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# Spatial Coupling Between Cropland Loss and Rural Settlement Expansion in China's Major Grain-Producing Region

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## Abstract

Cropland and rural settlements are core components of rural human–environment systems, and their coordinated development is crucial for regional sustainability, particularly in China's major agricultural production regions. Taking the Huang-Huai-Hai region as the study area, this study systematically investigates the spatiotemporal evolution of cropland and its coupling relationship with rural settlements using land use data from 1990 to 2020. Grid-based analysis and multiple spatial modeling methods were employed. The results show that: (1) From 1990 to 2020, the cropland in the region decreased by a net total of 21,021.94 km$^2$, with annual dynamic degrees ranging from −0.13% to −0.28%. Cropland conversion to other land uses far exceeded conversion from others, with construction land being the primary destination. Among these, rural settlements and urban construction land accounted for 43.75% and 55.58% of the total cropland loss, respectively. (2) The spatial distribution of cropland exhibited a distinct pattern of "hot in the center and south, cold in the periphery and north" (Moran's I = 0.232, $p < 0.001$), indicating significant positive spatial autocorrelation. Hot spot areas clustered in the North China Plain and the Huang-Huai Plain, while cold spot areas were distributed in the Yanshan–Taihang mountains and the hilly regions of the Shandong Peninsula, clearly controlled by topography. (3) Cropland change exhibited stage-specific characteristics. The pattern was relatively stable during 1990–2000. During 2000–2010, cropland conversion to other uses intensified, with high-value conversion areas concentrated around urban agglomerations. In the 2010–2020 period, these high-value conversion areas diffused from the core plain areas to urban fringe zones. (4) The spatial coupling between cropland and rural settlements was predominantly characterized by the Moderately Coordinated Type (MCT), accounting for 48.38–58.44% of the area. However, the proportion of Rural Settlement-Dominant Type (RC) increased from 15.51% to 21.58%, indicating a trend toward intensifying human–environment conflicts. Overall, the Huang-Huai-Hai region experienced significant cropland changes. While its spatial pattern remains relatively stable, the coupling relationship between cropland and rural settlements is deteriorating, posing challenges to regional food security and rural sustainable development.

**Keywords:** cropland; rural settlements; coupling relationship; spatial analysis; Huang-Huai-Hai region

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## 1. Introduction

Cropland loss and rural settlement expansion are two interdependent processes that increasingly shape rural landscapes worldwide, particularly in rapidly urbanizing agricultural regions. Cropland systems and rural settlements serve as core analytical frameworks for understanding rural development trajectories. Their complex interactions are particularly critical in agricultural regions undergoing rapid socioeconomic transformation. As the material foundation of agricultural production and the spatial carrier of rural livelihoods, cropland and rural settlements jointly shape the evolving patterns of human–environment relationships in rural areas [1]. The degree of their coordinated development profoundly influences regional food security, rural sustainability, and the realization of national strategies such as agricultural modernization and rural revitalization. Thus, understanding spatiotemporal dynamics and coupling mechanisms between these two key land use types has become a central topic in land system science and agricultural research. In many major grain-producing regions worldwide, rapid urbanization and rural transformation are driving concurrent cropland loss and rural settlement expansion, often with conflicting outcomes for food security and land sustainability. Globally, many major agricultural regions are experiencing similar tensions between cropland protection and rural–urban expansion, making this study of cropland–settlement coupling a pressing international issue.

China’s major agricultural production regions are experiencing unprecedented pressure from urbanization, industrialization, and land use transformation. Since 2000, China’s urbanization rate has surged from 36.22% to over 65%, triggering dramatic changes in urban–rural land systems [2]. A particularly noteworthy phenomenon is the coexistence of rural population decline and rural residential land expansion. The paradox of “population decrease alongside land increase” largely characterizes contemporary rural China [3]. The decoupling of population and land use dynamics has intensified competition between agricultural production and residential functions for limited land resources, posing complex challenges for cropland protection and rural spatial governance.

The Huang-Huai-Hai Plain embodies these human–environment tensions with particular acuity. As one of China’s most important agricultural regions, this area accounts for only 4.3% of the nation’s land area yet contributes approximately 20.6% of cropland, supports 22.5% of its population, and produces 30.8% of its grain [4]. Its flat terrain, fertile soil, and favorable hydrothermal conditions support intensive agricultural production, earning it the reputation of “national granary.” Simultaneously, the region encompasses some of China’s most dynamic urban agglomerations, including the Beijing–Tianjin–Hebei, Shandong Peninsula, and Central Plains urban agglomerations [5]. The convergence of agricultural importance and urbanization pressure makes the Huang-Huai-Hai region an ideal study area for examining cropland-rural settlement interactions and their implications for regional sustainability.

Existing research has largely focused on cropland loss and its driving factors in the Huang-Huai-Hai region. Research indicates that 72.25% of cropland reduction in the region can be attributed to construction land occupation [6]. The conversion of high-quality cropland to urban and rural construction land has raised profound concerns about regional food production capacity. Meanwhile, research on rural settlements has revealed their spatial expansion patterns, identifying household income growth, improved housing demand, and inadequate village planning as primary driving factors [7]. Internationally, scholars have increasingly recognized the need to examine cropland and settlement dynamics as integrated social–ecological systems [8]. Domestically, researchers have explored the mechanisms of rural settlement expansion [9] and the conflicts between construction land and cropland under tense human–land relationships [10], particularly in major agricultural regions [11]. These studies provide important theoretical and empirical foundations. How-

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ever, studies that dynamically analyze cropland and rural settlements as a coupled system remain insufficient. Specifically, a key knowledge gap is how the spatial coupling between these two land types evolves over time—and what this implies for regional sustainability—particularly in major agricultural regions undergoing rapid urbanization. Most existing research examines single land types in isolation, neglecting the intrinsic connections between agricultural production space and rural living space. In agricultural regions, the historical pattern of "settlements following cropland" has profoundly shaped settlement distributions. The linkages between cropland and rural settlements demand integrated analytical approaches capable of capturing their synergistic interactions. Recent advances in land use transition research provide frameworks for filling this analytical gap, with scholars increasingly emphasizing the need to examine cropland and rural settlement as interconnected processes [8].

The Huang-Huai-Hai region serves as a typical and representative case for studying cropland–settlement coupling, as it embodies the acute tensions between agricultural production and urbanization faced by many major grain-producing regions globally. While our empirical analysis focuses on this region, the analytical framework (grid-scale coupling analysis, Settlement-Cropland Ratio Index) and the broader findings are transferable to other agricultural regions undergoing rapid socioeconomic transformation. This study aims to analyze the spatiotemporal dynamics and coupling relationships between cropland and rural settlements in the Huang-Huai-Hai region from 1990 to 2020, addressing three specific objectives: (1) characterize the temporal trajectory and spatial pattern of cropland change over the 30-year period; (2) analyze spatial transfer dynamics between cropland and other land use types, with particular attention to conversion to rural settlements; and (3) quantify and map coupling types between cropland and rural settlements, identifying their spatial distribution patterns and temporal evolution. This research contributes to the literature by examining cropland–settlement coupling at a finer grid scale (5 km $\times$ 5 km) and by applying the Settlement-Cropland Ratio Index to characterize quantitative allocation relationships between the two land types. These approaches allow us to capture dynamic coupling evolution that previous single-type or coarse-scale studies have missed. By elucidating these coupling dynamics, this study seeks to provide scientific bases for spatially differentiated land governance strategies that balance cropland protection with rural development needs.

## 2. Materials and Methods

### 2.1. Study Area

The Huang-Huai-Hai region, situated in eastern China (112–122° E, 32–40° N), spans parts of seven provinces (Beijing, Tianjin, Hebei, Shandong, Henan, Anhui, and Jiangsu), encompassing a total area of approximately 300,000 km$^2$. This region constitutes the main body of the North China Plain, China's largest alluvial plain, characterized by flat and open terrain with elevations predominantly below 100 m. Formed by alluvial deposits from the Yellow, Huai, and Hai Rivers, the region features deep, fertile soil layers. The Huang-Huai-Hai region experiences a warm temperate semi-humid monsoon climate, with mean annual precipitation of 500–900 mm. The coincidence of rain and heat, abundant light and thermal resources, and favorable irrigation conditions make it China's most important grain-producing area and commercial grain base. The region is densely populated with rapid urbanization processes, serving as the core area for the Beijing–Tianjin–Hebei, Shandong Peninsula, and Central Plains urban agglomerations. Simultaneously, it is a typical agricultural region with extensive rural settlement distribution, where spatial conflicts between cropland and construction land are increasingly prominent. Against the background of national food security and rural revitalization, the evolution of human–land

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relationships in the Huang-Huai-Hai region exhibits typicality and sensitivity, rendering it an ideal area for studying the synergistic dynamics between rural settlements and cropland.

### 2.2. Data Sources

The 30 m resolution land use data utilized in the study were obtained from the Chinese Multi-Period Land Use and Land Cover Remote Sensing Monitoring Data Set (CNLUCC), provided by the Resource and Environment Science and Data Center, Chinese Academy of Sciences (http://www.resdc.cn) [12]. The dataset, generated through manual interpretation of Landsat remote sensing imagery, has been extensively validated and exhibits high classification accuracy. Specifically, the overall classification accuracy of the CNLUCC dataset is reported to exceed 90%, based on validation using field survey points and high-resolution imagery. The main processing procedures included: (1) radiometric calibration and geometric correction of the original Landsat images; (2) manual visual interpretation and digitization of land use types according to a unified classification system; (3) quality control and accuracy assessment through cross-validation; and (4) projection unification and clipping to the study area boundary. To reveal the coupling relationships and evolutionary patterns between cropland and rural settlements, data from four periods were selected, including 1990, 2000, 2010, and 2020. The selection was based on the following considerations: first, the completeness of data information in each period ensures comprehensive analysis; second, the ten-year intervals are sufficient to capture significant trends in land use changes; third, 2020 serves as the most recent time point, providing practical relevance for subsequent research. Land use types were classified according to the dataset's classification system, with a focus on cropland, rural settlements, city regions, forests, grasslands, water areas, and other land types. Administrative boundary data were sourced from the Standard Map Service System of the Ministry of Natural Resources (http://mnr.gov.cn).

To mitigate the scale effects of administrative units and accurately characterize local features of cropland–settlement relationships, grid-based analysis units were introduced. Following relevant studies [13–15] and comparing the effects of different grid scales, including 1 km × 1 km, 5 km × 5 km, and 10 km × 10 km, on analytical outcomes, the 5 km × 5 km grid was ultimately adopted as the basic research unit. The 1 km × 1 km grid was found to introduce excessive noise and zero inflation, as many cells contained no cropland or settlements due to the high fragmentation of land use at fine scales. The 10 km × 10 km grid, while computationally efficient, tended to over-smooth spatial heterogeneity and failed to capture the urban fringe dynamics that are central to this study. The 5 km × 5 km grid provided a balanced solution, retaining local spatial patterns. A total of 22,368 valid grids covering the entire region were generated using the create fishnet tool in the ArcGIS 10.7 platform.

### 2.3. Research Methods

#### 2.3.1. Single Land Use Dynamic Degree

The single land use dynamic degree is primarily employed to quantify the rate and direction of change for a specific land use type over a given period, reflecting the intensity of land use change [16]. Its expression is as follows:

$$Q = \frac{S_b - S_a}{S_a} \times \frac{1}{T} \times 100\% \quad (1)$$

where $S_a$ and $S_b$ represent the area (km$^2$) of a land use type at the beginning and end of the period, respectively; $T$ is the length of the period (year); and $Q$ is the single land use dynamic degree (%) of a land use type during a given period. Positive $Q$ values indicate an area increase, while negative values denote a decrease; larger absolute $Q$ values signify more dramatic changes in the land type.

### 2.3.2. Land Use Transfer Matrix

The land use transfer matrix can calculate the areas of mutual conversion between different land types at the beginning and end years, thereby characterizing land use structure and change directions for various land types [17]. Its expression is as follows:

$$S_{pq} = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix} \quad (2)$$

where $n$ is the number of land use types; $i$ and $j$ ($i$, $j$ = 1, 2, 3, . . . , $n$) represent the land use types before and after transfer, respectively, and $S_{ij}$ is the area of land use type $i$ at the beginning of the study period that was converted to land use type $j$ at the end of the study period.

### 2.3.3. Local Spatial Cluster Analysis

To detect local spatial agglomeration characteristics of cropland, Local Moran's $I$ was employed. The index identifies whether similar or dissimilar observed values are clustered together in local areas within the study region [18]. To measure the correlation between region $i$ and its neighbors, the corresponding Local Moran's $I$ is defined as:

$$I_i = \frac{(x_i - \overline{x})}{s_x^2} \sum_j \left[ w_{ij} \left( x_j - \overline{x} \right) \right] \quad (3)$$

where $x_i$ and $x_j$ are the observed values of regions $i$ and $j$, respectively; $\overline{x}$ is the mean of all observed values; $w_{ij}$ is the spatial weight matrix; $n$ is the total number of regions. A positive $I_i$ indicates high–high clustering (a high value surrounded by other high values) or low–low clustering (a low value surrounded by other low values), signifying that the element is part of a cluster; A negative $I_i$ indicates low–high clustering (a low value surrounded by high values) or high–low clustering (a high value surrounded by low values), signifying that the element is an outlier.

### 2.3.4. Hot Spot Analysis

The Getis–Ord $G_i^*$ index was used to identify hot and cold spot areas where cropland area is significantly clustered in space [19]. Unlike Local Moran's $I$, the $G_i^*$ index directly distinguishes high-value clusters (hot spots) and low-value clusters (cold spots), reflecting the cold-hot differentiation pattern of cropland in local space. The calculation formula is:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij} x_j - A \sum_{j=1}^{n} w_{ij}}{S \sqrt{\frac{\left[ n \sum_{j=1}^{n} w_{ij}^2 - \left( \sum_{j=1}^{n} w_{ij} \right)^2 \right]}{n-1}}} \quad (4)$$

where $x_j$ is the cropland area (km$^2$) of grid $j$; $w_{ij}$ is the spatial weight matrix; $n$ is the total number of grids; $A$ and $S$ are the mean and standard deviation of cropland area for all grids, respectively. When $G_i^*$ is positive and significant, it indicates that the grid and its neighborhood constitute a hot spot with high-value clustering of cropland; when $G_i^*$ is negative and significant, indicating a cold spot with low-value clustering. The analysis was implemented using the hot spot analysis tool in ArcGIS, with confidence levels set at 90%, 95%, and 99%.

2.3.5. Settlement-Cropland Ratio Index

The Settlement-Cropland Ratio Index was adopted to diagnose the quantitative allocation relationship between cropland and rural settlements, reflecting the land use allocation status between rural settlements and cropland and the human–land relationship within the study area [20]. The index is defined as the ratio of rural settlement area to cropland area within a grid, characterizing the relative pressure of residential land on agricultural land at the local scale. The expression is as follows:

$$L = S_e / S_f \tag{5}$$

where $L$ is the Settlement-Cropland Ratio Index of the grid, $S_e$ is the rural settlement area within the grid, and $S_f$ is the cropland area within the grid. A smaller $L$ value indicates relatively abundant cropland and a more coordinated human–land relationship; a larger $L$ value indicates lower cropland and an increasingly tense human–land relationship [21].

To rationally classify coupling types, referring to the world average cropland area per capita (1920 $m^2$/person) and world average construction land area per capita (83 $m^2$/person), a threshold of 0.04 was calculated (83 ÷ 1920 ≈ 0.043, rounded to 0.04). Referring to the FAO-defined per capita cropland warning line (533.30 $m^2$/person) and the rural per capita construction land range stipulated for China's new-type urbanization construction (150 $m^2$/person), a threshold of 0.28 was calculated (150 ÷ 533.30 ≈ 0.281, rounded to 0.28). Based on this, grids were classified into the following types: (1) No Cropland or Rural Settlements ($L$ = 0); (2) Cropland-Rich Type (CR, 0 < $L \leq$ 0.04); (3) Moderately Coordinated Type (MCT, 0.04 < $L \leq$ 0.28); and (4) Rural Settlement-Dominant Type (RC, $L$ > 0.28).

## 3. Results

### *3.1. Temporal Characteristics of Cropland in the Huang-Huai-Hai Region*

From 1990 to 2020, the cropland in the Huang-Huai-Hai region exhibited a continuous downward trend, decreasing from 325,422.72 $km^2$ in 1990 to 304,400.78 $km^2$ in 2020, representing a cumulative net reduction of 21,021.94 $km^2$ over the 30-year period. As indicated by the single land use dynamic degree (Table 1), all periods were negative, confirming the continuous contraction of cropland area. The $Q$ value was −0.13% during 1990–2000, expanded to −0.25% during 2000–2010, and further intensified to −0.28% during 2010–2020, demonstrating a progressively accelerating trend. This progression indicates that the rate of cropland loss in the Huang-Huai-Hai region has been continuously accelerating, with later-stage changes being more pronounced than earlier ones. The $Q$ value for the entire period (1990–2020) was −0.22%, reflecting a considerable intensity of change in regional cropland with an overall declining trend.

**Table 1.** Single dynamic degree of cropland in the Huang-Huai-Hai region from 1990 to 2020.

| Year | Cropland ($km^2$) | Period | Change ($km^2$) | Q (%) |
|---|---|---|---|---|
| 1990 | 325,422.72 | 1990–2000 | −4083.04 | −0.13 |
| 2000 | 321,339.68 | 2000–2010 | −8102.00 | −0.25 |
| 2010 | 313,237.68 | 2010–2020 | −8836.90 | −0.28 |
| 2020 | 304,400.78 | 1990–2020 | −21,021.94 | −0.22 |

To further elucidate the conversion patterns between cropland and other land types, this study constructed land use transfer matrices and mapped the transfer relationships between cropland and other land use types (Figure 1). In Figure 1, each land use type is represented by a node; arrows indicate the direction of conversion, with arrow thickness

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proportional to the transferred area. For instance, the prominent arrow from cropland to rural settlements reflects the substantial loss of cropland to rural residential expansion. The analysis reveals that while cropland engaged in conversion relationships with other land use types, the area of cropland outflow consistently exceeded that of inflow, underscoring a severe cropland loss problem.

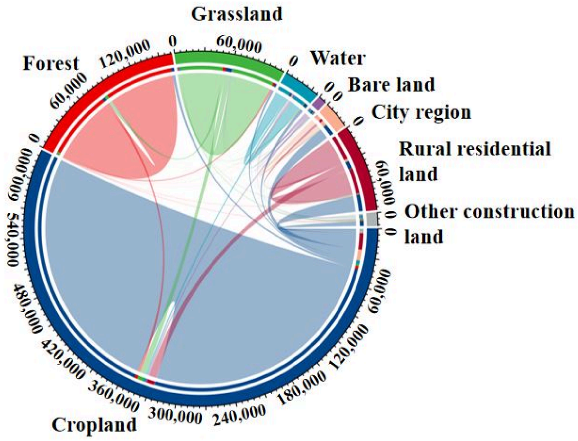


**Figure 1.** Transfer of cropland and other land use types in the Huang-Huai-Hai region from 1990 to 2020. Note: The thickness of arrows represents the transfer scale, and different colors represent conversion relationships between different land types.

During 1990–2000, the total cropland inflow area was 2372.58 km$^2$, primarily sourced from water area (884.44 km$^2$), grassland (781.92 km$^2$), and forest (398.31 km$^2$). The total cropland outflow area was 6457.44 km$^2$, mainly directed to rural settlements (2386.62 km$^2$) and urban construction land (2383.79 km$^2$). The net difference between cropland inflow and outflow was −4084.86 km$^2$, resulting in a net decrease in cropland. During 2000–2010, the total cropland inflow area increased markedly to 22,372.72 km$^2$, with significantly increased transfer scales between land use types. Inflow sources were predominantly rural settlements (9600.18 km$^2$), grassland (5816.49 km$^2$), water area (2266.34 km$^2$), and forest (2235.36 km$^2$). The total cropland outflow area reached 30,476.63 km$^2$, with outflow destinations mainly being rural settlements (13,849.69 km$^2$) and urban construction land. The net difference between cropland inflow and outflow was −8103.92 km$^2$, indicating an accelerated decline in cropland. The scale of net cropland outflows to urban construction land (7434.83 km$^2$) and rural settlements (4249.50 km$^2$) further expanded. During 2010–2020, the total cropland inflow area decreased to 5000.09 km$^2$, only 22.35% of the previous period's inflow. The total cropland outflow area was 13,825.64 km$^2$, predominantly to construction land, including rural settlements (3931.52 km$^2$), urban construction land (2464.60 km$^2$), and other construction land (2517.18 km$^2$). These three types of construction land account for 64.47% of total cropland outflow. The net difference between cropland inflow and outflow was −8825.56 km$^2$, representing the highest net cropland loss across the study period.

Over the entire 30-year scale (1990–2020), there was a net cropland outflow of 21,021.94 km$^2$, primarily flowing to urban construction land (11,679.73 km$^2$) and rural settlements (9193.53 km$^2$). Overall, cropland outflow consistently exceeded inflow throughout the study period, resulting in substantial cropland loss, with rural settlements being one of the main destinations.

### *3.2. Spatial Characteristics of Cropland in the Huang-Huai-Hai Region*

#### 3.2.1. Spatial Distribution Pattern

The Huang-Huai-Hai region, as one of China's most important grain production bases, exhibits cropland distribution characterized by typical plain-intensive patterns. From the spatiotemporal distribution perspective (Figure 2), cropland distribution across the Huang-Huai-Hai region was extensive from 1990 to 2020, with overall patterns remaining relatively stable without significant pattern restructuring. This macro-level stability is itself an important finding, as it indicates that the fundamental cropland pattern of the region has not been fundamentally altered despite rapid urbanization. The boundaries between areas of dense and sparse cropland distribution were clearly delineated, demonstrating pronounced terrain orientation. With the North China Plain as its core, cropland displayed contiguous, concentrated distribution patterns. These areas have flat terrain, fertile soil, and good irrigation conditions, forming the core dense areas of cropland distribution. In contrast, the eastern coastal areas of the Shandong Peninsula (hilly and peri-urban areas), the western Henan mountainous and hilly areas, the northern Hebei mountainous areas, and inter-provincial boundary mountainous areas, affected by urban expansion, terrain constraints, and environmental constraints, had relatively scattered and sparse cropland distribution with higher fragmentation [22]. Overall, although cropland spatial patterns remained relatively stable during the study period, the trend of cropland shrinkage in urban fringe areas and around towns became increasingly pronounced, with significant changes occurring in cropland landscapes at local scales.

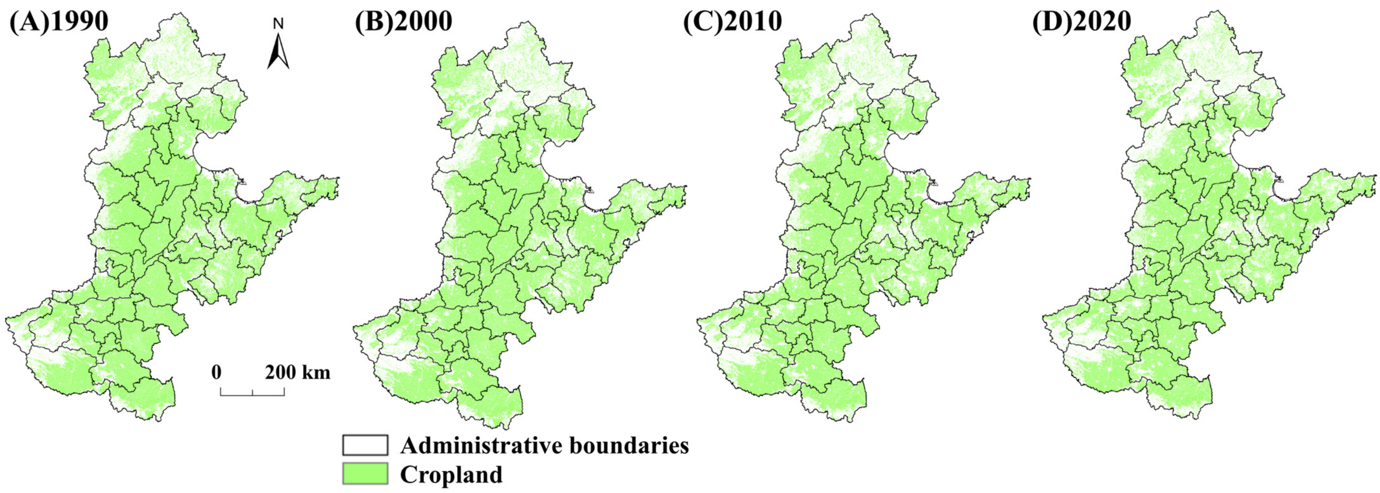


**Figure 2.** Spatiotemporal distribution of cropland in the Huang-Huai-Hai region from 1990 to 2020. (**A**) Spatial distribution of cropland in 1990; (**B**) Spatial distribution of cropland in 2000; (**C**) Spatial distribution of cropland in 2010; (**D**) Spatial distribution of cropland in 2020.

### 3.2.2. Spatial Agglomeration Characteristics

To further elucidate the spatial agglomeration characteristics of cropland distribution, this study employed the hot spot analysis tool in ArcGIS to map cold and hot spot distributions of cropland in the Huang-Huai-Hai region (Figure 3A). The results show that cropland cold and hot spots exhibited pronounced spatial differentiation, generally presenting a pattern of "hot centers and cold peripheries, hot south and cold north." Hot spot areas showed belt-like clustered distribution, while cold spot areas showed patchy, scattered distribution. Hot spots and sub-hot spot clusters were mainly distributed in the North China Plain and the Huang-Huai Plain, forming contiguous hot spot cluster belts. Specifically, these included central-southern Hebei (a flat, densely populated plain area) (Shijiazhuang, Baoding, Xingtai, Handan), northwestern Shandong (Dezhou, Liaocheng, Heze), northern Henan (Xinxiang, Anyang, Puyang), and the Huang-Huai Plain areas in northern Anhui and northern Jiangsu. These areas, characterized by flat and open terrain, deep and fertile soil layers, and superior irrigation conditions, are conducive to the contiguous clustered distribution of cropland and the formation of large-scale grain production bases. Cold spots and sub-cold spots were mainly distributed in mountainous and hilly areas. The Huang-Huai-Hai region is bordered by the Yanshan Mountains to the north, the Taihang Mountains to the west, the northern foothills of the Tongbai–Dabie Mountains to the south, and the Bohai Sea and Yellow Sea to the east. These mountainous, hilly, and coastal areas formed clusters of cropland cold spots, creating sharp contrasts with hot spot clusters in plain areas.

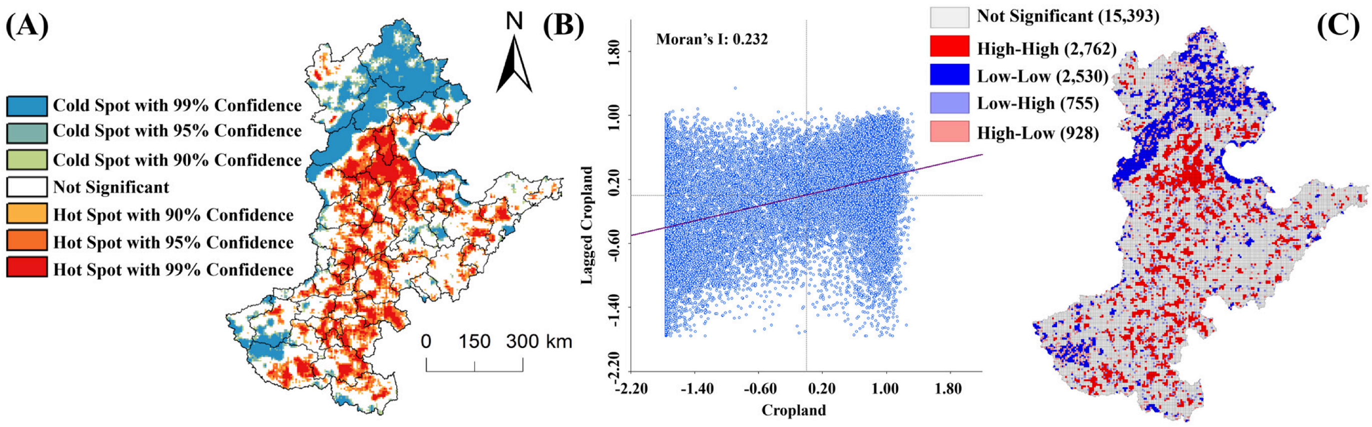


**Figure 3.** Distribution of cold and hot spots (**A**), Moran scatter plot (**B**), and LISA aggregation map (**C**) of cropland in the Huang-Huai-Hai region. Note: In Figure 3B, the $x$-axis represents the standardized cropland area for each grid, and the $y$-axis represents the spatial lag.

Further spatial autocorrelation analysis of cropland in the Huang-Huai-Hai region was conducted. The Moran's $I$ values for 1990, 2000, 2010, and 2020 are 0.246, 0.240, 0.228, and 0.232, respectively ($p < 0.001$), showing only minor fluctuations over the 30-year period. It indicated significant positive spatial autocorrelation in cropland distribution, exhibiting obvious spatial agglomeration characteristics. From the LISA cluster map (Figure 3C), excluding non-significant areas (15,393 grids), high–high clustering was relatively large (2762 grids), followed by low–low clustering (2530 grids). Conversely, high–low clustering (928 grids) and low–high clustering (755 grids) were relatively fewer, indicating that spatial heterogeneity in cropland distribution was mainly manifested as homogeneous clustering rather than heterogeneous interlacing. High–high clusters were mainly distributed in the core areas of the Huang-Huai-Hai Plain, with spatial distribution coinciding with hot spot areas. These areas exhibited high cropland area density, forming contiguous large-scale cropland cluster areas. Low–low clusters were mainly distributed in the northern Yanshan–Taihang mountainous areas, the southern foothills of the Tongbai–Dabie Mountains, and the eastern hilly areas of the Shandong Peninsula. These areas, characterized by substantial topographic undulation and ecological fragility, contained small cropland areas with low density and fragmented cropland, forming cropland sparse belts together with adjacent units.

### 3.2.3. Cropland Spatial Changes

Cropland spatial transfers in the Huang-Huai-Hai region from 1990 to 2020 are shown in Figure 4. Cropland spatial transfers across different periods showed significant phased characteristics. During 1990–2000, cropland changes were relatively stable with stable spatial patterns. Large-scale cropland conversion phenomena were rare during this period, with a scattered distribution of cropland outflow and inflow grids, no obvious cluster areas formed, and regional agricultural development was in a relatively stable stage. During 2000–2010, cropland spatial transfer intensity significantly increased, with obvious activity in cropland area outflow and inflow within grids. This period coincided with China's rapid urbanization advancement, with intensified pressure from construction land expansion on cropland occupation. High-value cropland outflow grids were mainly distributed in the Beijing–Tianjin–Hebei urban agglomeration (a major metropolitan region with rapid urban expansion) and surrounding areas, Shandong Peninsula urban agglomeration, and core areas of the Central Plains urban agglomeration [23]. These areas had population agglomeration and industrial expansion, with surging demand for construction land, leading to the occupation of large amounts of high-quality cropland. Although the number of cropland inflow grids was large, the inflow plots were relatively scattered. During 2010–2020, cropland spatial transfer patterns changed, with high-value outflow areas diffusing from plain core areas to fringe areas. Cropland outflow in cities such as Beijing remained significant, while high-value outflow areas began to spread to fringe areas around towns. The spatial distribution of cropland inflow grids showed a "marginalization" trend, mainly concentrated in northern Hebei, central-southern Shandong, and western Henan areas. These areas have relatively average terrain conditions, overall low cropland quality, and prominent spatial misalignment problems in cropland occupation and compensation.

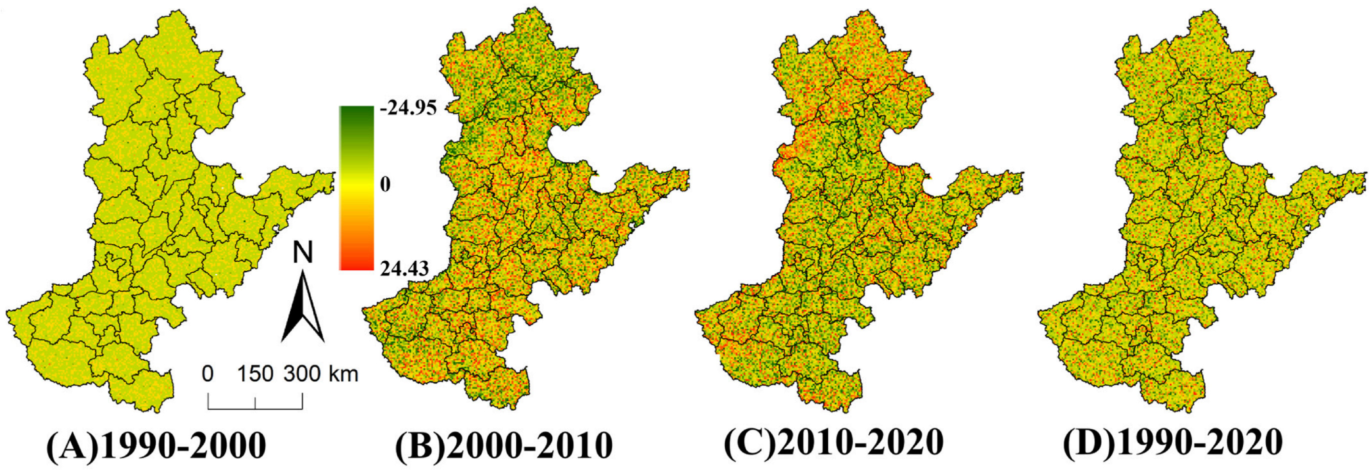


**Figure 4.** Spatial transfer of cropland in the Huang-Huai-Hai region from 1990 to 2020. (**A**) Spatial transfer of cropland from 1990 to 2000; (**B**) Spatial transfer of cropland from 2000 to 2010; (**C**) Spatial transfer of cropland from 2010 to 2020; (**D**) Spatial transfer of cropland from 1990 to 2020.

### *3.3. Coupling Relationship Between Cropland and Rural Settlements*

This study conducted an overlay analysis of cropland and rural settlements distribution data for 1990 and 2020, obtaining spatial transfer types between the two (Figure 5). During the study period, the total area of mutual conversion between cropland and rural settlements was approximately 26,492.75 km$^2$, showing significant characteristics dominated by the C-C type in spatial distribution. The C-C type was widely distributed in the Huang-Huai-Hai region, with an area of 28,149.35 km$^2$ and the highest proportion, concentrated in the North China Plain, Huang-Huai Plain, and other major plain agricultural areas. These areas are national core grain production areas with strong stability in cropland use. The R-R type was mainly distributed in traditional village cluster areas in plain regions, showing scattered point-like distribution patterns, highly coupled with cropland spatial distribution, reflecting the "living by the cropland" settlement distribution characteristics under the background of agricultural civilization in the Huang-Huai-Hai region [9], and reflecting the historical continuity of rural settlements. The C-R type was mainly distributed in areas with rapid urbanization advancement, such as the Beijing–Tianjin–Hebei urban agglomeration, the Central Plains urban agglomeration, and the Huaihai Economic Zone. These areas have rapid economic development and high population agglomeration, with relatively common occupation of cropland by rural infrastructure construction, leading to the conversion of some cropland to rural settlements. This type was basically consistent with urban expansion directions in space, representing an important manifestation of cropland loss in the urbanization process. The R-C type had a relatively scattered distribution, with a small area proportion (8649.61 km$^2$). Due to this type being small in area and scattered in distribution, the overall scale of reclamation from rural homesteads to cropland is limited [24].

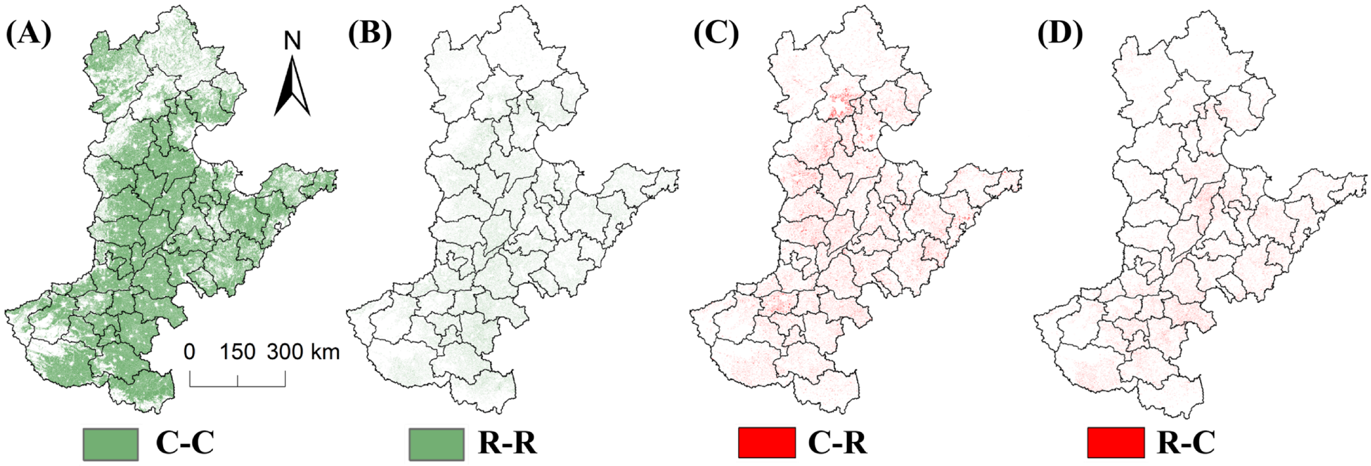


**Figure 5.** Spatial transfer of cropland and rural settlements in the Huang-Huai-Hai region from 1990 to 2020. Note: (**A**) C-C indicates cropland in both 1990 and 2020; (**B**) R-R indicates rural settlements in both 1990 and 2020; (**C**) C-R indicates cropland in 1990 converted to rural settlements in 2020; (**D**) R-C indicates rural settlements in 1990 converted to cropland in 2020.

The quantitative allocation relationship between cropland and rural settlements is an important indicator reflecting the coordination degree of human–land relationships in rural areas. This study used the settlement-cropland ratio index ($L$) to diagnose quantitative allocation differences between cropland and rural settlements, and classified grids into different coupling types according to thresholds (Table 2). From the statistical results, MCT was the dominant type in the study area during the study period, with proportions between 48.38% and 58.44%, reflecting that the coupling status between cropland and rural settlements in the Huang-Huai-Hai region was generally stable. MCT was mainly distributed in the core areas of the Huang-Huai-Hai Plain (Figure 6), including central-southern Hebei, northwestern Shandong, and eastern Henan traditional agricultural areas. These areas can better meet rural development demands for cropland, with relatively balanced human–land relationships, forming the foundation areas for regional agricultural sustainable development. The CR type, with relatively abundant cropland resources and a small proportion of rural settlements, had a relatively small and stable proportion (approximately 13%), mainly distributed in hilly and gully areas on the periphery of the Huang-Huai-Hai Plain and piedmont plain areas. These types had abundant cropland resources, but some areas experienced increased $L$ values due to urbanization advancement, rural settlement expansion, or cropland loss, gradually weakening cropland resource advantages. The RC type, with relatively scarce cropland and a high proportion of rural settlements, showed the most significant increasing trend during the study period, with grid proportions increasing from 15.51% in 1990 to 21.58% in 2020, an increase of 39.18%. The rapid growth of this type indicates that areas with poor coupling status between cropland and rural settlements and tense human–land relationships in the study area significantly increased, with increasingly prominent cropland resource constraints [10]. This type was mainly distributed around the Beijing–Tianjin–Hebei urban agglomeration and other areas with rapid urbanization advancement, as well as around central towns in some traditional agricultural areas.

**Table 2.** Statistics of grids with different coupling types between cropland and rural settlements in the Huang-Huai-Hai region from 1990 to 2020.

| *L* Index | Type | 1990 | | 2000 | | 2010 | | 2020 | |
|---|---|---|---|---|---|---|---|---|---|
| | | Count | Percentage | Count | Percentage | Count | Percentage | Count | Percentage |
| $L = 0$ | No cropland or rural settlements | 4793 | 21.43% | 4815 | 21.53% | 3357 | 15.01% | 3675 | 16.43% |
| $0 < L \leq 0.04$ | Cropland-Rich Type (CR) | 2999 | 13.41% | 2958 | 13.22% | 2831 | 12.66% | 3044 | 13.61% |
| $0.04 < L \leq 0.28$ | Moderately Coordinated Type (MCT) | 11,107 | 49.66% | 10,908 | 48.77% | 13,071 | 58.44% | 10,821 | 48.38% |
| $L > 0.28$ | Rural Settlement-Dominant Type (RC) | 3469 | 15.51% | 3687 | 16.48% | 3109 | 13.90% | 4828 | 21.58% |

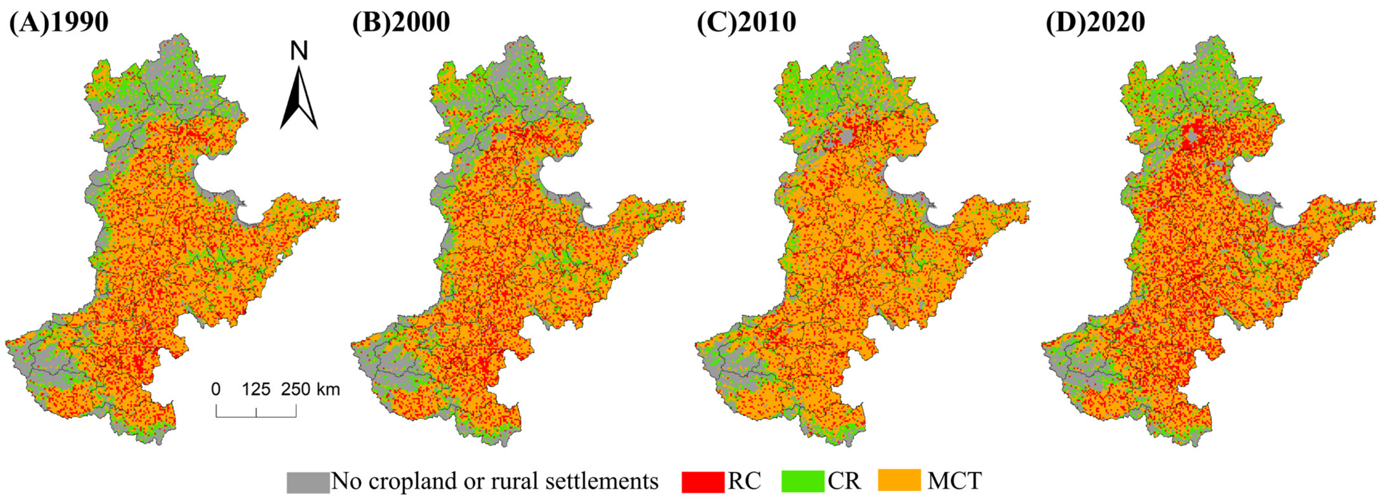


**Figure 6.** Spatial distribution of coupling types between cropland and rural settlements in the Huang-Huai-Hai region from 1990 to 2020. Note: RC: Rural Settlement-Dominant Type; CR: Cropland-Rich Type; MCT: Moderately Coordinated Type.

Overall, changes in the coupling relationship between cropland and rural settlements in the Huang-Huai-Hai region have the following characteristics: (1) Croplands are generally abundant, but regional differences are obvious. The plain core areas are dominated by MCT with relatively balanced human–land relationships; RC is concentrated around towns and urban agglomeration influence areas with prominent human–land conflicts; mountainous and hilly areas are dominated by CR, but with obvious cropland fragmentation. (2) Coupling types have undergone an obvious conversion. The proportion of RC increased from 15.51% in 1990 to 21.58% in 2020, indicating an overall deteriorating trend in the coupling status between cropland and rural settlements. This transformation significantly accelerated during 2010–2020, reflecting the profound impact of urbanization on cropland and rural settlement relationships in the past decade. (3) The evolution of coupling relationships is the result of multiple factors. The natural environment lays the foundation for the spatial pattern of cropland and rural settlements, but inter-annual changes are small with limited direct impact. Socioeconomic factors are the main driving forces. Rapid urbanization advancement has led to large-scale cropland occupation, while rural population reduction has not brought a synchronous reduction in residential land, but rather a new round of expansion due to housing improvement demands [21,25], resulting in dual pressures of cropland reduction and rural settlement increase. Policy factors have duality; systems such as occupation–compensation balance and increase–decrease linkage have alleviated cropland loss to some extent, but prominent problems exist in the quality and spatial misalignment of compensated cropland.

## 4. Discussion

This study demonstrates that the Huang-Huai-Hai region experienced significant cropland loss and rural settlement expansion from 1990 to 2020, with spatial coupling relationships between the two showing obvious spatiotemporal differentiation characteristics. While our findings broadly align with previous research [11], the present study extends existing knowledge by offering a finer grid-scale resolution, a quantitative coupling index, and updated temporal coverage. From the spatial pattern perspective, coupling types between cropland and rural settlements in the Huang-Huai-Hai region show significant "core-periphery" differentiation. The plain core areas are dominated by the Moderately Coordinated Type (MCT), while the Rural Settlement-Dominant Type (RC) is rapidly growing around towns and in mountainous areas. This spatial differentiation reflects the differential patterns of urbanization impacts on cropland changes [23]. The deep mechanism of coordinated changes between cropland and rural settlements in the Huang-Huai-Hai region lies in the "dual transformation" of urban–rural land use. On the one hand, urban expansion has led to continuous cropland loss, with a net cropland reduction of 21,021.94 km$^2$ from 1990 to 2020, mainly flowing to urban and rural residential land. On the other hand, rural population agglomeration toward towns has not brought a corresponding reduction in rural residential land, but rather an expansion of rural residential land due to housing improvement demands [26]. The rapid growth of RC in this study essentially represents the erosion of agricultural production functions by rural residential functions in the process of land resource competition between cropland and rural settlements. The "population decline with land increase" paradox deserves further attention. While the rural population has steadily decreased due to urbanization, rural residential land has continued to expand, driven by rising housing demand, improved living standards, and inadequate mechanisms for homestead withdrawal. This decoupling suggests that population change alone is not a reliable predictor of settlement dynamics, and that policies addressing land withdrawal are as important as those controlling new expansion.

From the food security perspective, as a core area of the national food security strategy, the evolution of human–land relationships in the Huang-Huai-Hai region has national-level impacts. This study found that high-value cropland outflow areas are concentrated around urban agglomerations such as Beijing–Tianjin–Hebei, Shandong Peninsula, and Central Plains, which are precisely the areas with the most concentrated high-quality cropland in northern China. Hong et al. showed that cropland reduction in the Huang-Huai-Hai Plain led to grain production losses, and the non-agricultural occupation and compensation of high-quality irrigated cropland further exacerbated production capacity loss risks [27]. The spatial misalignment of cropland occupation and compensation in this study—coexistence of plain high-quality cropland occupation and hilly low-quality land compensation—may lead to an overall decline in cropland quality, posing long-term challenges to regional agricultural sustainable development.

To address the above issues, differentiated land control strategies should be implemented in the future. For the Cropland-Rich Type (CR), strict enforcement of cropland protection red lines is necessary to prevent conversion of high-quality cropland to rural residential land, while promoting moderate agglomeration of rural residential land to avoid fragmented cutting of cropland by scattered construction. For MCT, coordinated control mechanisms for cropland and rural settlements need to be established, guiding concentrated farmer residence through village planning, controlling disorderly expansion of new homesteads, and preventing transformation to RC. For RC, active promotion of rural construction land consolidation should be pursued, with particular attention to addressing the "hollow village" phenomenon. Compensated exit mechanisms for idle homesteads should be explored, and the consolidation of scattered rural settlements should be promoted to improve land use efficiency and alleviate tense human–land relationships. Meanwhile, infrastructure layout should be optimized to adapt to the trend of population decline in villages.

This study reveals the coordinated change patterns of cropland and rural settlements in the Huang-Huai-Hai region at the grid scale, but certain limitations remain. Specifically, the 5 km $\times$ 5 km grid scale, while appropriate for regional analysis, may not capture fine-grained village-level dynamics such as scattered homestead expansions or hollow village phenomena. Additionally, the Settlement-Cropland Ratio Index does not account for cropland quality or irrigation conditions, which are important for assessing actual agricultural production capacity. We also acknowledge that our land-use data do not distinguish between agricultural workers and commuters living in rural settlements; understanding who lives in these villages would require integrating household survey data. For future research, we suggest introducing spatial econometric models to quantitatively analyze the relative contributions of natural conditions, socioeconomics, and policy institutions. Alternatively, attempts could be made from the perspective of social–ecological system resilience to construct dynamic assessment models, or integrate cropland quality indicators into the coupling assessment framework.

## 5. Conclusions

This study analyzed the spatiotemporal dynamics and coupling relationships between cropland and rural settlements in China's Huang-Huai-Hai region from 1990 to 2020. The main findings are as follows: From 1990 to 2020, the region experienced a net cropland reduction of 21,021.94 km$^2$, with dynamic degrees intensifying from $-0.13\%$ to $-0.28\%$. Construction land was the main outflow destination, with rural settlements and urban construction land accounting for 43.75% and 55.58% of the total outflow, respectively. Cropland distribution showed a "hot centers and cold peripheries, hot south and cold north" pattern (Moran's I = 0.232, $p < 0.001$). The coupling relationship between cropland and rural settlements was dominated by the Moderately Coordinated Type (48.38–58.44%), but the proportion of the Rural Settlement-Dominant Type increased from 15.51% to 21.58%, indicating increasingly tense human–land relationships.

Beyond this specific case, our findings have broader implications for other major grain-producing regions globally. The paradox of "population decline with land increase" reflects a common challenge in many major agricultural regions worldwide, suggesting that land governance must address both expansion control and idle homestead withdrawal. Methodologically, the grid-scale (5 km $\times$ 5 km) coupling analysis and the Settlement-Cropland Ratio Index offer a transferable framework for diagnosing cropland–settlement conflicts in other grain-producing regions. As a core area of national food security, the Huang-Huai-Hai region urgently requires coordinated mechanisms to balance food security and rural revitalization, treating cropland and rural settlements as a coupled system rather than separate land types.

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