Spatiotemporal Variation of County-Level Cropland in the Weibei Arid Loess Plateau Region of Shaanxi and Its Impact on Grain Production (Postprint)

Authors: Long Xiaocui

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Abstract

Farmland resources are the fundamental guarantee of national food security, and mastering the quantity and quality status of farmland is the prerequisite for rational utilization of regional farmland resources. Taking Hancheng City, located in the eastern part of the Weibei Dry Plateau in Shaanxi Province, as the study area, this study employs GIS spatial analysis technology, combined with farmland quality evaluation models, location index models, and gravity center migration models, to analyze the spatio-temporal changes of farmland in Hancheng City from 2009 to 2018 and their impact on grain production. The results show that: (1) From 2009 to 2018, the spatial distribution of farmland in the study area changed insignificantly, the farmland gravity center was mainly located in the eastern plain area, and the quantity of farmland exhibited a distribution pattern of less in the west and more in the east, dispersing from southeast to northwest. (2) The reduced farmland was mainly distributed in the central part of Longmen Town, the junction of Xincheng and Xizhuang Towns, the eastern part of Jincheng, and the eastern part of Zhichuan Town, with the main reasons for farmland reduction including accelerated urbanization, policy implementation, and adjustment of agricultural industrial structure. (3) During the 10-year period, the area of farmland quality grades exhibited polarization and significant changes, with more high-grade and less low-grade farmland, and all grades shifting towards higher levels, most notably from medium-grade to high-grade farmland. (4) Farmland quality showed significant regional characteristics, with quality grades gradually decreasing from the eastern Yellow River coast to the northwest, mainly in the Yellow River coast and plain areas, presenting a three-tier pattern of low-grade, high-grade, and medium-grade farmland from top to bottom. (5) The reduction in farmland quantity in the study area led to a decline in grain yield, the distribution pattern of farmland quality affected the location of grain production, the production areas of wheat and corn overlapped with the distribution areas of medium- and high-quality farmland, and the migration direction of the distribution gravity centers was consistent.

Full Text

Temporal and Spatial Changes of Cultivated Land and Its Impact on Grain Production in Weibei Dryland District of Shaanxi Province

LONG Xiaocui[12], LIU Jing[12], XU Zhongwei[12], WEI Fang[12]

[1]College of Resources and Environment, Northwest A&F University, Yangling 712100, Shaanxi, China
[2]Northwest Key Laboratory of Plant Nutrition and Agricultural Environment, Ministry of Agriculture, Yangling 712100, Shaanxi, China

Abstract: Cultivated land resources are the fundamental guarantee of national food security, and understanding the quantity and quality of cultivated land is a prerequisite for the rational utilization of regional cultivated land resources. Taking Hancheng City, located in the eastern part of the Weibei dryland district in Shaanxi Province, as the study area, this paper employs spatial analysis technology combined with a cultivated land quality evaluation model, location index model, and gravity center migration model to analyze the temporal and spatial changes of cultivated land from 2009 to 2018 and their impact on grain production. The results show that: (1) Reduced cultivated land is mainly distributed in the central part of Longmen Town, at the junction of Xincheng and Xizhuang Towns, in eastern Jincheng, and in eastern Zhichuan Town, exhibiting a spatial pattern of less land in the west and more in the east, dispersing from southeast to northwest. (2) The spatial distribution of cultivated land changed little during the study period, with the gravity center primarily located in the eastern plains. The main reasons for cultivated land reduction include accelerated urbanization, policy implementation, and agricultural industrial structure adjustment. (3) The area of each cultivated land quality grade showed polarized and significant changes, characterized by high quantity for high grades and low quantity for low grades, with all grades shifting toward higher levels, most notably from medium to high grades. (4) Regional differences in cultivated land quality are significant, with quality grades gradually decreasing from the Yellow River coast in the east toward the northwest. High-quality land is concentrated along the Yellow River and in plain areas, forming a vertical pattern of low-grade, high-grade, and medium-grade land from top to bottom. (5) The reduction of cultivated land quantity in the study area has caused a decline in grain yield, while the distribution pattern of cultivated land quality affects grain production location. Wheat and corn production areas overlap with medium- and high-quality cultivated land distribution areas, and their distribution gravity centers migrate in the same direction.

Keywords: cultivated land quality evaluation; temporal and spatial change of cultivated land; food security; Weibei dryland district

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Food security became a hot topic at the Two Sessions in 2021, with seeds and cultivated land identified as the primary pathways to ensure food security. Implementing and strengthening cultivated land protection to curb "non-agriculturalization" and prevent "non-grainization" has become an important research topic for governments and scholars. The quantity and quality of cultivated land are fundamental conditions for ensuring food security. Due to changes in cultivated land resource utilization, China' s grain production pattern has shown obvious differentiation. Exploring and analyzing the temporal and spatial variation characteristics of cultivated land quality and its impact on grain production is of great significance for solving regional cultivated land protection and non-grainization problems.

In recent years, numerous scholars have studied the impact of cultivated land changes on grain production from different perspectives. Domestic and foreign scholars have conducted in-depth research on cultivated land spatial patterns, dynamic monitoring of cultivated land resources, and cultivated land quality evaluation. Research on cultivated land resource patterns mainly uses landscape ecology methods to analyze spatial distribution patterns, focusing on quantity characteristics, landscape patterns, and scale effects—namely, the shape, size, density, and dynamic changes of cultivated land patches in space, which are compared with grain production pattern changes to explore their spatial relationships. Dynamic monitoring of cultivated land resources mainly uses data from land surveys or statistical yearbooks to analyze quantity changes, while employing time series, three-point moving average, grey prediction, and other models to calculate future trends and grain production potential. Cultivated land quality evaluation primarily conducts quantitative research on changes in soil fertility (natural attributes), specifically quantifying area changes, location changes, and gravity center migration of cultivated land quality grades and their impact on grain production.

In existing studies on the impact of cultivated land changes on grain production, differences in cultivated land resources between China and other countries have led to different research emphases. Europe and America have vast land with sparse populations, abundant cultivated land resources, well-maintained soil fertility, and high farm mechanization levels, with per capita cultivated land area exceeding the world average, focusing on analyzing the impact of cultivated land quality changes on single crop production. China is a country with complex topography, scarce per capita cultivated land resources, and uneven spatial distribution, thus emphasizing the impact of cultivated land quantity changes on grain production. On this basis, due to rapid economic development and increasing demands for ecological environmental quality in recent years, cultivated land area has shown a significant downward trend. While ensuring stable cultivated land area, improving cultivated land quality has become an important measure to guarantee food security. Therefore, how do cultivated land area and quality change in rapidly developing economic regions, and what impact do they have on regional grain production? This is an effective means to evaluate the effectiveness of relevant departments, policies, and measures, providing a theoretical basis for management decision-making departments on regional resource development and utilization.

The Weibei dryland district of Shaanxi is a transitional zone between the Loess Plateau and Guanzhong Plain, with coexisting plateau-gully and plain landforms, frequent human activities, and fragile ecological environments. Rapid economic development in recent years has significantly impacted regional cultivated land quantity and quality. This paper takes Hancheng City in the Weibei dryland district as the study area. The landform types in the region mainly include mountains, hilly gullies, and plains, with a continental monsoon climate, good light and temperature conditions, and relatively abundant annual precipitation concentrated in summer and autumn. The region' s pepper industry and other cash crops are developing rapidly, while grain crops are mainly wheat and corn. Studying the characteristics of cultivated land resource changes in Hancheng City and their impact on grain production is of great significance for deeply understanding regional cultivated land resource utilization characteristics, rationally utilizing and efficiently managing cultivated land resources, and ensuring regional food security.

1.1 Study Area Overview

Hancheng City is located in the eastern part of the Weibei dryland district in the transitional zone between the Loess Plateau and Guanzhong Plain (Fig. 1), between 110°07 19 -110°37 24 E and 35°18 50 -35°52 08 N, bordering the Yellow River to the east and Huanglong Mountain to the west, with an area of approximately 1621 km^2. Hancheng is a core industrial, energy, and cultural tourism city along the Yellow River, with terrain that is high in the northwest and low in the southeast. It has a warm temperate semi-arid continental monsoon climate with distinct seasons, mild climate, abundant sunlight, and relatively high rainfall. The average annual temperature is 13.5°C, and the $ $10°C accumulated temperature is 4626°C, which is favorable for agricultural development. The average annual precipitation is 559.7 mm, concentrated in summer and autumn. Cultivated land consists mainly of dry land and irrigated land, with overall natural conditions representative of the Weibei dryland district.

1.2 Data Sources

Cultivated land resource data in this study mainly come from Hancheng City' s land use status change survey database and China Land and Resources Statistical Yearbook. Grain sown area, grain yield, and other statistical data are primarily derived from the *Shaanxi Statistical Yearbook* and *China County (City) Socio-Economic Statistical Yearbook* (2009-2018).

1.3 Research Methods

(1) Cultivated Land Quality Evaluation Model Under the *GB/T 33469-2016* standard for cultivated land quality grade and based on the characteristics of cultivated land in Hancheng City, the cultivated land quality evaluation index system was selected as shown in Table 1. The analytic hierarchy process was used with the calculation formula:

$$R = \sum_{i=1}^{n} W_i \times F_i$$

where R is the final comprehensive index for each evaluation unit; F_i is the grade index (evaluation score) of the i-th evaluation factor; W_i is the combined weight value of the i-th evaluation factor; and n is the number of evaluation factors.

The combined weight W_i is calculated as:

$$W_i = \sum_{j=1}^{6} B_j \times C_i$$

where B_j is the eigenvector of the judgment matrix in layer B ($j = 1, 2, \dots, 6$), and C_i is the eigenvector of the judgment matrix in layer C ($i = 1, 2, \dots, 16$).

(2) Cultivated Land Quality Grade Location Index Model The cultivated land quality grade location index model is used to analyze regional differences and aggregation degrees of each grade in Hancheng City. The location index for each grade in each township is calculated as:

$$R_{ij} = \frac{S_{ij}/S_j}{\sum_{j=1}^{m} S_{ij}/\sum_{j=1}^{m} S_j}$$

where R_{ij} is the location index of grade i in township j; S_{ij} is the area of grade i cultivated land in township j; S_j is the total cultivated land area in township j; and m is the number of townships in Hancheng City.

(3) Distribution Gravity Center Migration Model The distribution gravity center migration model refers to the movement of the weighted average center during the study period along a specific direction. Using a certain element of each evaluation unit as the weight, the geographic coordinates of each evaluation unit are weighted and averaged to obtain the gravity center of that element. Here, it is used to analyze the migration of cultivated land quality distribution and grain production location gravity centers in the study area. The gravity center coordinates are calculated as:

Weighted coordinates:

$$X = \frac{\sum_{i=1}^{m} a_i x_i}{\sum_{i=1}^{m} a_i}, \quad Y = \frac{\sum_{i=1}^{m} a_i y_i}{\sum_{i=1}^{m} a_i}$$

Average coordinates:

$$\bar{x} = \frac{1}{m}\sum_{i=1}^{m} x_i, \quad \bar{y} = \frac{1}{m}\sum_{i=1}^{m} y_i$$

where (x_i, y_i) are the centroid coordinates of each evaluation unit; a_i is the value of element a in evaluation unit i, used as the weight; m is the number of evaluation units; (X, Y) are the weighted gravity center coordinates; and $(\bar{x}, \bar{y})$ are the average coordinates. Here, a represents the comprehensive cultivated land quality evaluation index and annual grain yield.

2.1 Temporal and Spatial Variation Characteristics of Cultivated Land Resources

From 2009 to 2018, the overall spatial distribution of cultivated land in the study area changed little (Fig. 2). The study area can be divided into three zones: the western mountainous ecological zone, the central hilly industrial zone, and the eastern plain living zone. The vast majority of cultivated land resources are concentrated along the Yellow River coast and in the eastern plain living zone, where the terrain is flat, elevation is low, and water sources are relatively close, resulting in continuous belt-like distribution of cultivated land. A smaller portion is scattered in the central hilly industrial zone, where slopes are gentle but terrain is undulating, and cultivated land mainly follows gullies and water systems in irregular linear patterns. The western mountainous ecological zone has steep slopes and large undulations, with cultivated land 零星 distributed along river sections, showing high fragmentation.

From the perspective of each township and the Yellow River coast, the eastern bank of the Yellow River has the largest and most concentrated area of cultivated land. This is followed by Zhichuan Town, Xizhuang Town, Xincheng Subdistrict, and Jincheng Subdistrict, where cultivated land is mainly distributed in the eastern parts of each town. Longmen Town, Zhiyang Town, and Banqiao Town have relatively small cultivated land areas with minor differences in area but large spatial distribution differences. Longmen Town has extensive cultivated land distribution, while Zhiyang and Banqiao Towns have scattered distribution. Sangshuping Town has the smallest cultivated land area, connecting from the western corner to the northern corner of the town.

From 2009 to 2018, the study area experienced a net reduction of 1.22 km^2 in cultivated land, with reductions showing regional characteristics (Fig. 2). The eastern plain living zone showed the most significant reduction, approximately

0.96 km^2, accounting for 78.71% of the total reduction. The central hilly industrial zone followed with a reduction of 0.27 km^2, accounting for 21.94%. Reduced cultivated land formed four radiation centers in the central part of Longmen Town, at the junction of Xincheng and Xizhuang Towns, in eastern Jincheng, and in eastern Zhichuan Town, diffusing outward in small ranges and appearing as scattered points. These four core points can be connected spatially to form a line parallel to the Yellow River basin, at a considerable distance from the coastal cultivated land belt. This region is located in the central urban area of the study area, where urbanization is rapid and policy impacts are significant. Cultivated land was mainly converted to construction land, transportation land, and garden land for post-disaster reconstruction in special years, public infrastructure construction under policy guidance, tourism and cultural investment driven by industrial guidance, and agricultural industrial structure adjustment. In the western mountainous ecological zone and central hilly industrial zone, cultivated land reduction was not obvious, with 零星 adjustments to other land uses, mainly converted to garden land for developing cash crops such as pepper.

Overall, cultivated land quantity is small and mainly concentrated in the eastern plains. The degree of cultivated land reduction is greatest in key urban construction and development zones. The quantity of cultivated land is less in the northwest and more in the southeast, with the distribution gravity center mainly in the eastern plains and essentially unchanged, showing a certain coupling relationship with the degree of industrial development and urbanization level.

2.2 Temporal and Spatial Variation Characteristics of Cultivated Land Quality

According to the relevant standards for cultivated land quality evaluation in the study area under *GB/T 33469-2016*, a comprehensive evaluation of cultivated land quality from 2009 to 2018 was conducted, with evaluation scores shown in Table 2. Cultivated land quality grades were divided from high to low into grades 1-5. The study area distributed grades 1-4, with no grade 5 land. During the study period, the average cultivated land quality grade increased by 0.2 levels. For analysis convenience, grades 1-2 were classified as high-grade land, grade 3 as medium-grade land, and grade 4 as low-grade land. The cultivated land quality transfer matrix was used to analyze area changes of each grade during the study period, and the cultivated land quality grade location index model was used to analyze the distribution of each grade.

2.2.1 Analysis of Cultivated Land Quality Area Changes The area changes and inter-grade transfers of each cultivated land quality grade are shown in Table 3. From the perspective of total area of each grade, there are large differences among grades, showing polarized changes—high quantity for high grades and low quantity for low grades. High-grade land (grades 1-2) had the largest area, with initial and final areas of 46.82 km^2 and 33.86 km^2 respectively, accounting for 36.36% and 33.13% of total area. Medium-grade land (grade 3) had initial and final areas of 22.40 km^2 and 21.49 km^2, accounting for 17.39% and 21.04% of total area. Low-grade land (grade 4) had initial and final areas of 10.95 km^2 and 9.87 km^2, accounting for 8.51% and 9.66% of total area.

From the perspective of grade transfers, all grades transferred during the study period, with transfer directions consistent with quality grades—high to high, medium to medium/high, and low to low/medium as the main directions. Grade 1 land transferred approximately 5.31 km^2, mainly to grade 2, with grade 1 area decreasing by 3.12 km^2. Grade 2 land transferred approximately 11.46 km^2, mainly to grade 1, with grade 2 area increasing by 2.19 km^2. Grade 3 land transferred approximately 8.17 km^2, mainly to grades 2 and 4, with grade 3 area decreasing by 4.16 km^2. Grade 4 land transferred approximately 4.22 km^2, mainly to grade 3, with grade 4 area decreasing by 1.08 km^2. Therefore, combined with Fig. 3, the main change in cultivated land quality area from 2009 to 2018 was the transfer from medium-grade to high-grade land.

2.2.2 Location Analysis of Cultivated Land Quality The location index model was used to calculate the location index of each grade in each township during 2009–2018. A higher index indicates greater aggregation of that grade in the township. Table 4 shows that high-grade land has a higher aggregation degree in eastern towns adjacent to the Yellow River, with Jincheng Subdistrict having the highest location index. Medium-grade land shows high aggregation along the southern Yellow River coast and in Sangshuping Town in the north. Low-grade land shows relatively high aggregation in Longmen Town and Sangshuping Town in the north.

From the spatial distribution of cultivated land quality changes (Fig. 4), the study area is dominated by high-grade land, accounting for approximately 33% of total area, concentrated along the Yellow River coast and loess tableland areas in the east. Medium-grade land accounts for about 21%, mainly distributed south of the Yellow River, in the southern loess tableland area, and in the southwestern hilly-gully region. Low-grade land accounts for about 10%, concentrated in the north of the study area, largely in the northern loess tableland area and extending westward into the hilly-gully region along rivers, with high fragmentation and density. Overall, a vertical pattern of low-grade, high-grade, and medium-grade land is formed from top to bottom, centered on the loess tableland area and Yellow River coast.

From the perspective of the study period, for high-grade land aggregation areas, the location index of grade 1 land was highest in Jincheng Subdistrict, decreasing from 2.35 to 1.89. The location index of grade 2 land was relatively high in Xincheng Subdistrict, with a slight increase. For medium-grade land aggregation areas, grade 3 land showed high aggregation along the Yellow River coast and in Sangshuping Town, with one index rising and one falling, both with small variation amplitudes. For low-grade land aggregation areas, grade 4 land showed the highest aggregation degree in Longmen Town, with the location index changing significantly from 2.78 to 3.45.

In summary, the temporal and spatial changes of cultivated land quality in the study area are characterized by significant area changes of each grade, large differences in area among grades, and obvious regional distribution patterns. The significant area changes indicate that under the premise of basically unchanged total quantity, there were substantial inter-grade conversions, meaning the specific scores of evaluation indicators changed. The indicator scores depend on measured values at sampling points, spatial interpolation operations, and specific calculation methods. Since the initial and final evaluation results used unified spatial operations and calculation models, the differences in indicator scores mainly originated from changes in original data. Basic and regional supplementary indicators changed significantly during 2009–2018, while relatively fixed evaluation factors such as terrain position, elevation, biodiversity, and groundwater depth require long-term natural forces or human intervention to change and are not obvious in the medium-short term. Evaluation factors directly related to farmland cultivation, such as soil nutrient status and farmland infrastructure, have gradually improved under the influence of cultivated land protection policies and farmers' awareness of land conservation, becoming the main factors for score improvement.

2.3 Impact of Cultivated Land Changes on Grain Production

Grain production is mainly influenced by natural factors such as climate change and water resource variation, as well as social factors including land use structure and agricultural technology. Climate change is suitable for large-scale, long-term regional studies and had no obvious impact on grain production changes in the study area from 2009 to 2018. Here, social factors such as cultivated land quantity, drainage and irrigation capacity, and agricultural science and technology played decisive roles. Changes in grain sown area were the main factor affecting grain yield changes. Using the area-weighted method to calculate grain yield per unit sown area, the study area had a grain sown area of 132.58 km^2 and total output of 79,400 tons in 2009, with a yield of 599.59 $t \cdot km^{-2}$. In 2018, the grain sown area was 84.51 km^2 with total output of 48,500 tons, and the yield was 574.33 $t \cdot km^{-2}$. The grain sown area decreased significantly due to extensive planting of pepper and apple crops in the study area, leading to a substantial reduction in grain sown area and grain yield. The net loss of grain production caused by reduced cultivated land was approximately 644 $t \cdot km^{-2}$.

Cultivated land quality is the main factor affecting grain production location. The main grain crops in the study area include wheat and corn, divided into annual double-cropping (wheat and summer corn) and annual single-cropping (spring corn). Overlay analysis of high-quality cultivated land distribution areas and grain production core areas dominated by wheat and corn shows high congruence, meaning grain crops are mainly distributed in high-quality cultivated land areas (Fig. 5). The wheat-summer corn double-cropping area is mainly in the eastern plain zone of Xincheng and Jincheng Subdistricts and on the east bank of the Yellow River, serving as the core area for building ten-thousand-mu grain production zones and the main area for high-standard farmland construction where cultivated land quality has been improved. The spring corn planting area is mainly in the western part of Sangshuping Town, with relatively small planting area throughout the region.

From the perspective of gravity center migration during the study period, the planting gravity centers of wheat and corn have the same migration direction as high-quality cultivated land distribution. Using each evaluation unit' s evaluation score as the weight for cultivated land quality distribution gravity center, the coordinates of high-quality cultivated land distribution gravity center were obtained by weighted calculation of each unit' s geographic coordinates. Using wheat and corn planting area as the weight for grain production location gravity center, the distribution gravity center of main grain production areas was calculated (Table 5). The gravity center distribution shows that the cultivated land quality distribution gravity center is located in Jincheng Subdistrict, where high-grade land is mainly distributed. When evaluation scores are used as weights, the gravity center shifts toward areas with higher scores. Similarly, the grain production location gravity center is at the junction of Jincheng and Xincheng Subdistricts, where major grain planting areas are located. Using grain planting area as weights shifts the gravity center toward main grain planting areas. The coordinates and gravity centers in the table and figure show that the distribution gravity centers of cultivated land quality and grain production location changed little during the study period, migrating overall toward the southeast, with consistent directions.

In summary, changes in cultivated land quantity and quality are the main factors causing changes in grain yield and production location in the study area. From 2009 to 2018, the change in cultivated land quantity caused a net grain loss of $644\ \mathrm{t \cdot km^{-2}}$. The distribution gravity center areas of medium- and high-quality cultivated land in the study area have high congruence with wheat and corn production core areas, with consistent migration directions.

3 Discussion

Grain yield changes are dominated by multiple factors, including climate change, cultivated land changes, seed breeding, farming methods, and planting management. Based on the premise of unchanged climate change and other related factors, cultivated land quantity changes in the study area were not obvious, so this study focused on exploring the impact of cultivated land quality changes on grain yield and production pattern changes. Existing literature mainly discusses the coupling relationship between cultivated land use intensity, cultivated land pressure index, and grain yield from the quantity perspective, expressing it through spatial patterns and quantity changes. Research areas focus on provinces and above, major grain production plains, and main river basins. This paper emphasizes the relationship between cultivated land quality and grain production from the spatial perspective, expressed through spatial layout and migration direction, aiming to analyze the relationship between cultivated land quality grade changes, spatial changes, and grain production location changes when cultivated land quantity changes are not obvious and continuous data are missing. A typical county-level study area was selected to reflect the situation of cultivated land and food security in ecologically fragile areas of non-grain producing regions.

From the research results, the cultivated land quality evaluation score in the study area increased while the average grade decreased. This is because farmers' awareness of cultivated land protection improved under relevant policy promotion, and the combination of cultivation and planting improved indicator scores to some extent. However, due to urbanization, policy implementation, and industrial adjustment, high-quality cultivated land in the eastern plain area partially decreased, the proportion of high-grade land declined, and the average cultivated land quality grade decreased. Grain production is affected by cultivated land quality changes, with the gravity center of main grain production areas shifting toward the gravity center of high-quality cultivated land distribution. The significant decrease in grain yield per unit area is the result of combined effects of cultivated land quantity reduction, low cultivated land utilization degree, and rapid development of non-grain cash crops.

The study area is in the Weibei dryland district, belonging to the food insecurity level, currently in a stage of rapid urbanization, frequent three-industry structure adjustment, and agricultural planting structure continuously tilting toward cash crops. Occupying a certain amount of cultivated land is inevitable. Based on the above characteristics and driving factors of cultivated land resource utilization, the study area should strictly control cultivated land use conversion, strengthen cultivated land protection, and introduce relevant policy guidance: (1) During land approval, increase benefit evaluation to ensure that approved land creates more value while compensating for reduced benefits from occupied cultivated land. (2) Addressing the current situation of low cultivated land utilization, strengthen planning and supervision of various cultivated land use zones, especially permanent basic farmland and high-standard farmland construction, to curb non-agriculturalization of cultivated land. (3) Optimize agricultural production structure, increase the proportion of grain crops, and vigorously promote ecological circular agriculture combining planting and breeding with yield-increasing agricultural extension technologies to simultaneously improve cultivated land quality and grain production capacity.

4 Conclusions

This study analyzed the temporal and spatial changes of cultivated land and their impact on grain production in Hancheng City, Weibei dryland district, from 2009 to 2018, reaching the following conclusions:

(1) From 2009 to 2018, the spatial distribution of cultivated land resources in the study area remained basically unchanged, concentrated in the eastern

plains and along the Yellow River, forming a "loess tableland-Yellow River cultivated land belt." Cultivated land quantity gradually decreased and dispersed from east to northwest, with reduced cultivated land mainly distributed in the central part of Longmen Town, at the junction of Xincheng and Xizhuang Towns, in eastern Jincheng, and in eastern Zhichuan Town, located in the main construction areas of the central urban area.

(2) Cultivated land quality in the study area changed significantly from 2009 to 2018, with large area differences among grades. Grade 2 cultivated land had the largest area proportion. Spatially, cultivated land quality gradually decreased from the eastern Yellow River coast toward the northwest, forming a vertical pattern of low-grade, high-grade, and medium-grade land from top to bottom. High-grade land is concentrated in Jincheng Subdistrict, Xincheng Subdistrict, and the east bank of the Yellow River in the eastern plain area, with high location indices. Medium-grade land is concentrated along the southern Yellow River coast and in Sangshuping Town, with relatively high location aggregation. Low-grade land has relatively high location indices in Longmen Town and Sangshuping Town.

(3) Changes in cultivated land quantity and quality are the main factors affecting grain yield and production location changes in the study area. From 2009 to 2018, cultivated land quantity changes caused a net grain loss of 644 $t \cdot km^{-2}$. The distribution gravity center areas of medium- and high-quality cultivated land in the study area have high congruence with wheat and corn production core areas, with consistent migration directions.

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Note: Figure translations are in progress. See original paper for figures.