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Coupling Coordination and Dynamic Evolution Analysis of Subsystems of Land Space Utilization Efficiency in China

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Abstract: Land space serves as the carrier for human survival and development, fulfilling functions such as urban development, agricultural production, and ecological regulation. However, urbanization intensifies conflicts in land use, making it imperative to study the efficiency of land space utilization and the coupling coordination of its subsystems from a sustainable perspective to optimize land layout and development. Based on the classification standards of urban, agricultural, and ecological spaces, this paper quantitatively analyzes the coupling coordination degree (CCD) of the three systems of China's land space utilization efficiency (LSUE) from 2010 to 2021. Through the LISA time path and spatiotemporal transitions, the study explores the evolutionary trends and spatial dynamics of CCD. The findings reveal that the spatial pattern of CCD exhibits strong stability and significant spatial cohesion. This research aims to provide planning and theoretical support for the sustainable utilization of territorial space in developing countries from the perspective of coupling coordination.

1. Introduction

According to World Bank statistics, with annual economic growth, approximately 14,000 square kilometers of land are converted to urban areas globally each year. Rapid urbanization and industrialization have encroached upon farmland, grasslands, and forests, leading to environmental degradation and climate crises[1]. Among the UN's 17 Sustainable Development Goals (SDGs) for 2030, Goals 11 (Sustainable Cities and Communities), 12 (Responsible Production and Consumption), and 15 (Life on Land) aim to achieve balanced progress in economic growth, social order, and environmental protection[2]. As a complex of natural elements, land space provides the foundation and resource support for economic and social development[3,4]. Therefore, optimizing urban living, agricultural production, and ecological conservation through strategic land planning and management is a crucial pathway to achieving sustainable development goals.

Resource efficiency serves as a key indicator to evaluate whether a region should increase output under current conditions, functioning as an effective tool for measuring spatial utilization levels.

Most scholarly studies on LSUE have focused on single land use types such as urban construction land[5,6] , industrial land[7,8] , and agricultural land[9,10] . LSUE comprises three subsystems: Urban Space Utilization Efficiency (USUE), Agricultural Space Utilization Efficiency (ASUE), and Ecological Space Utilization Efficiency(ESUE)[11,12] . The coordination among these subsystems is essential for achieving sustainable development. The primary model employed is the Coupled Coordination Model (CCDM), which has been widely used to study two-dimensional efficiency between economic-ecological and economic-agricultural systems[13,14] . However, it lacks comprehensive consideration of interactions among multiple efficiency categories and their overall impact on land spatial allocation. Additionally, traditional ccdms suffer from issues like concentrated C values and results dependent on T values, making it difficult to accurately reflect measured values. Wang Shujia's modified CCDM addresses the validity issue of C values, providing a more authentic representation of regional system coordination.

In conclusion, this paper takes 30 provinces of China as the research object, constructs the evaluation index system of USUE, ASUE, and ESUE, explains the spatiotemporal characteristics of the coordination relationship of the three systems at the provincial level from 2010 to 2021, as well as the static and dynamic change paths of LISA, aiming to improve the level of land management and utilization.

2. Overview of the study area

China is located in eastern Asia, on the western coast of the Pacific Ocean, with vast territory, complex climate, and terrain distributed in a stepped manner from east to west. Based on previous scholars' research, China is divided into three regions: eastern, central, and western[15] (as shown in Fig.1).

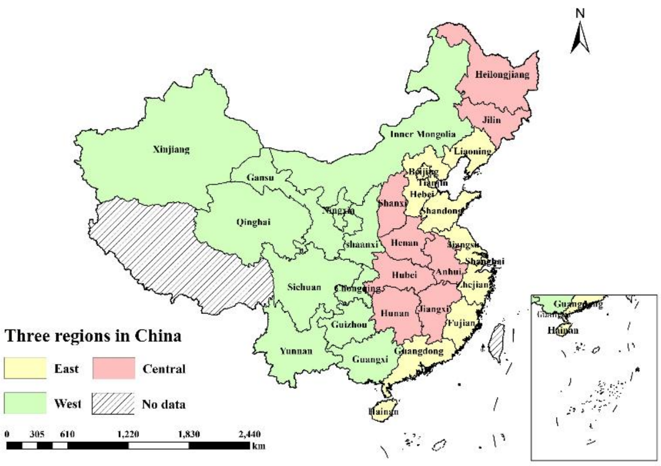

Fig.1 Location and administrative divisions of the study area.

Note: This map is drawn based on the standard map service website of the Ministry of Natural Resources with the map review number GS(2020)4619. The boundaries of the base map have not been modified.

3. Research Methods

3.1. Super-SBM Model

The SBM model, building upon the traditional DEA framework, incorporates undesirable outputs to address input-output variable slack, thereby enhancing efficiency assessment accuracy. Tone further integrates the concept of super-efficiency into the SBM model, creating the Super-SBM model that allows efficiency values exceeding 1, significantly improving evaluation outcomes. The specific formula is detailed in the research by Xu scholar[16] .

Referring to existing research and combining the actual conditions and data availability of 30 provinces in China, a regional LSUE evaluation index system consisting of 3 systems and 23 indicators was constructed(Table 1)[17,18] .

Table 1 LSUE Evaluation Index System.

LSUE	Primary indicator	Secondary indicator	Primary indicator	Secondary indicator
USUE	Input	Urban construction land area	Expected output	Added value of secondary and tertiary industries
		Number of people employed in the tertiary industry		Per capita disposable income of urban residents
		Urban population	Unwanted output	Carbon dioxide emissions
		gross fixed asset formation		PM2.5
ASUE	Input	Crop sown area	Expected output	Primary industry added value
		Number of agricultural workers		Per capita disposable income of rural residents
		Agricultural fertilizer application		grain yield
		farm machinery production	Unwanted output	Agricultural carbon emissions
ESUE	Input	Afforestation area	Expected output	Forestry output
		Employment in water resources, environment and public facilities management		Net Primary Productivity (NPP)
		Energy conservation and environmental protection expenditure		Green coverage rate of built-up areas
		Energy consumption per unit of GDP		

3.2. Improved Coupled Coordination Degree Model (CCDM)

The CCDM is employed to quantify the interdependence and constraints among three land use efficiency systems. Conventional CCDM models suffer from excessive concentration of C values at high levels and oversimplified structures. To address these limitations, this study adopts the revised CCDM model proposed by Scholar Wang [19].

$$C=\sqrt{1-\frac{\sqrt{(f_3-f_1)^2}+\sqrt{(f_2-f_1)^2}+\sqrt{(f_3-f_2)^2}}{3}\times\sqrt{\frac{f_1}{f_3}\times\frac{f_2}{f_3}}} \tag{1}$$

$$T=\alpha_1 f_1+\alpha_2 f_2+\alpha_3 f_3 \tag{2}$$

$$CCD=\sqrt{C\times T} \tag{3}$$

In Eq: C is the degree of coupling between USUE, ASUE, and ESUE, and T is the coordination index, and CCD indicates the coupling coordination degree of the three. Following standardization, f_1, f_2 and $f_3$represents the three subsystems' respective stages of development, assuming maxf_i is f_3. Referring to the research of previous scholars, the same weight is given to α, that is, α_1=α_2=α_3=1/3.

Based on Yang research, we classify CCDS into five grades[20]: highly coupled and coordinated (0.8<CCD≤1.0), moderately coupled and coordinated (0.6<CCD≤0.8), basically coupled and coordinated (0.4<CCD<0.6), moderately unbalanced (0.2<CCD<0.4), and severely unbalanced (0.0<CCD<0.2).

3.3. Exploratory Spatio-temporal Data Analysis (ESTDA)

ESTDA is crucial for exploring spatiotemporal variation models of research subjects, primarily consisting of two components: LISA temporal paths and LISA spatiotemporal transitions, which are used to analyze CCD spatiotemporal evolution patterns.

LISA Time Path: By revealing the dynamic migration of local Moran's I, the LISA time path reflects the stability of LISA coordinates over time, thereby characterizing the spatiotemporal differences and interactions in the local space of CCD. The geometric features of the LISA time path include its relative length, curvature, and movement direction, with corresponding calculation formulas as follows:

$$\text{Relative length: } l_i = \frac{N \times \sum_{t=1}^{T-1} d(L_{i,t}, L_{i,t+1})}{\sum_{i=1}^{N} \sum_{t=1}^{T-1} d(L_{i,t}, L_{i,t+1})} \tag{4}$$

$$\text{Curvature: } \varphi_i = \frac{\sum_{t=1}^{T-1} d(L_{i,t}, L_{i,t+1})}{d(L_{i,1}, L_{i,T})} \tag{5}$$

$$\text{Movement direction: } \theta_i = \arctan \frac{\sum_j \sin\theta_j}{\sum_j \cos\theta_j} \tag{6}$$

Where T is the study time interval; N is the number of units in the study case area; $L_{i,t}$ denotes t coordinate position (normalized value, spatial lag) of the study cell i in Moran's I scatter plot for year t ;$d\left(L_{i,t},L_{i,t+1}\right)$ denotes the distance traveled by provincial unit i has moved from the year t to the year t+1; θ_i denotes the average direction of movement of the provincial research unit i during the study period.

LISA spatio-temporal transition: Rey developed a spatiotemporal transition theory and transition probability matrix by integrating LISA temporal paths and distance attributes into traditional Markov chains. This framework reveals local spatial relationships and transition patterns in CCDs within the study area, which are categorized into four types (Table 2).

Based on the calculated spatial jump type situation, spatiotemporal flow (SF) and spatiotemporal coalescence (SC) are used to further account for the spatial stability of CCD in the study area, and m denotes the total number of all the provincial cells in the study area that may be subject to leap, which is expressed as follows:

$$SF = \frac{Type2 + Type3}{m} \tag{7}$$

$$SC = \frac{Typel + Type4a}{m} \tag{8}$$

Table 2 Main categories of space-time jumps.

Type	Transition form	Symbolic representation
Type 1	Self-stabilization, neighbor-stabilization	$HH_t \rightarrow HH_{t+1}, HL_t \rightarrow HL_{t+1}, LL_t \rightarrow LL_{t+1}, LH_t \rightarrow LH_{t+1}$
Type 2	Self-leaping, neighbor-stabilization	$HH_t \rightarrow LH_{t+1}, HL_t \rightarrow LL_{t+1}, LL_t \rightarrow HL_{t+1}, LH_t \rightarrow HH_{t+1}$
Type 3	Self-stabilization, neighbor-leaping	$HH_t \rightarrow HL_{t+1}, HL_t \rightarrow HH_{t+1}, LL_t \rightarrow LH_{t+1}, LH_t \rightarrow LL_{t+1}$
Type 4	Type 4a: Self and neighbor isotropic leaps	$Type4a = HH_t \rightarrow LL_{t+1}, LL_t \rightarrow HH_{t+1}$
	Type 4b: Self and neighbor reverse leaps	$Type4b = HL_t \rightarrow LH_{t+1}, LH_t \rightarrow HL_{t+1}$

4. Data Source

The research sample consists of 30 provinces in China. The data for USUE, ASUE, and ESUE indicators are primarily sourced from the "China Statistical Yearbook", "China Population and Employment Statistical Yearbook", "China Environmental Statistical Yearbook", and provincial statistical yearbooks; PM2.5 data comes from Washington University; and net primary productivity (NPP) data is from Modis data products.

5. Results

5.1. Analysis of LSUE

The LSUE subsystems in the study area and its three major regions (east, central, and west) demonstrate an overall upward fluctuation trend. Systems U, A, and E exhibit distinct spatial development patterns, with System A showing the lowest development level. Regionally, the eastern region consistently maintains the highest efficiency values, supported by abundant funding, technological resources, strong innovation capabilities, and advanced management expertise. The central region initially led the way but later saw rapid development in the western region, achieving a remarkable turnaround(Fig.2).

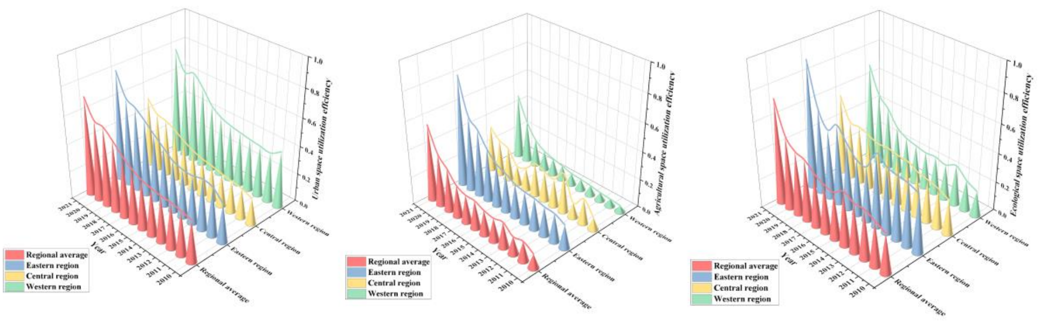

Fig.2 2011-2021 Level of development of subsystems U, A, and E in the subregion.

5.2. Space-time distribution of CCD

As shown in Fig.3, In terms of space, the CCD of China's LSUE subsystems shows a certain spatial distribution pattern, with the CCD evolving from a "localized patchy-sporadic-localized patchy" distribution from 2010 to 2021. In 2010, the CCD of the subsystem of LSUE in each province had small differences, demonstrating a spatial arrangement of medium-low surrounding-high, i.e., the CCD in the central region was lower than that in the eastern and western regions. The gap between the CCDs of the various provinces was further narrowed in 2014-2018, and the coupling and coordination level of the southeastern coastal provinces was in the leading position. By 2021, the level of coordinated development of LSUE among provinces gradually widen. China's capital Beijing, economic center Shanghai, coastal provinces Guangdong and Fujian, with good location advantages and rich related resources, have high urban-agricultural-ecological space utilization efficiency, with CCD higher than 0.8, and are in a highly coordinated development stage. Next are the provinces along the YREB and the northeastern provinces that have reached a basic level of coordination, and lastly, the central provinces of Hebei, Henan, and Shanxi, and the northwestern provinces of Gansu, Xinjiang, and Inner Mongolia have a lower value of coupled coordination. In general, the coordination level of national LSUE is better in the southern provinces than in the northern provinces, better in the southeast coastal provinces than in the inland provinces, and the coupling coordination level is roughly decreasing from southeast to northwest.

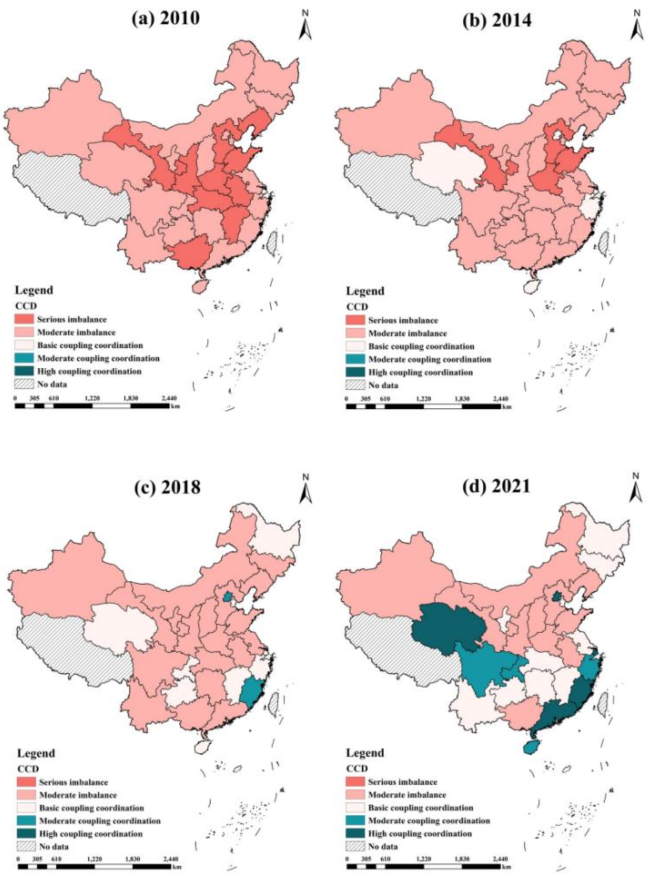

Fig.3 Spatial distribution of CCD in 2010, 2014, 2018 and 2021.

Note: This map is drawn based on the standard map service website of the Ministry of Natural Resources with the map review number GS(2020)4619. The boundaries of the base map have not been modified.

5.3. Characterization of spatiotemporal transitions in CCD

5.3.1. Geographical description of LISA time trajectory

Using Geoda to calculate CCD spatial aggregation characteristics, and combining the ArcGIS natural break method, the relative lengths and curvature of LISA time paths were classified into four levels: low, relatively low, high, and very high (Fig.4).

Relative length serves as an indicator of CCD's dynamic spatial structure. During the study period, 17 provinces (56.66%) exhibited low or relatively low relative lengths, with most maintaining stable CCD spatial patterns. The average relative length was 1. where 43.33% of provinces had lengths exceeding 1. High relative lengths were concentrated in Shanghai, Guangdong, Beijing, Tianjin, and Qinghai. The spatial distribution showed a "low in central regions, high in western areas" pattern, supported by national strategies like the Western Development Initiative and the Beijing-Tianjin-Hebei coordinated development, which bolstered CCD enhancement.

The curvature index reflects the degree of local spatial dependence in CCDs. A curvature index greater than 1 indicates significant spatial dependence. With all provinces showing values above 1, suggesting that CCDs are influenced by neighboring spatial factors and exhibit fluctuating dependency directions. Approximately 87% of provinces have low or relatively low curvature, while high or moderately high curvature is concentrated in Beijing, Tianjin, Hebei, and Henan. This concentration may be attributed to Beijing and Tianjin's economic prosperity and industrial vitality, which radiate and drive surrounding regions through enhanced population, technology, and capital flows. Hebei and Henan provinces, being significantly impacted, demonstrate pronounced spatial interactions, reflecting the effective implementation of the Beijing-Tianjin-Hebei integration strategy.

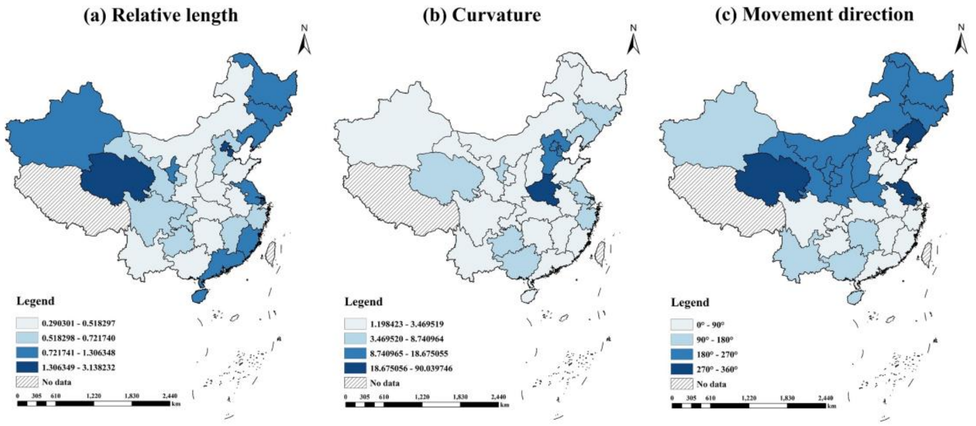

Fig.4 The LISA time trajectory characteristics for CCD from 2010 to 2021 are distributed spatially.

Note: This map is drawn based on the standard map service website of the Ministry of Natural Resources with the map review number GS(2020)4619. The boundaries of the base map have not been modified.

Migration patterns reflect the integration of local spatial patterns in ccds. Analysis shows that from 2010 to 2021, 21 provinces (70%) exhibited coordinated growth, demonstrating stronger spatial synergy than competitive growth. High-coordinated growth clusters concentrated in the Yangtze River Economic Belt and eastern coastal regions, while low-coordinated growth was concentrated in parts of central and northwestern China, all showing contiguous distribution patterns with strong spatial integration. Therefore, central and western regions need to accelerate economic development, optimize input-output structures, promote inter-provincial cooperation, and achieve a transition from low to high coordination levels.

5.3.2. LISA Spatiotemporal Transition Matrix

From 2010 to 2021, CCD exhibited Type1, Type2 and Type3 transitions, with no Type4 occurrences. Among them, the diagonal values are much larger than the non-diagonal ones, and Type1 is the main form, indicating that the local spatial correlation pattern of the CCD is stable, with a spatio-temporal condensation probability of 86.06%. The probability of Type2 is greater than that of Type3. In Type2, the transition probability from HL_t to HH_{t+1} is the highest, at 11.54%, while the rest is approximately 10%. In Type3, the transition probability from LH_t to HH_{t+1} is the highest, at 15.22%. Overall, only a single system (itself or its neighborhood) undergoes transformation without double transitions. The spatial distribution of CCDS has strong cohesion and is difficult to change in the short term(Table 3).

Table 3 Spatio-temporal jumps and probability matrices for CCDs.

t/t+1	HH	LH	LL	HL	Type	Percentage	SF	SC
HH	0.86867	0.0404	0	0.0909	Type1	0.8606	0.1394	0.8606
LH	0.1522	0.7391	0.1087	0	Type2	0.0515		
LL	0	0.0561	0.9252	0.0187	Type3	0.0879		
HL	0.1154	0	0.0513	0.8333	Type4	0		

6. Conclusion

Based on data from 2010 to 2021, this study uses an improved CCDM model to analyze the coupling coordination of USUE-ASUE-ESUE in 30 provinces of China, combined with LISA time paths and spatiotemporal transitions, and draws the following conclusions:

(1) Three systems' efficiency evolution: The urban (U) system leads initially, while the ecological (E) system gains prominence due to green and low-carbon concepts. The agricultural (A) system remains relatively underdeveloped but shows rapid growth in later stages. Regionally, the eastern region leads, with the central and western regions alternating in prominence.

(2) CCD coordination characteristics: The development levels and speeds of the three systems are mismatched. Although CCD has improved, most provinces have not reached the ideal state.

(3) CCD spatial dynamics: CCD exhibits strong spatial dependence and high coordination. The spatiotemporal transition matrix reveals robust spatial cohesion with stable short-term patterns.

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