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Spatiotemporal impact of cultivated land use transition on grain production: Perspective of interaction between dominant and recessive transitions

Wenhao Niu [a,b,c], Haoyang Wang [b], Lan Luo [d], Yu Shi [e], Yifan Sui [b], Le Wu [b], Bangbang Zhang [b,*], Qiang Yu [a,c,*]

[a] College of Natural Resources and Environment, Northwest A&F University, Yangling 712100, China
[b] College of Economics and Management, Northwest A&F University, Yangling 712100, China
[c] State Key Laboratory of Soil and Water Conservation and Desertification Control, College of Soil and Water Conservation Science and Engineering, Northwest A&F University, Yangling 712100, China
[d] School of Government, Nanjing University, Nanjing 210023, China
[e] Institute of Carbon Neutrality, Sino-French Institute for Earth System Science, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

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ABSTRACT

Clarifying the impact of cultivated land use transition (CLUT) on grain production can provide effective support for formulating land management policies to ensure food security. CLUT means the cultivated land use morphology changes from one to another, including cultivated land use dominant transition (CLDT) and cultivated land use recessive transition (CLRT). However, existing studies have the problem of separating the CLDT and CLRT, resulting in unclear spatiotemporal impact of interaction between them on grain production. In this study, the theoretical frameworks were developed to reveal the coupling interaction between CLDT and CLRT and its impact on grain production. This study further adopted the coupling coordination degree model to quantify the interaction between CLDT and CLRT, and explored the spatiotemporal characteristics of CLDT, CLRT, and coupling coordination degree between CLDT and CLRT (CCD-DR) in China from 2000 to 2020. Additionally, geographically and temporally weighted regression model was adopted to assess the spatiotemporal impact of CCD-DR on grain production. The results reveal that: the cultivated land use recessive morphology improved gradually, while the dominant morphology deteriorated in China from 2000 to 2020. Notably, the significant decline in CLDT was revealed in most provinces in 2005. The synergies between CLDT and CLRT in China have strengthened over the study period, and the eastern region had the stronger synergies than other regions. The development of CLDT lagged behind CLRT, leading to the low synergies between CLDT and CLRT in most provinces. The positive impact of CCD-DR on grain production in China increased from 2000 to 2020. The improvements of the synergies between CLDT and CLRT significantly promoted grain production in most provinces, particularly in western and southern regions, but hindered grain production in northeastern region. This study not only can support policy-making of cultivated land protection to ensure food security, but also can contribute to addressing the previously overlooked correlation between CLDT and CLRT, offering a comprehensive understanding of cultivated land use transition theory.

1. Introduction

At present, the growing global population takes a great challenge to achieving the goal of food security (Sustainable Development Goal 2), implying that more cultivated land may be required (Godfray et al., 2010; Gu et al., 2019; Zhu et al., 2023; Fanzo et al., 2024). However, due to rapid urbanization, frequent disasters, and illegal use, the cultivated land around the world is losing (Pribadi and Pauleit, 2015; Zhou et al., 2023; Zhou et al., 2021). Research indicated that about 2 % of the global best croplands would be disappeared because of urbanization in the future, leading to the serious crop production losses (Bren d'Amour et al., 2017). Therefore, it is urgent to implement effective measures to

* Corresponding authors at: Northwest A&F University, NO.3 Taicheng Road, Yangling, Shaanxi, China.
E-mail addresses: bangbang.zhang@nwafu.edu.cn (B. Zhang), yuq@nwafu.edu.cn (Q. Yu).

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protect and manage cultivated land.

The in-depth investigation of cultivated land use transition (CLUT) can offer valuable insights for protection and management of cultivated land (Long and Qu, 2018; Ma et al., 2020). As the key part of the land use transition, CLUT means the changes in cultivated land use morphology in a certain region over a certain period of time, driven by innovation and socio-economic, including cultivated land use dominant transition (CLDT) and cultivated land use recessive transition (CLRT) (Long and Qu, 2018). The CLDT involves changes in the cultivated land quantity structure and spatial pattern, while CLRT refers to changes in the characteristics of cultivated land quality, property rights, management model, input, output, and function (Long et al., 2020).

Currently, the influence of CLUT on grain production has become the focus issue of CLUT (Tang et al., 2021). Scholars have measured this issue from two main research paths of CLDT and CLRT. On the one hand, many studies have investigated the impact of the changes in cultivated land fragmentation (Looga et al., 2018; Knippenberg et al., 2020), area (Ge et al., 2018), and spatiotemporal pattern (Xu et al., 2017; Chai et al., 2019) on grain production. On the other hand, scholars have analyzed the effects of changes in cultivated land quality (Shi et al., 2013; Du et al., 2024), input factors (Tian et al., 2019; Zheng et al., 2020), management (Neumann et al., 2010), and property rights (Liu et al., 2018; Qiu et al., 2020) on grain production. However, most of these studies only established the linear relationship between CLUT and grain production in the temporal or spatial dimension, without considering the spatiotemporal heterogeneity of relationship between the two.

According to the CLUT theory, CLDT and CLRT are not entirely independent, their interaction has driven the transition in cultivated land utilization (Long, 2022; Long et al., 2020). It is increasingly revealed that there are complex interactions between CLDT and CLRT, for example, the changes in structure and quantity can significantly influence material inputs and management practices of cultivated land (Hiironen and Riekkinen, 2016; Duan et al., 2021; Xiang et al., 2022; Zhang et al., 2024). On the contrary, the changes in property rights and agricultural production cost can significantly promote the transformation of cultivated land use structure and quantity (Lu et al., 2018; Zhang et al., 2023). The study of interaction between CLDT and CLRT can help coordinate the conflict between dominant and recessive morphologies of cultivated land use, thereby contributing to regional sustainable development (Zhang and Li, 2022; Zou et al., 2024). However, there are few studies exploring the interaction between CLDT and CLRT. Additionally, it is necessary to consider the interaction between CLDT and CLRT in assessing the impact of CLUT on grain production, which will help the government formulate a comprehensive land use policy to ensure food security.

China accounts for only 7.8 % of the world's cultivated land but contributes approximately 21 % of global grain production (Lu et al., 2024), which means that promoting the sustainable transition of cultivated land utilization is crucial for feeding a large population in China and achieving global food security goal. In recent years, the regional cultivated land use morphology in China has changed dramatically (Ma et al., 2020; Yang et al., 2023), making China a representative case for CLUT studies. Therefore, using the panel data of 31 provinces, this study examined the spatiotemporal evolution of interaction between CLDT and CLRT and its nonlinear impact on grain production in China from 2000 to 2020. The main contributions of this study are as follows: (1) Based on the CLUT, and human-nature relationship areal system (HNRAS) theories, a new theoretical framework was developed to reveal the interaction between CLDT and CLRT, providing deeper insights into CLUT theory. The coupling coordination degree model was further used to quantify this interaction, making the complex correlation between CLDT and CLRT "white box". (2) By incorporating grain production and interaction between CLDT and CLRT into geographically and temporally weighted regression (GTWR) model, this study revealed the spatiotemporal nonlinear impact of CLUT on grain production, offering valuable guidance for region-specific cultivated land management policies to ensure food security.

2. Theoretical framework

2.1. Interaction between cultivated land use dominant and recessive transitions

HNRAS is a large, open, and complex system, including the natural environment and human society subsystems. Material circulation and energy conversion between these two subsystems constitute a mechanism for the development and change of HNRAS. Specifically, human beings have subjective initiative and can actively recognize, utilize, and transform the natural environment. Besides, natural environment is the spatial carrier and material basis for human survival, constraining the speed, depth, and breadth of human activities (Wu, 1991; Stern, 1993; Liu, 2018). CLUT theory highlights that socio-economic development is often accompanied by changes in cultivated land use morphology, including dominant and recessive morphologies (Ge et al., 2018; Long and Qu, 2018; Long et al., 2020). Dominant morphology mainly represents the natural environment attribute of cultivated land, while recessive morphology mainly reflects the human activities attribute of cultivated land (Liu and Long, 2016). Therefore, according to the HNRAS theory, the regional CLUT can be considered as the process of interaction between CLDT and CLRT (Long, 2022; Zhang and Li, 2022). In this study, a theoretical framework was developed to describe the interaction between CLDT and CLRT (Fig. 1).

On the one hand, during the process of CLDT, the changes in structure and quantity of cultivated land can lead to the transformation of agricultural input, output, and management model. For instance, land fragmentation problem will restrict the application of advanced agricultural machinery, reduce the agricultural production efficiency, and increase agricultural production costs (Wang et al., 2020; Janus et al., 2023). On the contrary, the improvement of land fragmentation will upgrade the agricultural management model, optimize the agricultural input factor structure, and enhance the agricultural productivity (Zhang et al., 2019; Niu et al., 2025). On the other hand, CLRT can provide feedback on CLDT. For instance, adjustment of property rights often leads to the change in spatial pattern of cultivated land (Lu et al., 2018). Increase in agricultural input cost will lead to the abandonment of cultivated land and promote the transformation of cultivated land to

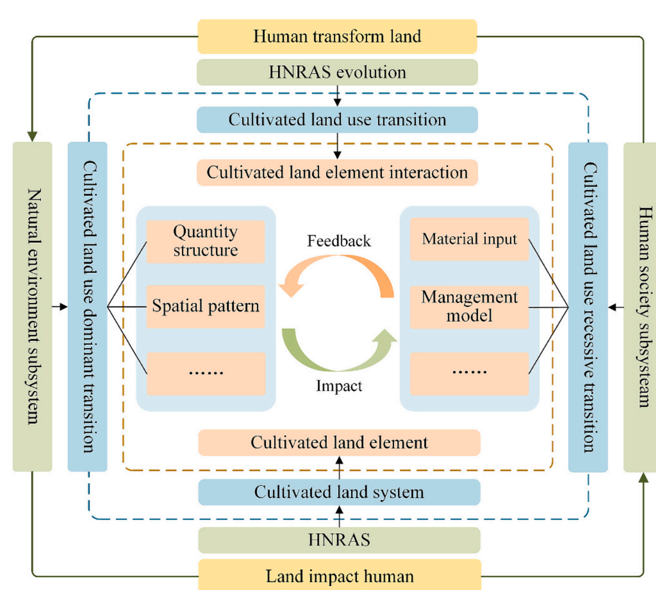

Fig. 1. The theoretical framework of interaction between cultivated land use dominant transition and cultivated land use recessive transition based on the human-nature relationship areal system theories.

other land use types (Zhang et al., 2023). Moreover, improvement of agricultural production technology will push agricultural operators to improve the cultivated land spatial pattern by the implementation of land consolidation and promote the land transfer to form a large operation of cultivated land (Zhang et al., 2019; Niu et al., 2025).

2.2. The impact of interaction between cultivated land use dominant and recessive transitions on grain production

As the key type of the land use cover, cultivated land is an important carrier of grain production (Ge et al., 2018). Grain production is a direct outcome of agricultural operators' land use behavior, which can be regarded as the external performance of the coupled interaction between natural and socio-economic elements within the cultivated land use system (Hampf et al., 2018; Du et al., 2022). Specifically, natural elements mainly correspond to the cultivated land use dominant morphology, laying the physical condition for grain production. Cultivated land characterized by larger area, lower fragmentation, and more regular plot shape tends to support economy of scale in grain production. In contrast, social-economic elements mainly correspond to the cultivated land use recessive morphology, functioning as the driving force behind grain production. Optimized material input and advanced agricultural management model will enhance the grain productivity (Lou et al., 2021; Zang et al., 2024). Cultivated land use dominant and recessive morphologies coexist in the cultivated land use system, influencing each other. Their coordinated development plays a critical role in improving the quality and efficiency of grain production. On the one hand, the high-quality dominant morphology can promote optimization of agricultural input factors and upgrading of agricultural management model, thereby further improving grain productivity. On the other hand, high-quality recessive morphology can maximize the advantages of favorable land attributes, such as larger land size and spatial regularity, further reinforcing economy of scale in grain production. Accordingly, the synergies between CLDT and CLRT not only reflect the operational efficiency of the cultivated land use system but also form a crucial precondition for achieving high-level grain production (Hampf et al., 2018; Du et al., 2022).

Based on the above analysis, a theoretical framework was developed to express the impact of coupling interaction between cultivated land use dominant and recessive transitions on grain production (Fig. 2). In this framework, four types of coupling states are identified, according to the performance of CLDT and CLRT. Type I: low-CLDT and low-CLRT (Low coupling coordination degree). In this scenario, CLDT and CLRT are coupled but both exhibit low performance. Cultivated land is characterized by small area, high fragmentation, and irregular shape which obstruct the realization of economies of scale in grain production. Besides, unreasonable agricultural input structure and outdated agricultural management model restrict improvement of grain productivity. The mutual constraint between low-CLDT and low-CLRT results in low-level grain production (Liu et al., 2022; Hao, 2023; Ye et al., 2024). Type II: high-CLDT and low-CLRT (Moderate coupling coordination degree). In this case, CLDT and CLRT are not coupled, and the performance of CLDT is higher than that of CLRT. Although the high-CLDT contributes to the acquisition of economy of scale in grain production, the lack of supportive management practices and inefficient input under low-CLRT constrains grain productivity. As a result, only moderate-level economy of scale and low-level grain productivity are attained, leading to moderate-level grain production. Type III: low-CLDT and high-CLRT (Moderate coupling coordination degree). In this type, CLDT and CLRT are not coupled, and the performance degree of CLDT is lower than that of CLRT. Similar to type II, optimized input structures and advanced management models under high-CLRT improve grain productivity, yet low-CLDT limit the obtaining of economies of scale in grain production. Consequently, the low-level economy of scale and moderate-level grain productivity result in the moderate-level grain production. Type IV: high-CLDT and high-CLRT (High coupling coordination degree). Here, CLDT and CLRT are coupled, both of which are at a high degree of performance. The high-CLDT realizes the acquisition

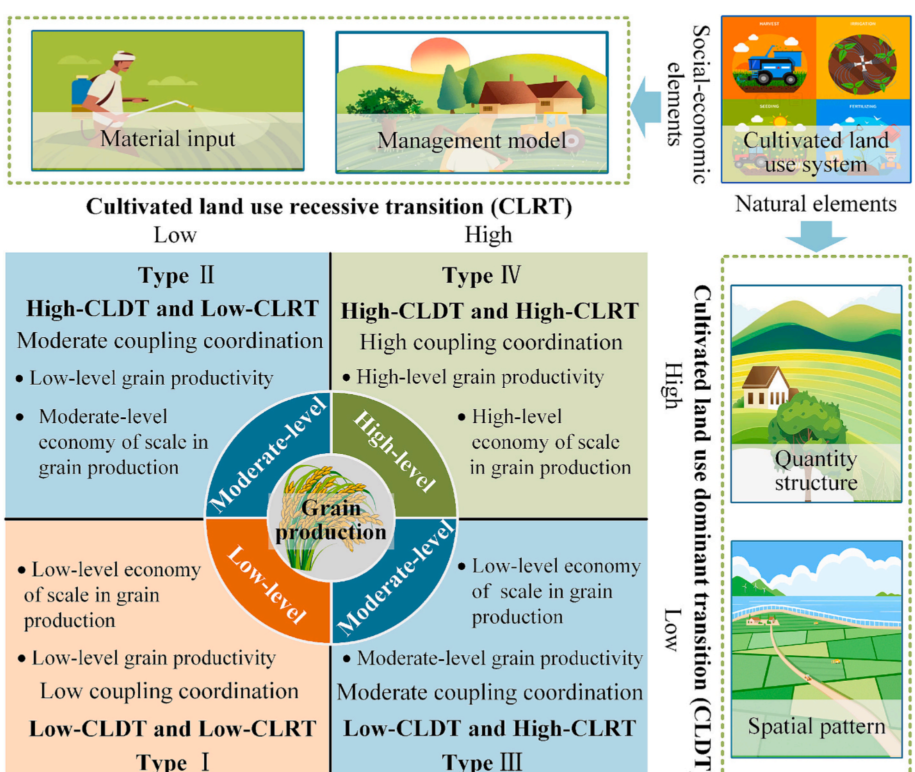

Fig. 2. The theoretical framework of the impact of coupling interaction between cultivated land use dominant transition (CLDT) and cultivated land use recessive transition (CLRT) on grain production.

of high-level economy of scale in grain production, while the high-CLRT realizes the acquisition of high-level grain productivity. Their synergistic interaction significantly enhances cultivated land use system efficiency, resulting in high-level grain production (Zhang et al., 2019; Niu et al., 2025).

As posited in the theoretical framework (Fig. 2), the coupling coordination degree between CLDT and CLRT (CCD-DR) is positively related to grain production. Notably, this linear positive relationship may not hold across all types shown in Fig. 2. In type I and II, excessive agricultural inputs—chemical fertilizers, pesticides, and plastic film—tend to depress CLRT, thereby lowering the coupling coordination degree between CLDT and CLRT. Even so, such overapplication can raise yields in the short run, and it produces a transitory negative association between CCD-DR and grain production: lower CCD-DR coincides with temporarily higher yields. However, this pattern is unsustainable. Prolonged input overuse degrades soil and ultimately reduces yields (Wu et al., 2018; Wang et al., 2025a), prompting managers to adjust practices and optimize input structures. As CLRT recovers, the negative association reverses and CCD-DR again promotes grain production.

3. Methods and data

3.1. Data sources

The study data is the panel data of 31 provinces in China for the period 2000–2020, including socio-economic statistic and land use data. The socio-economic statistic data was sourced from *China Statistical Yearbook* (2001–2021) (https://data.cnki.net/yearBook/single?id=N2006010338), *China Rural Statistical Yearbook* (2001–2021) (https://data.cnki.net/yearBook/single?id=N2006042767), and the Statistical Yearbook of 31 Provinces (2001–2021) (https://data.cnki.net/yearBook?type=type&code=A). Missing data was supplemented using nearest-neighbor interpolation. The land use data (for the years 2000, 2005, 2010, 2015, and 2020) was obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/) at 30 m resolution.

3.2. Methods

3.2.1. Measurement for indexes of CLDT and CLRT

The indexes of CLDT and CLRT were calculated by entropy weight method in four steps as follows.

Step 1: Based on previous studies (Liu and Long, 2016; Long and Qu, 2018; Ge et al., 2018; Long et al., 2020; Chen et al., 2023; Zhao et al., 2024) and considering data availability, 11 indicators were chosen in the indicator system to describe CLDT and CLRT (Table 1).

Step 2: The indicators were standardized to common measurable units using the following equation.

$$y_{ij} = \left(x_{ij} - x_{j\min}\right) \Big/ \left(x_{j\max} - x_{j\min}\right) \tag{1}$$

$$y_{ij} = \left(x_{j\max} - x_{ij}\right) \Big/ \left(x_{j\max} - x_{j\min}\right) \tag{2}$$

Where x_{ij} represents indicator j of province i. y_{ij} represents the standardized value of indicator j of province i. Eq. (1) and Eq. (2) denote the standardization for positive and negative indicators, respectively.

Step 3: The weight of indicator j was obtained by the following equations.

$$P_{ij} = y_{ij} \Big/ \sum_{i=1}^{n} y_{ij} \tag{3}$$

$$E_j = -(\ln n)^{-1} \sum_{i=1}^{n} P_{ij} \ln P_{ij} \tag{4}$$

Table 1
Indicator system of cultivated land use dominant and recessive transitions.

	Indicators	Unit	Computational formula	Attribute	Weight
CLDT	Cultivated land area per capita	ha/ 10^4people	Cultivated land area / total population	+	0.201
	Land reclamation ratio	%	(Cultivated land area / total land area) × 100 %	+	0.128
	Patch density	number per 100 ha	Number of cultivated land patches / total landscape area	−	0.038
	Edge density	km/km^2	Total cultivated land edge length / total landscape area	−	0.083
	Mean patch area	ha	Total cultivated land patch area / number of cultivated land patches	+	0.440
	Percent of landscape	%	(Total cultivated land patch area / total landscape area) × 100 %	+	0.110
CLRT	Fertilizer input	t/ha	Total chemical fertilizers consumption / cultivated land area	−	0.117
	Pesticide input	t/ha	Total pesticide consumption / cultivated land area	−	0.084
	Agricultural plastic film input	t/ha	Total agricultural plastic film consumption / cultivated land area	−	0.047
	Agricultural machinery input	kw/ha	Total agricultural machinery power / cultivated land area	+	0.352
	Percent of irrigated area	%	(Irrigated cultivated land area / cultivated land area) × 100 %	+	0.400

$$H_j = 1 - E_j \tag{5}$$

$$W_j = H_j \Big/ \sum_{i=1}^{n} H_j \tag{6}$$

Where P_{ij} represents the specific gravity value of y_{ij}. E_j represents the information entropy of indicator j, If $P_{ij} = 0$, then defined $\ln P_{ij} = 0$. H_j is the difference coefficient of indicator j. W_j is the weight of indicator j.

Step 4: The CLDT and CLRT indexes were calculated using Eq. (7).

$$R_i = \sum_{j=1}^{n} y_{ij} W_j \tag{7}$$

Where R_i represents the CLDT or CLRT index for province i. The range of R_i is [0,1]. Here, the CLDT and CLRT indexes were denoted as R_{Di} and R_{Ri}, respectively.

3.2.2. Coupling coordination degree model

Coupling means the phenomenon in which two or more different systems affect each other through interaction (Bryan et al., 2018; Ge et al., 2023). The coupling degree calculated by coupling model can represent correlation degree among systems. However, the coupling model cannot describe the development level of different systems. The coupling coordination degree model overcomes the disadvantages of the coupling model, and indicates the coordination ability of the interaction among different systems (Cheng et al., 2023). Currently, the coupling coordination degree model has been widely adopted in different fields, such as sustainable poverty reduction (Ge et al., 2023; Li et al., 2023), land use transition (Zhang and Li, 2022; Qu et al., 2024), and ecological environment (Chen and Shi, 2022; Cheng et al., 2023). The coupling coordination degree model is formulated by the following equations:

$$C_i = 2\sqrt{\frac{R_{Di} \times R_{Ri}}{(R_{Di} + R_{Ri})^2}} \tag{8}$$

$$T_i = \alpha R_{Di} + \beta R_{Ri} \tag{9}$$

$$CCD_i = \sqrt{C_i \times T_i} \tag{10}$$

Where $C_i \in [0,1]$ denotes the coupling degree, reflecting the interaction between the CLDT and CLRT systems of province i. $T_i \in [0,1]$ denotes the comprehensive evaluation index of the two systems. α and β represent the contribution of CLDT and CLRT systems to the comprehensive system, respectively, and $\alpha + \beta = 1$. Here, this study set $\alpha = \beta = 0.5$, meaning that CLDT and CLRT systems contribute equally to the comprehensive system. CCD_i is the coupling coordination degree of two systems of province i. According to the relevant studies (Cheng et al., 2023; Qu et al., 2024), the coupling coordination degree is classified into 10 types as shown in Table 2.

3.2.3. Geographically and temporally weighted regression (GTWR)

Compared to the traditional multiple linear regression model, GTWR extends the time dimension on the basis of geographically weighted regression (GWR), considering the nonstationary features of space and time (Huang et al., 2010; Wu et al., 2014; Wang et al., 2022; Han et al., 2023). This study applied GTWR model to analyze the spatiotemporal impact of CCD-DR on grain production. The GTWR model is constructed as follows:

$$y_i = \beta_0(u_i, v_i, t_i) + \sum_{k=1}^{m} \beta_k(u_i, v_i, t_i) X_{ik} + \varepsilon_i \tag{11}$$

Where X_{ik} represents the k-th independent variable of sample i; y_i represents the dependent variable of sample i; (u_i, v_i, t_i) denotes the spatiotemporal coordinates of sample i; $\beta_0(u_i, v_i, t_i)$ is the intercepts at coordinate point (u_i, v_i, t_i); $\beta_k(u_i, v_i, t_i)$ represents the local spatiotemporal regression parameter of the k-th independent variable at coordinate point (u_i, v_i, t_i); ε_i represents the random error term of sample i.

The spatiotemporal weight matrix in this study is determined by gaussian function as follows:

$$W_{ij}^{ST} = \exp\left[-\left(d_{ij}^{ST} / b_{ST} \right)^2 \right] \tag{12}$$

$$d_{ij}^{ST} = \sqrt{\lambda\left[(u_i - u_j)^2 + (v_i - v_j)^2 \right] + \delta (t_i - t_j)^2} \tag{13}$$

Table 2
Type of coupling coordination degree classification.

Coupling coordination degree	Type of coupling coordination degree	Code
$0 < D \leq 0.10$	Extreme imbalance	EI
$0.10 < D \leq 0.20$	Serious imbalance	SI
$0.20 < D \leq 0.30$	Moderate imbalance	MOI
$0.30 < D \leq 0.40$	Mild imbalance	MII
$0.40 < D \leq 0.50$	Almost imbalance	AI
$0.50 < D \leq 0.60$	Almost coordination	AC
$0.60 < D \leq 0.70$	Primary coordination	PRC
$0.70 < D \leq 0.80$	Intermediate coordination	IC
$0.80 < D \leq 0.90$	Good coordination	GC
$0.90 < D \leq 1.00$	Perfect coordination	PEC

Where W_{ij}^{ST} denotes the spatiotemporal matrix; d_{ij}^{ST} denotes the spatiotemporal distance between sample i a nd j; b_{ST} represents the bandwidth. λ and δ represent scale factors.

This study takes grain yield as the dependent variable, and CCD-DR as core independent variable. Furthermore, economic structure, rural residents' income, and employment in primary industry are introduced to the GTWR model as the control variables. The detailed information of each variable is shown in Table 3.

4. Results

4.1. Spatiotemporal evolution of CLDT and CLRT

This study calculated the CLDT and CLRT indexes for 31 provinces from 2000 to 2020, as shown in Fig. 3. The CLDT witnessed a downward trend in 16 provinces, especially in Tianjin, Shanghai, and Jiangsu. During the rapid urbanization process, the expansion of construction land in these provinces led to serious cultivated land loss and fragmentation. In contrast, other provinces such as Heilongjiang, Jilin, and Xinjiang, exhibited an upward trend, suggesting that cultivated land protection efforts in these regions have been effective. Furthermore, traditional agricultural provinces like Henan, Shandong, Heilongjiang, and Jiangsu often had high CLDT values due to their larger cultivated land areas. Notably, CLDT experienced a significant decline in most provinces in 2005, followed by a gradual increase thereafter. This trend may be driven by reforms to China's cultivated land protection policies, particularly the upgrading of requisition-compensation balance policy.

Compared to CLDT, CLRT showed an upward trend from 2000 to 2020 on a national scale, with 29 provinces following this trend, except for Xinjiang and Tianjin. This indicates that China's input of cultivated land production factors has gradually been optimized over the past 21 years. Notably, the CLRT in Xinjiang and Tianjin decreased during this period, likely due to extensive agricultural production inputs. The regions with high CLRT value were predominantly located in economically developed provinces such as Shandong, Zhejiang, Beijing, Tianjin, and Hebei. These provinces have relatively advanced agricultural production technology.

Additionally, this study further compared the relative performance of CLDT and CLRT, revealing significant differences between the two at the provincial scale. The development of CLDT in most provinces lagged behind that of CLRT, indicating that these provinces should focus on improving CLDT in the future. In contrast, provinces such as Heilongjiang, Liaoning, and Jilin may need to pay more attention to the improvement of CLRT.

4.2. Spatiotemporal pattern of CCD-DR

Using the coupling coordination degree model, this study calculated the CCD-DR to quantify the interaction between CLDT and CLRT. High value depicts synergies, while low value depicts trade-offs between CLDT and CLRT. The Fig. 4 shows that spatiotemporal pattern of CCD-

Table 3
Descriptive statistics of variables.

Variable	Unit	Computational formula	Mean	SD
Grain yield	t/ha	Grain yield per unit area	5.402	1.037
CCD-DR	–	Calculate by the coupling coordination degree model	0.582	0.092
Economic structure	%	Gross domestic product of the primary industry / gross domestic product	12.576	6.975
Rural residents' income	10^3yuan	Disposable income of rural residents per capita	8.435	6.681
Employment in primary industry	%	Number of employed persons in the primary industry / Number of employed persons	38.345	16.382

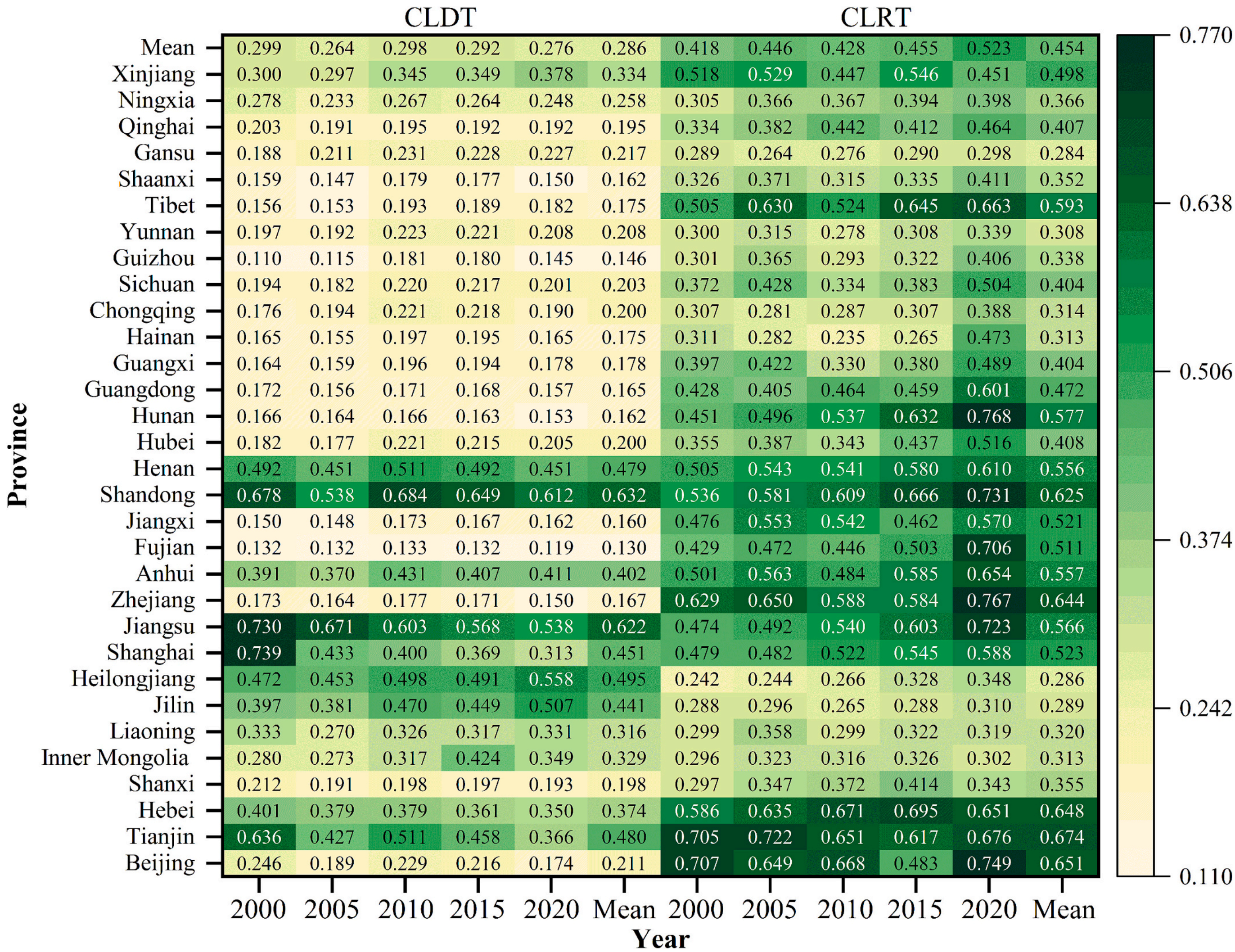

Fig. 3. Spatiotemporal evolution of indexes of cultivated land use dominant transition (CLDT) and cultivated land use recessive transition (CLRT) from 2000 to 2020.

DR in China over the period 2000–2020, revealing substantial spatiotemporal variability in CCD-DR across provinces.

In terms of temporal trends, overall, the CCD-DR generally increased from 0.574 to 0.598 at the national scale from 2000 to 2020, indicating that synergies between CLDT and CLRT in China have strengthened. Specifically, most provinces exhibited an increasing trend in CCD-DR over time. However, in four provinces—Beijing, Tianjin, Hebei, and Shanghai—the CCD-DR decreased by approximately 7 %, 13 %, 1 %, and 15 %, respectively, over the same period. These provinces also experienced a rapid decline in CLDT.

In terms of spatial distribution, in general, high CCD-DR (mean > 0.7) were concentrated in the eastern region, including Henan, Shandong, Tianjin, Hebei, and Jiangsu, with the strong synergies between CLDT and CLRT. In contrast, low CCD-DR (mean < 0.5) was mostly located in the central, southern, and western regions, including Gansu, Shaanxi, Chongqing, Guizhou, and Hainan, with the strong trade-offs between CLDT and CLRT.

After analyzing the spatiotemporal distribution of CCD-DR, this study divided the provinces into different types based on the rule in Table 2, and traced the changes in CCD-DR types for 31 provinces in China from 2000 to 2020 (Fig. 5). Overall, five CCD-DR types were identified across China, with the AC type being the most prevalent. Twelve provinces consistently maintained the AC type over the past 21 years. Additionally, CCD-DR types changed in 12 of the 31 provinces over the period 2000–2020. Specifically, three provinces (Beijing, Tianjin, and Shanghai) experienced a degradation, while nine provinces experienced an upgrade in CCD-DR types, indicating progress toward achieving synergies development between CLDT and CLRT in China.

To understand the relative lagging aspects that hinder synergistic development, this study compared the performance on CLDT and CLRT of each province and distinguished them into two types: CLDT lag (CLDT < CLRT) and CLRT lag (CLDT > CLRT) types (Fig. 6). Overall, 26 out of 31 provinces were classified as CLDT lag types, meaning that the development of CLDT lagged behind CLRT, hindering synergistic development between CLDT and CLRT in these regions. CLRT lag type was located in Shandong, Jiangsu, Inner Mongolia, Jilin, and Heilongjiang, with the lower CLRT. These findings suggest that appropriate policies need to be formulated for different provinces, considering their performance difference between CLDT and CLRT. Notably, all provinces with low CCD-DR values belonged to the CLDT lag type, indicating that a strong dominant morphology may be a prerequisite for synergistic development between CLDT and CLRT.

4.3. Spatiotemporal impact of CCD-DR on grain production based on the GTWR

In this study, the GTWR was used to reveal the spatiotemporal nonlinear impact of CCD-DR on grain production in China from 2000 to 2020. Before GTWR, the multicollinearity of each variable was tested. The variance inflation factor (VIF) of all variables was less than 10,

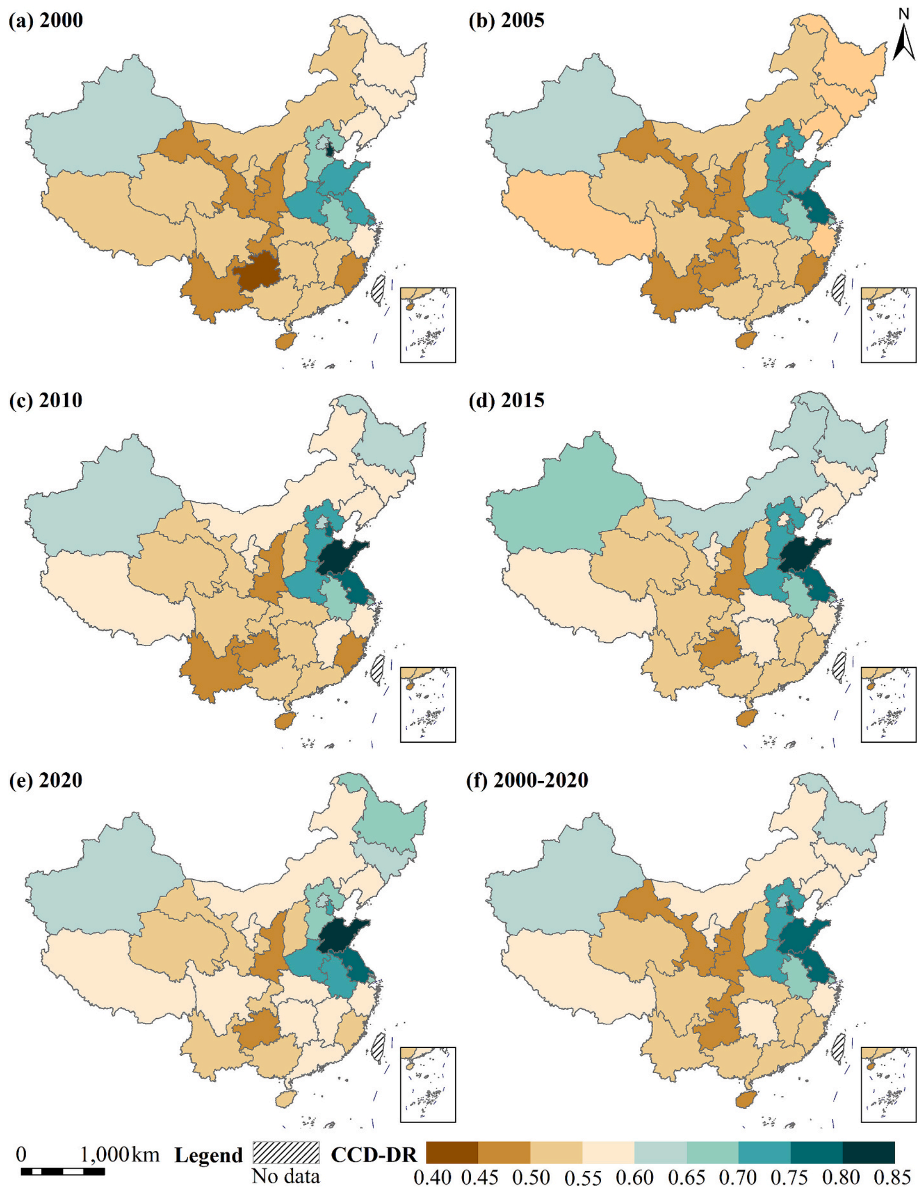

Fig. 4. Spatiotemporal pattern of coupling coordination degree between cultivated land use dominant and recessive transitions (CCD-DR) from 2000 to 2020.

indicating that there was no significant multicollinearity in the model. Additionally, the relevant parameters of ordinary least squares (OLS) regression, GWR, temporally weighted regression (TWR), and GTWR were compared in Table 4. The results suggested that the GTWR generally has the better model fit, compared with other models.

This study further calculated the regression coefficients of each variable on grain production, and summarized the basic information in Table 5. The minimum and maximum coefficients of CCD-DR were −17.279 and 22.382, respectively, meaning the significant variability in the impact of CCD-DR on grain production. The mean coefficient of CCD-DR was 4.290, suggesting that the CCD-DR has positive impact on the grain production.

As displayed in Fig. 7, this study analyzed the spatiotemporal distribution of the regression coefficient of CCD-DR on grain production from 2000 to 2020. In terms of temporal trends, overall, the regression coefficient of CCD-DR on grain production in China has increased positively by 54.61 % over time. In other words, the positive impact of CCD-DR on grain production has strengthened during the research period. Specifically, six provinces—Jiangxi, Hubei, Sichuan, Yunnan, Shaanxi, and Xinjiang—experienced the most significant increases in coefficients, exceeding 150 %. In contrast, Shanghai, Hainan, Gansu, Qinghai has decreased by 2.58 %, 54.54 %, 15.74 %, and 1.25 % in coefficients, respectively, indicating that the relationship between CCD-DR and grain production was decoupling in these provinces.

In terms of spatial distribution, at the provincial scale (Fig. 7f), this study revealed significant spatiotemporal variability in the impact of CCD-DR on grain production across provinces, with regression coefficients ranging from −6.807 to 21.269 from 2000 to 2020. Generally, high regression coefficients were concentrated in western region, namely, the CCD-DR in this region had more significant impact on grain production. In contrast, low regression coefficients were located in eastern region, indicating that grain production in this region was less responsive to changes in CCD-DR. Notably, three provinces in northeastern region including Heilongjiang, Liaoning, and Jilin had negative regression coefficients of CCD-DR on grain production, implying that higher CCD-DR values were associated with lower production in this region. These provinces had the lower CLRT level, which may be related to these results.

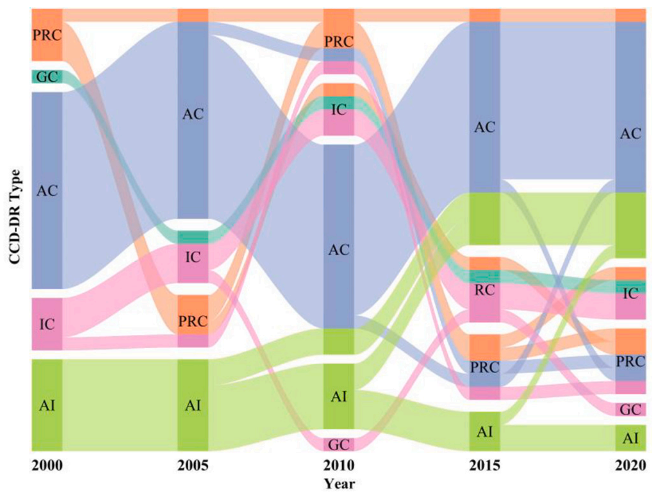

Fig. 5. Change in type of coupling coordination degree between cultivated land use dominant and recessive transitions (CCD-DR) in China from 2000 to 2020. (AI, AC, PRC, IC, and GC refer to the types of almost imbalance, almost coordination, primary coordination, intermediate coordination, and good coordination, respectively.)

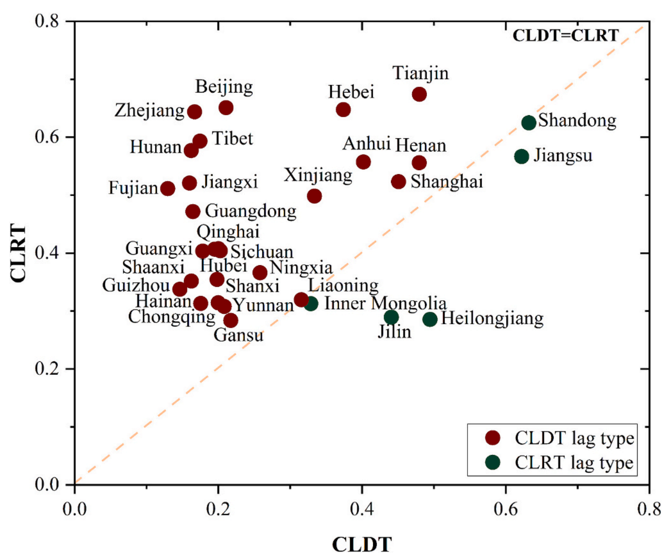

Fig. 6. Lag type of coupling coordination degree between cultivated land use dominant and recessive transitions (CCD-DR) of China's provinces from 2000 to 2020. (CLDT and CLRT refer to cultivated land use dominant transition and cultivated land use recessive transition, respectively.)

Table 4
Statistical results of different models performance metrics.

Parameters	OLS	GWR	TWR	GTWR
R^2	0.473	0.861	0.496	0.892
Adjust R^2	–	0.857	0.482	0.889
Bandwidth	–	0.115	0.618	0.117
AICc	360.929	249.959	362.541	262.836

5. Discussion

5.1. The reason of the changes in cultivated land use transition in China

During the past few decades, the cultivated land use morphology has experienced the rapid changes in China (Ge et al., 2018; Ma et al., 2020). This research revealed the spatiotemporal evolution characteristics of CLUT in China by constructing a systematic indicator system. Our study found that China has faced the serious deterioration of cultivated land use dominant morphology in the past 21 years. Notably, most provinces in China experienced a significant decrease in CLDT index from 2000 to 2005. During this period, rapid population growth and accelerating urbanization sharply increased the demand for construction land, driving substantial occupation of cultivated land. (Ma et al., 2020; Li et al., 2024). Although the implementation of cultivated land requisition-compensation balance policy helped to curb these losses (Liu et al., 2023). Design defects and weak enforcement led to widespread practices of "occupying superior cropland and compensating inferior one" and "occupying integrated cropland and compensating fragmented one", thereby intensifying cultivated land fragmentation (Zhou et al., 2022; Wang et al., 2025b). As a result, the CLDT index declined.

Table 5
Regression coefficient of each variable on grain production.

Variables	Minimum	Maximum	Mean	SD
CCD-DR	−17.279	22.382	4.290	6.327
Economic structure	−0.153	0.189	0.018	0.062
Rural residents' income	−0.067	0.257	0.064	0.055
Employment in primary industry	−0.114	0.095	−0.011	0.036

After 2005, CLDT in most provinces that experienced a decline began to increase. The study by Ge et al. (2018) supported our results. In 2005, the Chinese government issued the "*Notice on Carrying out the Basic Work of Supplementing the Quantity and Quality of Cultivated Land by Grade Conversion*", mandating quality-based classification of cultivated land. Subsequently, a series of technical specifications on quality acceptance and grade classification were promulgated, further strengthening the cultivated land requisition-compensation balance policy. In 2006, China set a binding red line of 1.8 billion mu of cultivated land (≈120 million ha) and established a national land-inspection system. In 2008, the concept of permanent basic farmland was introduced, and 1.55 billion mu (≈103 million ha) were later designated nationwide. Additionally, a series of cultivated-land consolidation projects—especially high-standard farmland construction—were implemented to improve cultivated land use dominant morphology (Hao et al., 2024; Liu and Zhang, 2024). Overall, the maturation of the cultivated land protection policy system has reversed much of the downward trend in the CLDT index across most provinces.

This study also found that CLRT displayed an overall upward trend from 2000 to 2020, a finding consistent with Ma et al. (2020). During this period, the implementation of cultivated land consolidation projects has improved the agricultural infrastructure, and also provided the favorable conditions for the improvement of mechanization level and optimization of agricultural element inputs. Official statistical data indicated that total agricultural machinery power in China rose from 5257.4 × 10^5kw in 2000 to 10,562.2 × 10^5kw in 2020. Moreover, the Chinese government introduced the "*Regional Formulas and Fertilization Recommendations for the Three Major Grain Crops—Wheat, Maize, and Rice*" in 2013, and launched "*Double Reduction Action of Chemical Fertilizer and Pesticide*" in 2015, which successfully controlled the abuse of chemical pesticides and fertilizers. Between 2015 and 2020, the consumption of chemical fertilizers, pesticides, and plastic films declined by 12.82 %, 26.36 %, and 8.25 %, respectively. As a result, CLRT indexes increased significantly across most provinces during this period.

Due to the differences in resource endowment, topography, and economic development level, the China's CLDT and CLRT exhibited significant spatial heterogeneity. The traditional agricultural provinces with extensive cultivated land operation scales and relatively flat terrain, such as Henan, Shandong, Heilongjiang, and Jiangsu, tended to have higher CLDT indexes. However, the performance of CLRT in northeastern provinces remains relatively low, primarily due to excessive reliance on chemical inputs and insufficient adoption of sustainable

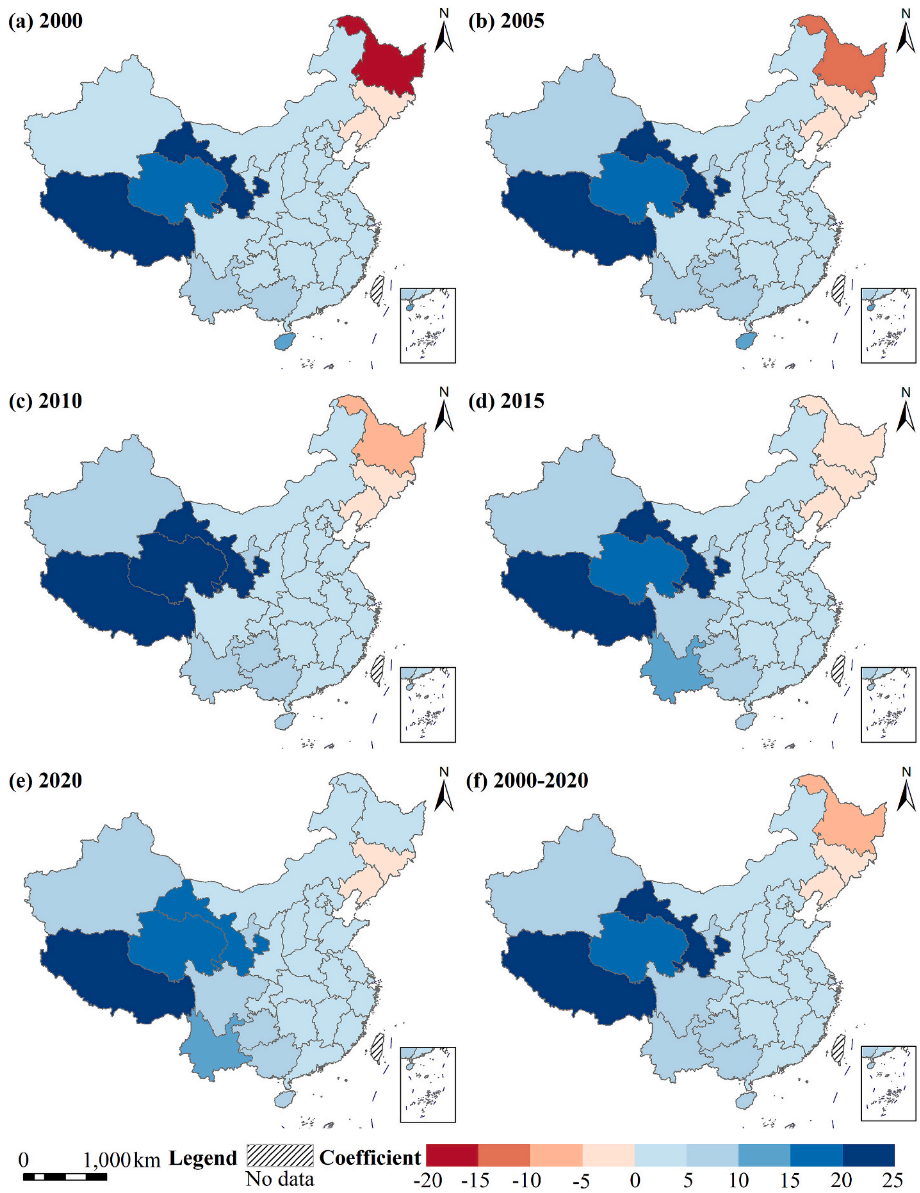

Fig. 7. Spatiotemporal distribution of regression coefficient of coupling coordination degree between cultivated land use dominant and recessive transitions (CCD-DR) on grain production from 2000 to 2020.

agricultural practices. The provinces located in the eastern coastal area, such as Beijing, Zhejiang, and Shanghai, are among the most developed provinces in China with rapid technological progress and high economic development level. Over the past few decades, these provinces have experienced accelerated urbanization, resulting in substantial conversion of cultivated land into construction land. This process has not only led to a significant reduction in the overall area of arable land but also exacerbated the problem of land fragmentation, thereby leading to the lower CLDT levels. On the contrary, these developed provinces recorded the high CLRT values, largely due to their adoption of advanced agricultural technologies, which have enabled the optimization of input structures and promoted greener agricultural practices (Chai et al., 2025). Furthermore, the prevalence of land fragmentation caused by complex terrain contributed to lower CLDT values in many central, western, and southern provinces, such as Gansu, Yunnan, and Shanxi. Low CLRT levels in these regions are closely linked to the population loss, smallholder ageing, and outdated agricultural production technology.

5.2. Spatiotemporal variability in CCD-DR and its impact on grain production

Improvements in CLDT or CLRT cannot guarantee that the regional cultivated land utilization toward sustainable development. Realizing the coordinated development between CLDT and CLRT is crucial for cultivated land protection and food security. This study revealed that the coupling coordination relationships between CLDT and CLRT exhibited significant spatial heterogeneity. Over the period 2000–2020, the synergies between CLDT and CLRT improved in most provinces, primarily driven by the enhancement of cultivated land use recessive morphology. Conversely, in provinces such as Beijing, Tianjin, Hebei, and Shanghai, a sharp deterioration in dominant morphology contributed to a decline in the CCD-DR. Except for the eastern provinces, strong trade-offs between CLDT and CLRT were observed in the majority of provinces. In many southern and southeastern provinces, low levels of dominant morphology constrained the CCD-DR. In contrast, most central and western provinces experienced low CCD-DR values due to the combined effects of both underperforming dominant and recessive morphologies.

Furthermore, this study employed GTWR model to assess the spatiotemporal impact of CCD-DR on grain production from 2000 to 2020. Overall, the positive impact of CCD-DR on grain production in China has witnessed a significant increase from 2000 to 2020, suggesting that the coupling coordination between CLDT and CLRT has played an increasingly essential role in grain production. However, the progress of improving coupling coordination between CLDT and CLRT is slow because of various problems, such as the pressure of urbanization development. Hence, more effective policies for optimizing the interaction between CLDT and CLRT should be proposed by the government to increase food production in China.

Our study found that the impact of CCD-DR on grain production exhibited significant spatial heterogeneity in China. Compared to the eastern provinces, the positive impact of CCD-DR on grain production was more significant in most western and southern provinces. This suggests that the impact of synergies between CLDT and CLRT on grain production followed a law of diminishing marginal returns. In eastern provinces, the relatively high level of CCD-DR was associated with a limited marginal effect on grain production, suggesting that the potential for further gains from improved coordination has been largely exhausted. The underperformance of both CLDT and CLRT in western and southern provinces reflected a weak coupling relationship, highlighting significant potential for coordination improvement. Therefore, implementing targeted strategies for enhancing the cultivated land use dominant or recessive morphology can effectively improve the CCD-DR in these provinces and gain the high returns on grain production.

Notably, the CCD-DR in Heilongjiang, Jilin, and Liaoning has negative impacts on grain production, showing the obvious trade-offs between CCD-DR and grain production in northeastern region. These trade-offs illustrated the substantial reliance of grain production in the region on chemical fertilizers, pesticides, and agricultural plastic film. According to official statistics, in 2020, the average consumption of chemical fertilizers, pesticides, and plastic films in Heilongjiang, Jilin, and Liaoning reached 195.7×10^4 t, 5.08×10^4 t, and 7.87×10^4 t, respectively, significantly exceeding the national average level. The overapplication of agricultural chemicals lowered the regional CLRT index and CCD-DR, yet boosted yields in the short term, thereby generating a negative relationship between CCD-DR and grain production. Over the long term, however, sustained excessive input of agricultural chemicals degrades soil conditions and poses serious risks to the sustainable use of cultivated land and to food security. Therefore, the green transition of agricultural production should be promoted in this region, gradually reducing the dependence of grain production on fertilizers, pesticides, and agricultural plastic film.

5.3. *Policy recommendations toward promoting the coordinated development between cultivated land use dominant and recessive transitions in China*

Our study for coupling coordination relationships between CLDT and CLRT exhibit significant spatial heterogeneity, and in most provinces, show trade-offs between CLDT and CLRT aspects. Therefore, targeted management strategies will need to be imposed by region considering coupling coordination development between CLDT and CLRT to ultimately succeed in mitigating trade-offs and realizing the sustainable utilization of cultivated land.

For the developed eastern coastal provinces, the CLDT level—reduced by rapid urbanization—limited the potential for CCD-DR enhancement. Therefore, it is recommended that these provinces should implement the stricter approval policies for cultivated land occupation. In particular, the integration degree of cultivated land should be taken as an important standard for cultivated land requisition-compensation balance policy, ensuring that any newly compensated land is of comparable or superior quality and spatial configuration. Additionally, urban planning should adopt a more land-saving and compact development approach to minimize unnecessary agricultural land loss. Strengthening land use monitoring systems and linking land approval with environmental and food security performance assessments can also serve as effective deterrents to excessive land occupation.

The provinces in northeastern region have historically exhibited high CLDT performance, yet CLRT levels have persisted at relatively low values. Accordingly, a transition toward green and resource-efficient agricultural practices is essential. Policies should promote the adaptation of green production technologies such as soil testing and formula-based fertilization, straw return to fields, biomass-based pesticides, and organic soil conditioners, which can gradually reduce chemical dependency. Furthermore, the establishment of pilot zones for ecological farming, combined with incentives for environmentally friendly practices, could accelerate the shift toward more sustainable land use patterns in the northeast.

Most provinces located in central, western, and southern regions have the bad performance of CLDT and CLRT. On the one hand, these provinces should prioritize high-standard farmland construction initiatives, such as land leveling, irrigation infrastructure development, and field road improvement. Meanwhile, promoting cultivated land transfer markets and property rights clarification can help consolidate fragmented plots, facilitating the formation of moderate-scale farming operations. On the other hand, positive talent introduction policies should be implemented, such as “return-to-village” incentives for young professionals, vocational training for new farmers, and rural entrepreneurship support programs. Enhancing the level of agricultural mechanization can partially offset the labor shortage while improving production efficiency, thus the promotion of agricultural machinery subsidy policies and improvement of socialized service system also need to be emphasized in these provinces. Additionally, regional cooperation and technological support from developed regions can be boosted to promote updates in agricultural technology.

5.4. *Limitations and prospects*

Despite the insights gained in the spatiotemporal impact of CCD-DR on grain production in China from 2000 to 2020, this study still has limitations. One limitation relates to the selection of indicators used to measure CLDT and CLRT. Based on previous research, we selected the reasonable indicators to measure the performance of CLDT and CLRT. We acknowledge that other indicators, which were not considered in this study due to the data restriction, could also be critical for CLUT. However, this limitation is not sufficient to alter the key results in this study, as the unaccepted indicators are often closely related to those already considered. Moreover, due to the limitations in the availability of high-resolution land use data, it was not feasible to extend the study period to 2023. However, a comparative analysis between the 2020 dataset and the updated 2023 statistical data revealed no significant differences. Therefore, the temporal lag in the study data is unlikely to have a substantial impact on the robustness of our conclusions. Finally, predicting the change trends of CCD-DR still has a broad space for discussion, which is a meaningful research direction in the future, and also can provide the better advice on the land resources management for decision-making.

6. Conclusion

Analyzing the spatiotemporal impact of CLUT on grain production is crucial for formulating cultivated land management policies to ensure food security. In this study, the theoretical frameworks were developed to reveal the interaction between CLDT and CLRT and its impact on grain production. This study further adopted the CCD model to quantify the interaction between CLDT and CLRT, and explored the spatiotemporal characteristics of CLDT, CLRT, and CCD-DR in China from 2000 to 2020. Additionally, GTWR model was employed to investigate the spatiotemporal nonlinear impact of CCD-DR on grain production. The key findings of this study are as follows:

(1) The cultivated land use recessive morphology improved gradually, while the dominant morphology deteriorated in China from 2000 to 2020. Specifically, 16 out of 31 provinces experienced a decrease in CLDT, and 29 out of 31 provinces saw an increase in CLRT, except for Xinjiang and Tianjin. Notably, the significant decline in CLDT was revealed in most provinces in 2005.
(2) The synergies between CLDT and CLRT in China have strengthened over the study period. However, in some provinces including Beijing, Tianjin, Hebei, and Shanghai, these synergies have decreased over time. Compared to the other regions, the eastern region had the stronger synergies between CLDT and CLRT. Moreover, three provinces experienced a degradation in CCD-DR types, while 9 provinces saw an improvement from 2000 to 2020. Additionally, the development of CLDT lagged behind CLRT, leading to the low synergies between CLDT and CLRT in most provinces.
(3) The positive impact of interaction between CLDT and CLRT on grain production in China increased from 2000 to 2020. The impact of CCD-DR on grain production exhibited significant spatial heterogeneity, specifically, the improvements of the synergies between CLDT and CLRT significantly promoted grain production in most provinces, particularly in western and southern regions, but hindered grain production in northeastern region.

CRediT authorship contribution statement

Wenhao Niu: Data curation, Investigation, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Haoyang Wang:** Writing – original draft, Writing – review & editing. **Lan Luo:** Writing – original draft, Writing – review & editing. **Yu Shi:** Writing – original draft. **Yifan Sui:** Data curation, Writing – original draft. **Le Wu:** Data curation, Writing – original draft. **Bangbang Zhang:** Conceptualization, Resources, Supervision, Project administration, Funding acquisition, Writing – review & editing. **Qiang Yu:** Conceptualization, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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