Jiayuguan, Suzhou, Ganzhou, and Shandan, located in the middle of the Hexi Corridor; Figures (**g**,**h**) are located in the south of the Hexi Corridor, encompassing Gulang, Jinchuan, and Minqin.

3.2. Quantitative Evolution of PLES

3.2.1. The Characteristics of the Scale Evolution of PLES Quantity

As of 2020 (Table 6), ES covered an area of 168,996.09 km^2, accounting for 68.31% of the total area, and stands as the predominant category. The EPS area is 60,658.36 km^2, accounting for 24.52% of the total area. The PES area spans 15,989.58 km^2, accounting for

6.46% of the total area. PLS has the smallest area of 1758.32 km^2, accounting for 0.71% of the total area. Over the past 40 years, there have been changes in the areas of these PLES categories. The PES area increased by 2469.08 km^2, equivalent to 1.00% of the total area. The PLS area experienced an increment of 742.32 km^2, comprising 0.30% of the total area. Conversely, the EPS area decreased by 689.03 km^2, accounting for 0.28% of the total area. The ES area saw a reduction in 2523.06 km^2, representing 1.02% of the total area.

Table 6. Area and proportion of PLES from 1980 to 2020.

Date	PES		PLS		EPS		ES	
	Area/km^2	Proportion /%	Area/km^2	Proportion /%	Area/km^2	Proportion /%	Area/km^2	Proportion /%
1980	13,520.50	5.46	1016.00	0.41	61,347.39	24.80	171,519.15	69.33
1990	13,568.40	5.48	1018.34	0.41	61,141.03	24.71	171,675.08	69.39
2000	13,951.74	5.64	1084.73	0.44	60,999.65	24.66	171,366.73	69.27
2010	15,814.77	6.39	1282.97	0.52	60,524.87	24.46	169,780.63	68.63
2020	15,989.58	6.46	1758.32	0.71	60,658.36	24.52	168,996.09	68.31

The comprehensive dynamic index of PLES has undergone increasingly dramatic changes over time (Table 7). The most significant change in the Comprehensive Dynamic Index occurred during the 2000–2010 period, registering a substantial increase in 0.08, which was notably higher than in other periods. This surge was primarily attributed to a sudden and considerable expansion of production space coupled with a gradual decrease in ecological space. During the study period, PES and PLS exhibited a large expansion trend, with a dynamic index of 1.83% and 7.31%, respectively. The most noticeable expansion for PES occurred during 2010–2020, with a change rate of 1.34%. Likewise, the most prominent expansion for PLS was observed during 2010–2020, with a dynamic rate of 3.71%. On the other hand, EPS and ES displayed a tendency to contract, with dynamic rates of −0.11% and −0.15%, respectively. EPS tended to initially decrease and then increase, whereas ES exhibited the opposite trend.

The conflict between cultivated land and construction land and forest, grassland, and desert land is prominent in the Hexi Corridor. The decrease in the area of ES and EPS is due to the fact that the development of the Hexi Corridor requires an increasing amount of construction land as the urbanization process accelerates and policies and strategies such as Western Development are promoted. The conversion of ES into EPS is mainly from unutilized land (sand, Gobi, etc.) to grassland and forest land. The area of EPS turns from decreasing to increasing, indicating the obvious role of ecological environmental protection projects in the Hexi Corridor. Typically, built-up land will only represent a small portion of land use, but the increase is nevertheless concerning due to the negative impacts of human activity concentrated in these areas [45]. Both the increase in areas of construction land and the conversion of desert land and Gobi to grassland and forest land place additional pressure on scarce water resources in this arid region [56,57].

Table 7. Dynamic Index of PLES from 1980 to 2020.

Date	Single Dynamic Index (%)				Comprehensive Dynamic Index (%)
	PES	PLS	EPS	ES	
1980–1990	0.04	0.02	−0.03	0.01	0.01
1990–2000	0.28	0.65	−0.02	−0.02	0.02
2000–2010	1.34	1.83	−0.08	−0.09	0.08
2010–2020	0.11	3.71	0.02	−0.05	0.03
1980–2020	1.83	7.31	−0.11	−0.15	5.00

3.2.2. The Characteristics of the Spatial Distribution Evolution of PLES Quantity

By comparing the transfer matrix for the four periods (Table 8), it was evident that the transfer area of PLES exhibited a significant increase in 2000–2010 and 2010–2020, particularly with a notable rise in the net transfer area of PES and PLS. In 2000–2010, the net transfer area of EPS was the largest, totaling 1862.98 km^2, and the net transfer area of ES was also substantial, at 1586.38 km^2. In 2010–2020, the net transfer area of PLS reached 475.35 km^2, and the net transfer area of ES was 783.82 km^2. Next, the transition matrix was visualized, and the evolution pattern of the PLES type was obtained (Figure 3). PES was composed of fragmented spaces that gradually connected into cohesive units. PLS space continued to expand, with stable point-like rural settlements, while planar urban settlements exhibit varying degrees of expansion. Linear PLS indicates a stronger connection between cities and towns. After experiencing a sharp reduction in EPS from 2000 to 2010, the period exhibited an expanding trend. ES has been showing a declining trend, but other spaces are also transforming into ES.

Table 8. Spatial transformation of PLES from 2000 to 2020.

Date	Space Category	Transfer Area (km^2)				
		PES	PLS	EPS	ES	Reduced Area
1980–1990	PES	-	1.54	27.02	65.37	93.93
	PLS	0.40	-	0.01	0.01	0.41
	EPS	36.17	0.01	-	346.21	382.39
	ES	105.28	1.20	149.04	-	255.52
	Increased area	141.85	2.75	176.07	411.59	-
1990–2000	PES	-	52.44	66.82	8.59	127.85
	PLS	0.2	-	0.02	0.00	0.22
	EPS	253.79	6.86	-	45.35	305.99
	ES	257.21	7.32	97.76	-	362.30
	Increased area	511.21	66.62	164.60	53.94	-
2000–2010	PES	-	72.51	466.07	146.65	685.23
	PLS	75.24	-	4.64	22.90	102.77
	EPS	1044.51	52.42	-	1400.24	2497.17
	ES	1428.46	176.08	1551.62	-	3156.17
	Increased area	2548.21	301.01	2022.33	1569.79	-
2010–2020	PES	-	123.75	456.40	390.86	971.00
	PLS	52.67	-	34.90	52.88	140.45
	EPS	523.16	65.39	-	986.16	1574.71
	ES	569.98	426.65	1217.09	-	2213.72
	Increased area	1145.81	615.80	1708.38	1429.90	-
1980–2020	PES	-	205.62	387.13	182.74	775.49
	PLS	87.37	-	8.73	4.15	100.25
	EPS	1229.06	108.17	-	1502.49	2839.72
	ES	1928.13	528.77	1754.96	-	4211.87
	Increased area	3244.57	842.57	2150.82	1689.37	-

As illustrated in Figure 3a, Dunhuang experienced relatively calm periods in 1980–1990 and 1990–2000, a contraction of PLS in 2000–2010, and a significant increase in three groups in 2010–2020. The transition from ES to PLS is attributed to the local government's promotion of the photoelectric industry. Figure 3b illustrates the PLS in Yumen, which increased in the 1980–1990, 1990–2000, and 2000–2010 periods and decreased in 2010–2020 due to resource exhaustion, leading to the town's inability to sustain its past prosperity. Figure 3c depicts Jiayuguan as a newly emerging resource town, where PLS expansion was intense in 2000–2010 and 2010–2020, displaying distinct characteristics of group development. Figure 3d–g reveals the convergence of PLES evolution characteristics in the central oasis area of the Hexi Corridor. In most cases, ES transforms into PLS, PES, and EPS, indicating continuous expansion of the oasis area in the central and southern regions. Finally, as shown in Figure 3h, the ongoing transformation of ES into PES/EPS results from the Chinese government's ecological restoration and regulation project in Minqin, successfully preventing the convergence of the Badain Jaran Desert and Tengger Desert.

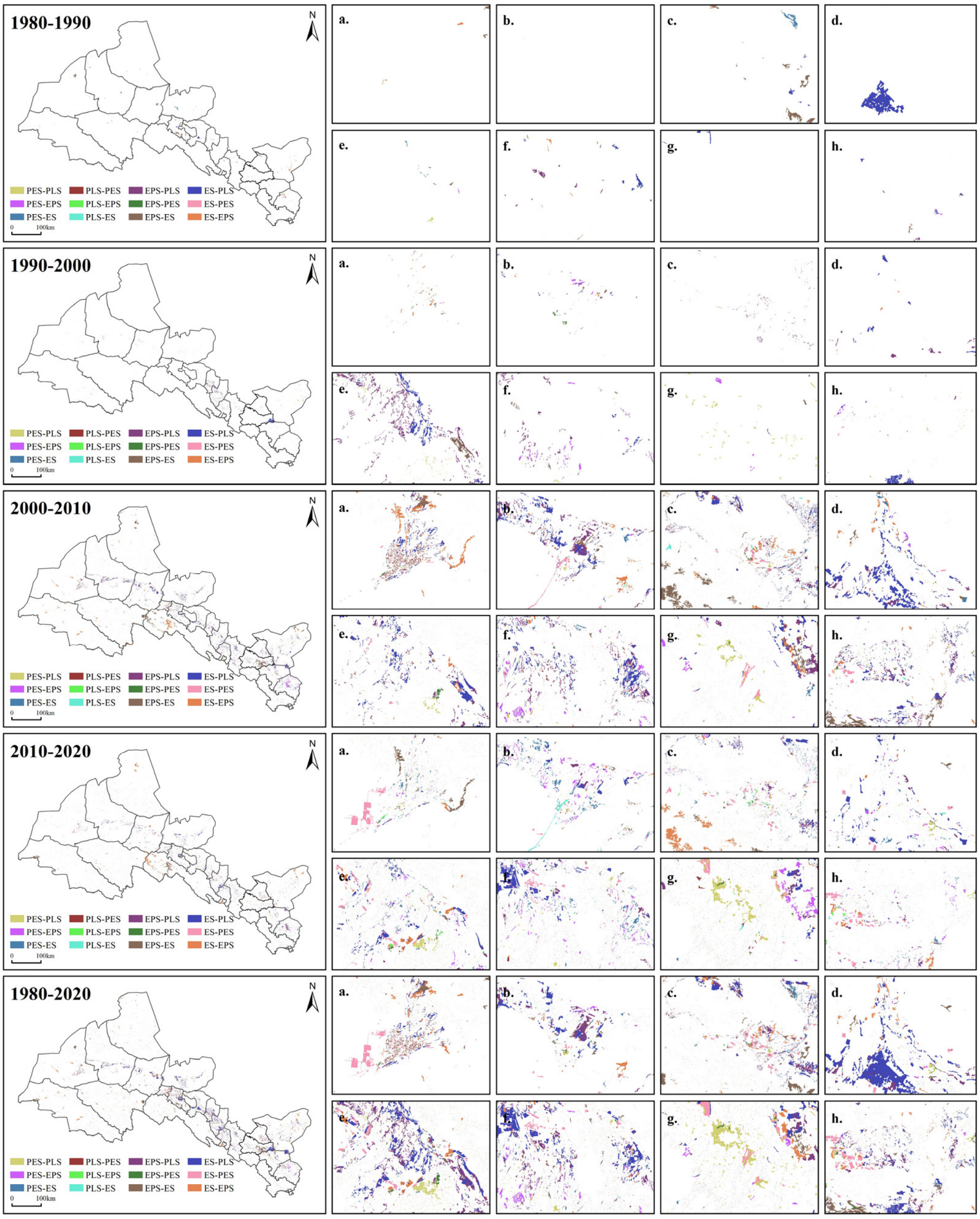

Figure 3. Spatial transformation of PLES. Figures (**a**,**b**) represent Dunhuang and Yumen, respectively, located in the north of the Hexi Corridor; Figures (**c**–**f**) are Jiayuguan, Suzhou, Ganzhou, and Shandan, located in the middle of the Hexi Corridor; Figures (**g**,**h**) are located in the south of the Hexi Corridor, encompassing Gulang, Jinchuan, and Minqin.

3.3. Evolution of PLES Quality

Characteristics of Scale Evolution of PLES Quality

The five PLES functional scores (PLESFS) for 1980, 1990, 2000, 2010, and 2020 are represented on a grid scale of 1 km × 1 km. The threshold values of function scores for different periods are standardized. The spatial evolution characteristics of PLES quality in the Hexi Corridor are described by shrinking, maintaining, and expanding (Figure 4).

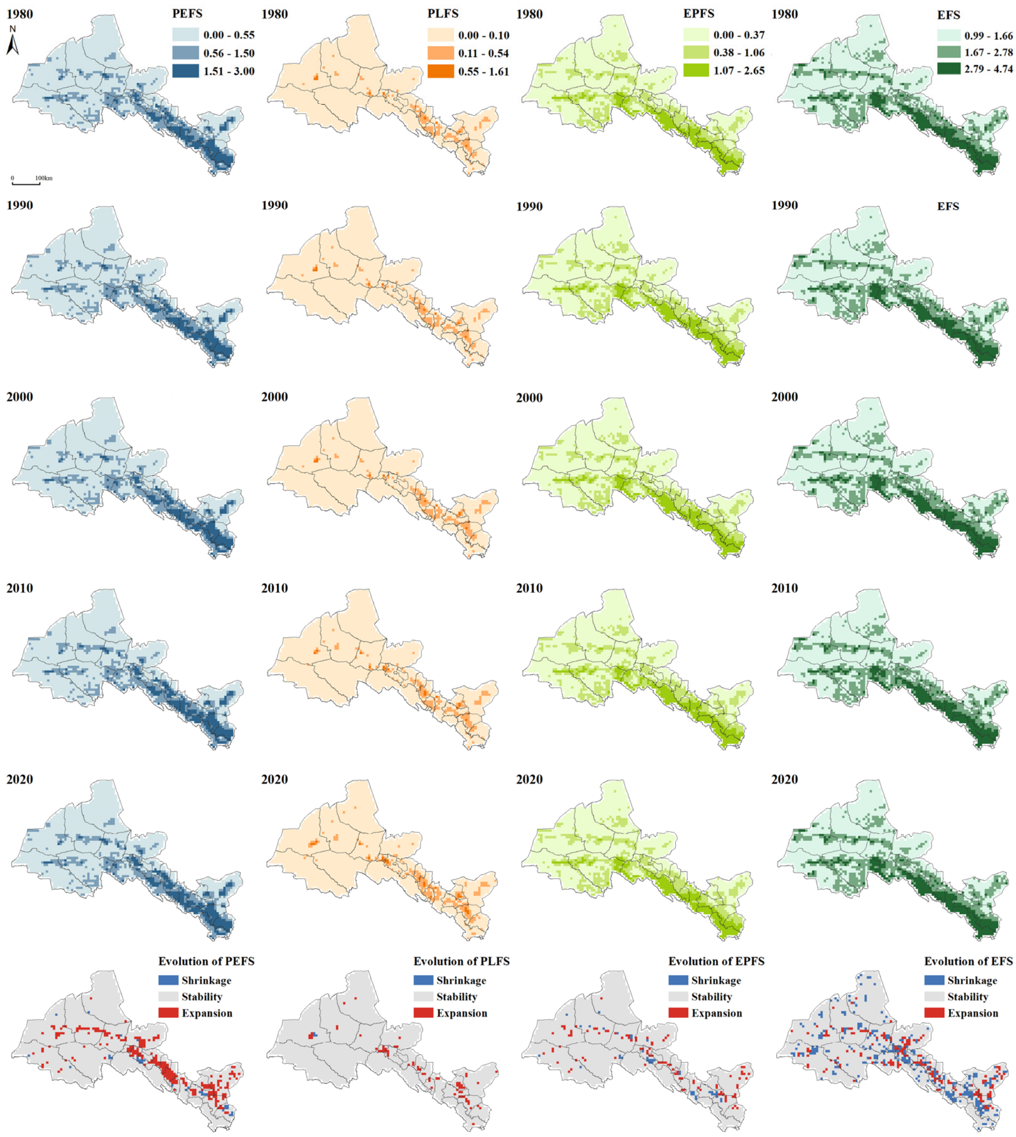

Figure 4. Spatial pattern of PLES in the Hexi corridor.

The high-value area of EPFS is mainly distributed in the central and southern parts of the Hexi Corridor, with most expansion areas being concentrated along riverbanks and major oasis areas. Northern areas, such as Guazhou and Yumen, show a linear expansion trend along the river. Regions in the middle of the corridor, including Jinta, Jiayuguan, Suzhou, Gaotai, Linze, and Ganzhou, exhibit concentrated continuous expansion similar to the oasis distribution in the middle of the Hexi Corridor. The primary expansion areas in the south, such as Minqin, Jinchuan, Yongchang, and Liangzhou, are valley delta plains formed by river alluvial and artificial irrigation areas covered by the Hongyashan reservoir.

The spatial distribution of PLFS is high in the south and low in the north, with various oases as the core. This is related to the fact that the local population is mainly concentrated in major oasis towns. The distribution of PLS expansion regions is more consistent with the high-value region of PLFS, showing characteristics of multi-center cluster expansion, but the expansion region is more widely distributed. This indicates that the distribution range of PLS also presents a diffusion trend. Four PLS clusters are formed in the Hexi Corridor, namely Dunhuang, Jiayuguan, Jinchuan, and Ganzhou.

The high-value area of EPFS is mainly concentrated near the Qilian Mountains, particularly in Sunan and Tianzhu. The melting glaciers of the Qilian Mountains have formed many inland rivers, and the grassland nearby is an important agricultural and pastoral area in the Hexi Corridor, with widely distributed cultivated land and grassland. EPFS expansion regions are located in the peripheral region of its high-value region, showing a diffusion trend. However, EPFS also exhibits a shrinking trend in some regions, primarily in Yongchang, Suju, and Shandan, due to the conversion of some woodland and grassland to arable land.

EFS tended to be high in the south and middle, coinciding with the southern and middle high-value regions, whereas it was low in the north. The distribution pattern of EFS is consistent with the geomorphic distribution pattern of the Hexi Corridor. The Qilian Mountain region, Shule River basin, Shiyang River basin, and Heihe River basin are not only important ecological resources in the Hexi Corridor but also high-value distribution areas of EFS. The EFS contraction area and expansion area are interwoven in the Hexi Corridor.

3.4. Geodetector-Based Analysis of Influence Factors for PLESFS Differentiation

Since some of the socio-economic data were collected only from 2000 onwards, only the periods 2000, 2010, and 2020 are considered in the content of this section. In this study, based on pertinent research findings on the driving mechanisms of PLES distribution [29,31], we selected 16 indicators that fell within 2 categories: natural factors and social and economic development factors. These indicators serve as independent variables for geographical exploration, whereas the PLES function score was designated as the dependent variable (Y). The natural factors examined herein included average annual temperature (X1), average annual precipitation (X2), normalized difference vegetation index (NDVI) (X3), average altitude (X4), average slope (X5), annual evaporation (X6), annual sunshine duration (X7), soil type (X8), and soil erosion degree (X9). The social and economic development factors included population density (X10), per capita GDP (X11), added value of the primary industry (X12), added value of the secondary industry (X13), added value of the tertiary industry (X14), and total grain production (X15). Considering data availability, this study encompassed three periods of data from 2000, 2010, and 2020 to measure the influence of each factor on the evolution of PLES, thereby gaining insights into the driving mechanism of both the quantity and quality of PLES.

3.4.1. Geodetector-Based Analysis of Natural-Social-Economic Factor Detection

The single-factor detection results of PLES spatial differentiation are illustrated in Figure 5. The *p*-values of each single factor are 0, and the results were tested at a 0.05 significance level. Our findings indicated that natural factors have a higher explanatory degree in the spatial differentiation of PLES, with this effect being dominated by ecological functions. The spatial differentiation of production and living functions was also largely explained by social and economic factors such as X3, X7, X9, and X10, whereas other factors contribute more to the spatial differentiation effect of PEFS in the study area. X9, X10, and other factors contributed more to the spatial differentiation effect of PLFS. X3, X6, X7, X8, and X9 contributed significantly to the spatial differentiation of EPFS and EFS.

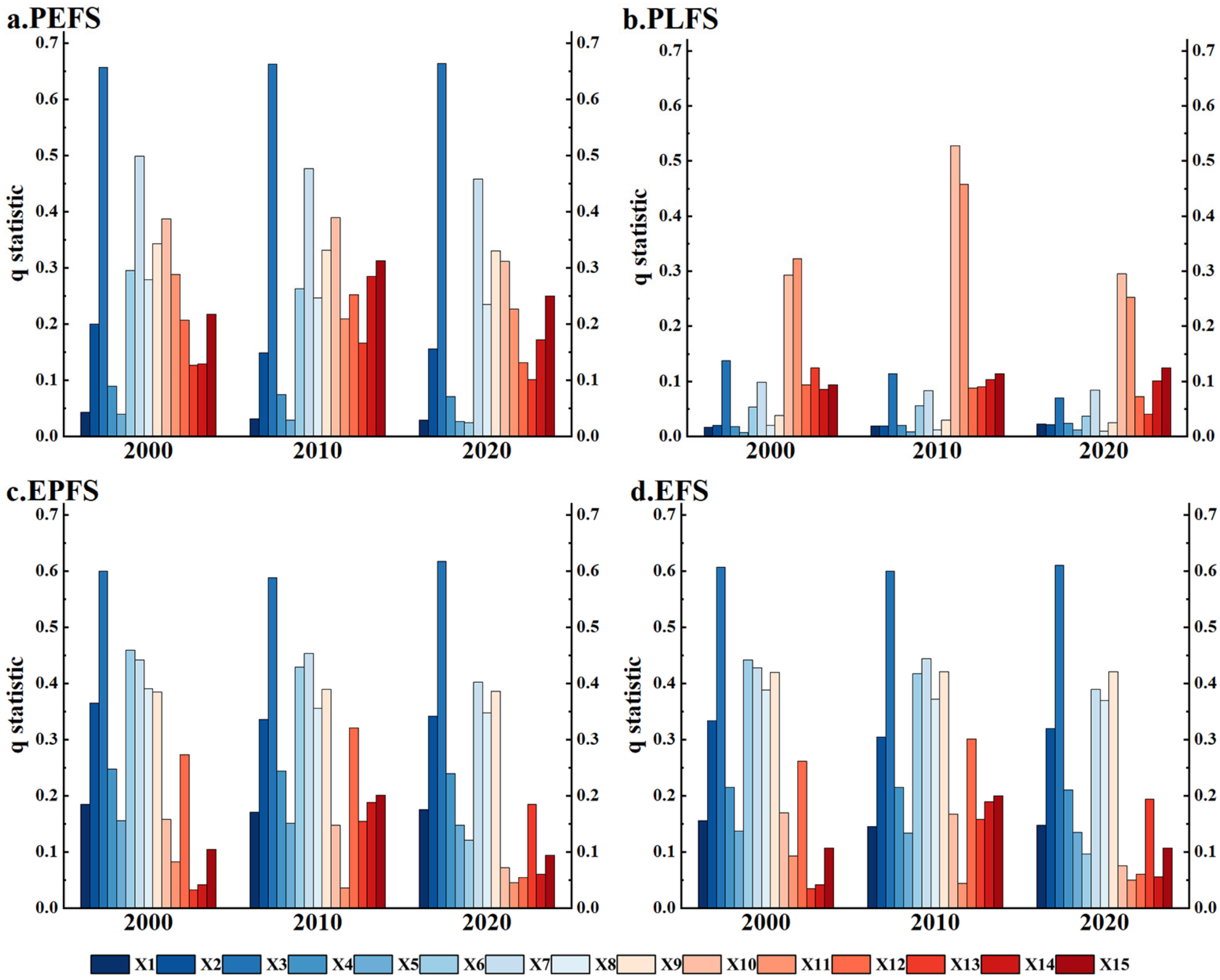

Figure 5. Results of factor detectors.

3.4.2. Geodetector-Based Factor Interaction Detection Analysis

The interactive detection of the drivers of the PLES utility is shown in Figure 6. The interaction of any two of the 15 drivers is greater than that of a single factor, indicating that PLESFS is influenced by a combination of many factors. For PEFS, interactions between X3 and X10 had the greatest impact in 2000 and 2010, while interactions between X3 and X6 had the greatest impact in 2020. For PLFS, interactions between X3 and X11 had the greatest impact in 2000, X10 and X15 interactions had the greatest impact in 2010, and interactions between X3 and X10 had the greatest impact in 2020. For EPFS, interactions between X2 and X3 had the greatest impact in 2000 and 2010, and interactions between X3 and X6 had the greatest impact in 2020. For EFS, the interaction between X3 and X8 had the greatest influence in 2000, the interaction between X3 and X4 had the greatest influence in 2010, and the interaction between X1 and X3 had the greatest influence in 2020.

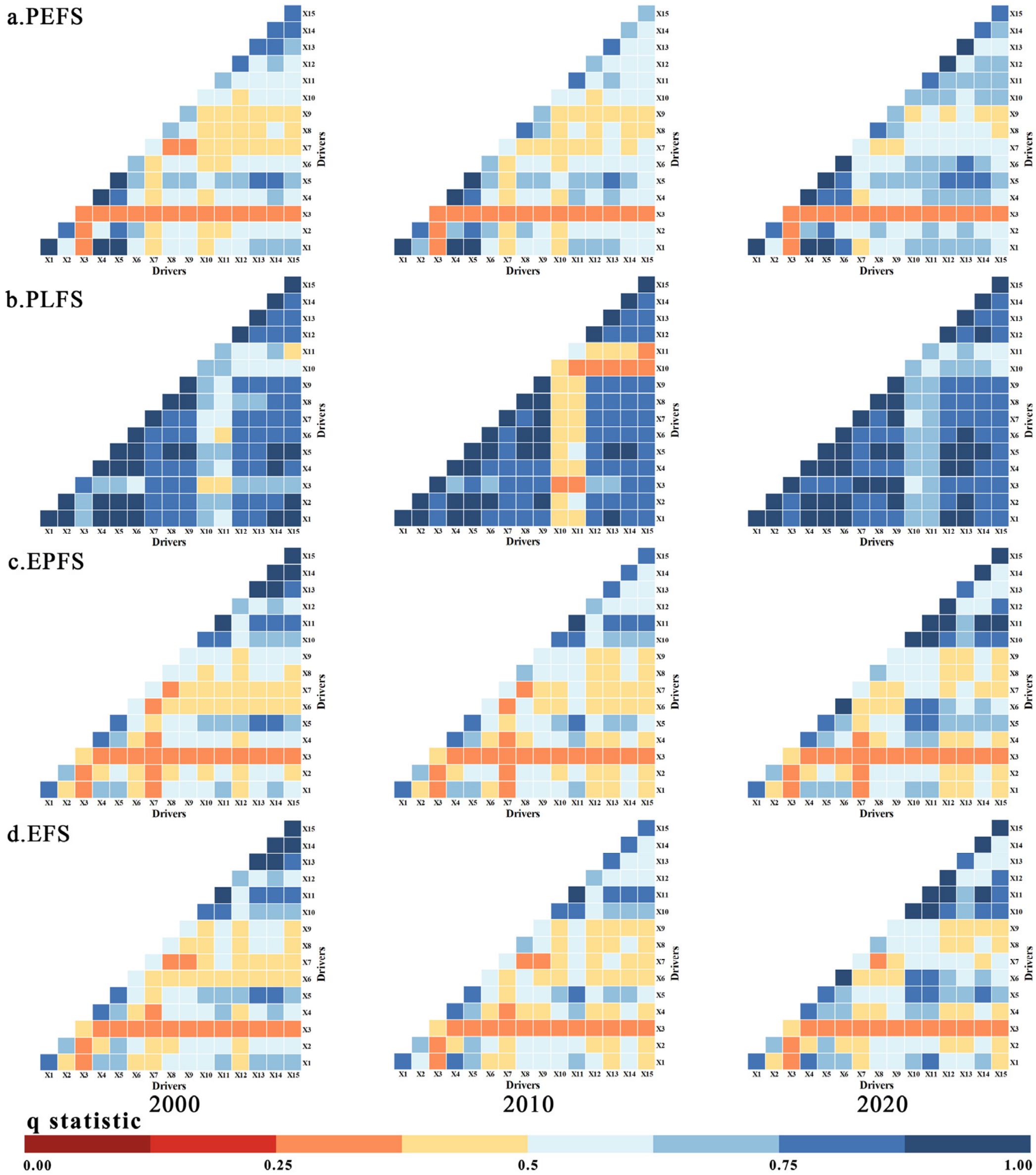

Figure 6. Results of interaction detectors.

4. Discussion

When examining the spatial and temporal evolution and driving mechanisms of the ecotone in the Hexi Corridor, gaining insights into the diversity and complexity of land use is essential. The ecological transition zone exhibits significant environmental gradients, strong heterogeneity, and pronounced edge effects, leading to higher species richness and a more complex community structure. Moreover, this zone is particularly sensitive to global climate change. In contrast to existing studies, this paper assesses the spatial and temporal variability and formation mechanisms of PLES in the ecological transition zone of the Hexi Corridor, considering both the quality and quantity of PLES. This approach aids decision-makers in identifying inappropriate land protection and utilization strategies in specific regions based on the overall development characteristics of the area. Therefore, our findings provide a foundation for optimizing territorial spatial patterns as well as for land management and allocation.

4.1. Multifunctionality of Land Use

According to the needs of human beings at different levels, land has formed different types of land use and different land use structures. Structure determines function, and the products and services supplied under different land-use structures differ greatly, resulting in spatial differences in land-use functions [58]. Under the role of regional dominant functions, the spatial pattern of PLES is formed. Space is the carrier of function, and function is the important basis for identifying and optimizing PLES [21]. The multifunctionality of land use is the ability of a region to provide various products and services to human beings in a certain period of time during the process of human beings transforming and utilizing the land according to their needs, and it is a variety of functional characteristics formed by the interconnection and interaction of different types of land use, including living function, production function, and ecological function [59]. The multifunctionality of land use analyzes the well-being of land for human society from the perspective of supplying products and services demanded by human beings and reflects the ability of land use to meet human needs [60,61], which coincides with the essence of PLES identification and the optimization concept of "human-centeredness" [21].

4.2. Spatiotemporal Evolution of PLES

The findings indicate that the primary function of the ecotone in the Hexi Corridor is ecological, with the highest proportion of area and function score, aligning with results from other ecotone studies [27,31]. This result is consistent with the current regional development strategy and circumstances in the Hexi Corridor. Positioned between the Qilian Mountains and the Tengger Desert in northwest China, the Hexi Corridor boasts abundant resources and stands as a crucial grain-producing area in China. However, it faces challenges such as inadequate infrastructure and water resources [43]. Currently, the primary industry serves as the main source of local income, with industrial development gaining momentum. Consequently, the ecological function level in the ecological transition zone of the Hexi Corridor is notably prominent, whereas the production function falls in the lower-middle range and the living function is relatively low.

The spatial and temporal evolution of PLES in the Hexi Corridor differs significantly from economically developed areas [26,31]. In economically developed eastern coastal areas of China, the proportion of PS and LS areas is higher, the proportion of ES areas is lower, and the function scores for production and living are higher, while the ecological function scores are lower. What sets the Hexi Corridor apart from the development histories of other regions is the noticeable increase in the maximum ecological function score, indicating strengthened ecological environment protection in certain areas. However, at the same time, the decrease in the minimum score for ecological function also suggests environmental degradation in certain areas.

4.3. Impact Mechanisms of Driving Factors

The geodetector results highlight significant variations in the influence of 15 driving factors on PLEFS in the Hexi Corridor. NDVI (X3) was identified as the most influential factor affecting the spatial differentiation of PEFS, EPFS, and EFS in the study area. This can be attributed to the substantial diversity in land types and distinct variations in vegetation growth states within the Hexi Corridor [21]. Population density (X10) and GDP per capita (X11) explained the PLFS to the highest degree, indicating that population distribution interacts with the distribution of construction land and that there is a tendency for population agglomeration in urban oasis areas [38].

The results from both interactive detection and single-factor detection complement each other, providing a more comprehensive understanding of the driving mechanism. In the context of PLESFS, natural environmental factors, especially the demand for water resources, play a decisive role in variation within the Hexi Corridor. In arid regions with limited rainfall, the influence of X6 (annual evaporation) often surpasses that of X2 (average annual precipitation), indicating that transpiration has a greater impact on the formation of river systems, the growth of alpine meadows, and unused land such as deserts and the Gobi [43].

Analysis of the driving factors influencing the three life spaces in the Hexi Corridor suggests that the initial selection of spatial utilization patterns is driven by towns and villages according to local conditions. Afterward, the cumulative impact of various social activities and the formulation and implementation of policies continue to shape spatial functions, with socio-economic factors becoming crucial short-term influencers. However, with the ongoing urbanization process and the unique geographical factors of the Hexi Corridor, natural factors related to resource and environmental carrying capacity gradually assume a decisive role in the region's transformations [26].

4.4. Influence of the Ecological Transition Zone of the Hexi Corridor

The evolution and driving factors of Production-Living-Ecological Space (PLES) spatial and temporal distribution are influenced by the natural conditions, location conditions, and the social and economic development level of the study area. While previous studies often attribute the spatiotemporal evolution of PLES in various regions to socio-economic factors such as economic development, urbanization level, and population growth [23,27,41], this study underscores the varying degrees of influence of the same factors on PLESFS in different periods. This observation highlights the complexity and diversity of PLES evolution in the Hexi Corridor. In the Hexi Corridor, natural factors play a predominant role in influencing the distribution of ES, whereas population and socio-economic factors exert a more substantial influence on the distribution of PS and LS. Densely populated areas with robust economic and social development experience spatial-temporal evolution primarily in cultivated land, construction land, and ecological land. The rapid urbanization in these areas intensifies the competition between environmental protection, food security, and economic development. Conversely, in the Hexi Corridor, where large-scale desert distribution was prevalent, factors such as climate, water resources, and natural conditions imposed greater constraints on environmental protection, food security, and economic development. Therefore, when discussing the mechanisms that drive PLES distribution in a region comprising several ecotones, such as the Hexi Corridor, natural conditions, social and economic development degree, and land use should be comprehensively considered.

4.5. Strategies and Suggestions for Sustainable Development and Space Management

The results of this study emphasize the significance of the NDVI as a major factor influencing the sustainable development of oases in the Hexi Corridor. Previous research has already highlighted the importance of precipitation and temperature in the increasing trend of NDVI in the region [62,63]. This aligns with the notion that water resources' carrying capacity significantly impacts sustainable development in arid areas.

Based on these findings, our study proposes a spatial management and control strategy for the ecological transition zone of the Hexi Corridor to ensure production that meets needs while simultaneously avoiding irreversible degradation of soil, ecosystems, and water resources [37]. Based on our findings, we propose that spatial management and control strategies could be organized with respect to three distinct regions:

1. Qilian Mountains-front meadow area. This region, characterized by the distribution of ES and EPS (Figure 2), holds the highest ESFS (Figure 3). To preserve the native vegetation and conserve water and soil resources, the study recommends implementing strict use control policies in this area.
2. Oasis town area. This region is dominated by the distribution of PLS and PES in the Hexi Corridor; this region represents the primary distribution area of high-value agglomeration for PLFS and PEFS (Figures 2 and 3). According to the river system that supplies each oasis, we suggest establishing upper limits for oasis town construction based on the water resources' environmental carrying capacity. Additionally, promoting agricultural systems suitable for oases, exploring ecological agriculture and tourism, and facilitating industrial transformation are proposed strategies.

3. Desert-Gobi region. ES is mainly distributed in this region, accounting for more than 50% of the total area of the Hexi Corridor (Table 4). Soil and water conservation and ecological restoration in this area are emphasized. Based on our findings, we recommend establishing anti-desertification forests on the desert's edge to enhance the protection of vegetation authenticity and integrity in desert areas.

5. Conclusions

Based on its complex geographical features, our study examined PLES distribution in the Hexi Corridor, focusing on the land use coverage data of the fifth period from 1980 to 2020, which was supplemented with other geospatial data and various socio-economic data. Particularly, we examined the spatiotemporal evolution and driving mechanism of PLES distribution in the Hexi Corridor. The main conclusions of this study are outlined below:

1. More than 99% of the Hexi Corridor's total area is covered by spaces with ecological functions, demonstrating strong continuity. Specifically, Ecological Space (ES) covers over 65%, mainly distributed around the Qilian Mountains and Tengger Desert. Ecological-Production Space (EPS) accounts for about 25%, primarily in the grassland in front of the Qilian Mountains. Production-Ecological Space (PES) covers approximately 6%, concentrated in various oases within the corridor. Production-Living Space (PLS) constitutes less than 1%, mainly comprising oasis towns and villages.
2. From 1980 to 2020, the changes in the Hexi Corridor in the past 10 years were more profound than in the previous 30 years. Particularly, the spatial fluctuation of PLES has gradually become more drastic, shifting from ES and EPS to PES and PLS. The past decade has seen higher change intensity than the previous 30 years. Quality-wise, PLS, PES, and EPS function scores increased, while ES function scores decreased. High- and low-value areas of PLES functions exhibited an agglomerated distribution, with less occurrence of low and high clustering.
3. The spatial-temporal evolution of PLES in the Hexi Corridor results from the interaction of natural and socioeconomic factors. Nonlinear enhancements and two-factor enhancement effects were observed for each factor in the spatial-temporal evolution of PLES. Notably, NDVI (X3) had a significant influence on EFS, PEFS, and EPFS, while population density strongly affected PLFS. In the current conditions, the impact of annual evaporation is greater than that of annual precipitation.

Given the vastness and rich natural resources of the ecological transition zone in the Hexi Corridor, the study recommends formulating sustainable development strategies. It emphasizes the unique location, transportation advantages, and human conditions of the region. The proposed strategies highlight the corridor's green ecological characteristics and underscore the importance of coordinated development in ecology, production, and living.

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