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Coordination analysis and evaluation of population, water resources, economy, and ecosystem coupling in the Tuha region of China

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The non-coordination between the socio-economic systems and ecosystems of a region is a crucial obstacle to sustainable development. To reveal the relationships between complex urban systems and achieve the goal of sustainable and coordinated urban development, we constructed a coupling coordination degree model (CCDM) and coupling angle model (CAM) and analyzed the degree of coupling coordination and evolution process among the population, water resources, economy, and ecology (PWEE) system of the Tuha region for 2005–2020. The results indicated that: (1) During 2005–2020, the comprehensive development index (CDI) of the population, water resources and economy subsystems was 0.21–0.65, with the three subsystems portraying an overall increase; the average values of the RSEI at five-year intervals were 0.29, 0.28, 0.28, and 0.26, indicating a downward trend in the environmental quality. (2) The coupling coordination effect of the PWEE system portrayed a low level; the coupling coordination degree (CCD) values were 0.28–0.58, portraying a fluctuating upward trend. The level of CCD increased from low disorder to marginal coordination. (3) The PWEE system's scissor difference reflects large evolutionary characteristics. The ecological support capacity was not observed until the late stage. We conclude that the PWEE composite system of the region is in a stage of disordered development. These findings significantly bolster the theoretical underpinnings of sustainable development studies, offering essential scientific theories and methodological frameworks for crafting sustainable development policies tailored to urban systems in the Tuha region.

Keywords Coupling coordination degree model (CCDM), Population-water resources-economy-and ecosystem (PWEE systems), Remote sensing ecological index (RSEI), Google earth engine (GEE), Sustainable management

Cities' growth depends on specific ecological environments and natural resources. The carrying capacity of these resources is restricted, which consequently restrains the growth of the cities. The need to achieve ecological and environmental protection with urban growth has received considerable attention^{1,2}.

The concept of coupling originates from capacity coupling in physics³; in recent years, there have been theoretical and empirical studies on coupled coordination mechanisms^{4–7}; the majority of these studies focus on large-scale regions, such as river basins, urban agglomerations, or multiple cities^{8–10}, and rarely involve a single city or small-scale area. Moreover, these studies primarily integrate economic, social, and ecological systems^{11–14}, with less emphasis on specific resource challenges like water scarcity. Our study, although based on previous research, considers the characteristics of the shortage of water resources in the region¹⁵, significance of water resources in human survival and growth^{16–18}, wholeness and comprehensiveness of the system coordination requirements; furthermore, our study separates the 'water resources' system from the 'ecological environment'

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system, highlights the importance of this demarcation, and analyses the complex system of population, water resources, economy, and ecosystem (hereinafter referred to as the PWEE system) for the Tuha area.

Previous studies that employed multi-system coupling coordination typically built assessment index systems based on statistical data to thoroughly assess the development and evolution of different subsystems^{19–21}. In this research, we used the remote sensing ecological index (RSEI) to accurately and intuitively understand the status of ecological environment quality. This approach, proposed by Hanqiu²², is based on remote-sensing technology. It has a high application value and can be used for flexible monitoring, rapid ecological environment evaluation, and accurate visualization. Additionally, Google Earth Engine (GEE), which uses Google's powerful computing power to process and analyze a large amount of global-scale geoscientific information available online and visualize the data, can be used to respond to a multitude of environmental and socioeconomic issues²³. In recent years, extensive environmental monitoring studies based on the GEE have been conducted extensively, owing to the GEE's powerful arithmetic and cloud data-storage capacity^{24,25}. Based on the GEE, we used Landsat data for 2005–2020 to calculate the RSEI of the region, to characterize the ecological quality and analyze its changes.

The region of Turpan and Hami cities (referred to as 'Tuha') is located in the eastern part of China's Xinjiang Uygur Autonomous Region; the region has abundant mineral resources (including coal and oil) and can support large-scale industrial development, fruit agriculture, and tourism. Notably, the region is a key location in the Silk Road Economic Belt and a major hub for Chinese transportation. The world has seen rapid industrialization and urbanization within the last 40 years. However, the extremely limited water resources in Tuha have led to serious groundwater overexploitation, and several ecological and environmental issues have been caused by both natural and man-made factors^{26,27}. Note that Tuha is an essential base for the coordinated development of China's northwest region. The non-coordination in the population, water resources, economy, and ecological environment of the region poses a significant challenge to the region's sustainable development²⁸. Studying the characteristics of coupled and coordinated changes and dynamic coupling features of urban systems in the Tuha region of China is conducive to clarifying the direction of sustainable urban development, proposing strategic policies, and providing strong support for achieving regional development goals.

However, it has been found that current indicator systems constructed by many scholars are often weakly connected with the characteristics of the study area. In contrast, the research objective of this study is to address the current issues of uncoordinated social development in the complex urban system within the Tuha area, which is a typical representative of arid zones in Northwestern China. This study aims to focus more on the area's unique characteristics, building upon a better understanding of the current state of urban development and the ecological environment in the study area. The novelty of this paper lies in establishing the water resources system as a separate subsystem, with significant effort devoted to adjusting the structure of the indicator system to better reflect the ecological and environmental conditions, particularly the severe water scarcity, which represents the greatest developmental obstacle in the study area. Additionally, most relevant studies tend to evaluate the comprehensive development status of subsystems using a single statistical method. Another novelty of this study lies in the application of remote sensing technology to evaluate ecological subsystems that are more suitable for remote sensing expression. However, there are relatively few studies that combine both methods.

This study integrated the statistical and remote-sensing image data of the region, constructed a PWEE system, analyzed the integrated development status of each subsystem, applied a coupling coordination degree (CCD) model (to assess the characteristics of the regional PWEE system), and constructed a model of the angle of coupling (to discuss the dynamic coupling of the trends in the changes of the PWEE system process) (Fig. 1).

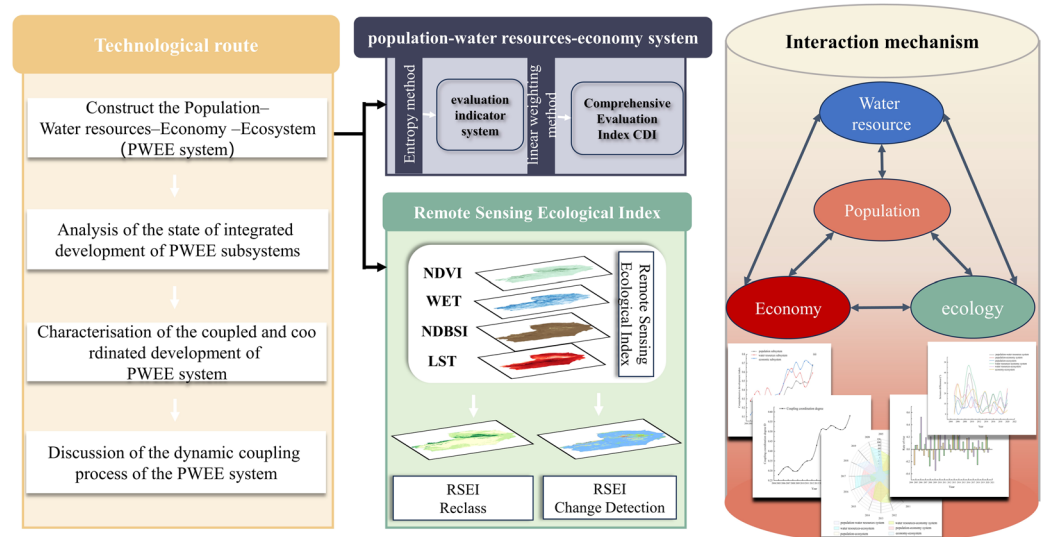


Figure 1. Illustration of the study framework. Abbreviations: the normalized difference vegetation index (NDVI), tassle-based moisture component (WET), normalized difference bare soil index (NDBSI), land surface temperature (LST), remote sensing ecological index (RSEI).

Notably, our study provides a theoretical framework to achieve ecological environmental protection and superior economic and social development in the Tuha region.

Materials and methods

Study area

Tuha is the collective name for the Turpan and Hami cities (latitude $41^{\circ}18'–43^{\circ}43'$ N, and longitude $86^{\circ}40'–96^{\circ}04'$ E) (Fig. 2); the region covers an area of about 220,000 km². Tuha is situated in the Eurasian continent's interior; the geomorphological features in the area are high in the central region and low in the northern and southern regions; its center is considered to be the main vein of the Tianshan Mountains, extending in northwest and southeast directions. The region has a temperate continental arid climate, with scanty precipitation (an average of 47.5 mm per year) and high evaporation (annual evaporation of 2712.6 mm), and an average of 3056.4 h of sunshine annually. Under these topographical and climatic conditions, the industry, agriculture, and tourism sectors in the region are all still developing, albeit at a rapid pace, and the ecological risks and water-resource constraints are becoming increasingly evident.

Data sources and pre-processing

In this work, we considered the Tuha region in China as the study area to construct an evaluation index system; the data sources included the Xinjiang, Hami, and Turpan statistical yearbooks and the Hami City National Economic and Social Development Statistical Bulletin. Due to the confidentiality of the regional data, the population data of Hami City was derived from the LandScan population dataset (<https://landscan.ornl.gov>) for 2000–2022. The sum of the raster values for the townships and villages in the region was used to derive the annual population; the missing values were filled in using the data processing technique of linear interpolation. To evaluate the Tuha region's ecological environment quality, we used the Landsat-5, -7, and -8 images for April–September of study period (after de-cloud processing), which were generated in the GEE cloud platform (according to the scope of the study area). The Joint Research Centre (JRC) Yearly Water Classification History data product was used for water-body masking to exclude the impact of water bodies on the load distribution of the moisture principal component. Subsequently, principal component analysis (PCA) was utilized to calculate the RSEI.

Methods

Entropy method

By calculating the weights of all the indicators based on their degree of variability, the entropy approach can be used as an objective weighting technique that can successfully prevent the errors caused by the use of subjective variables^{29,30}.

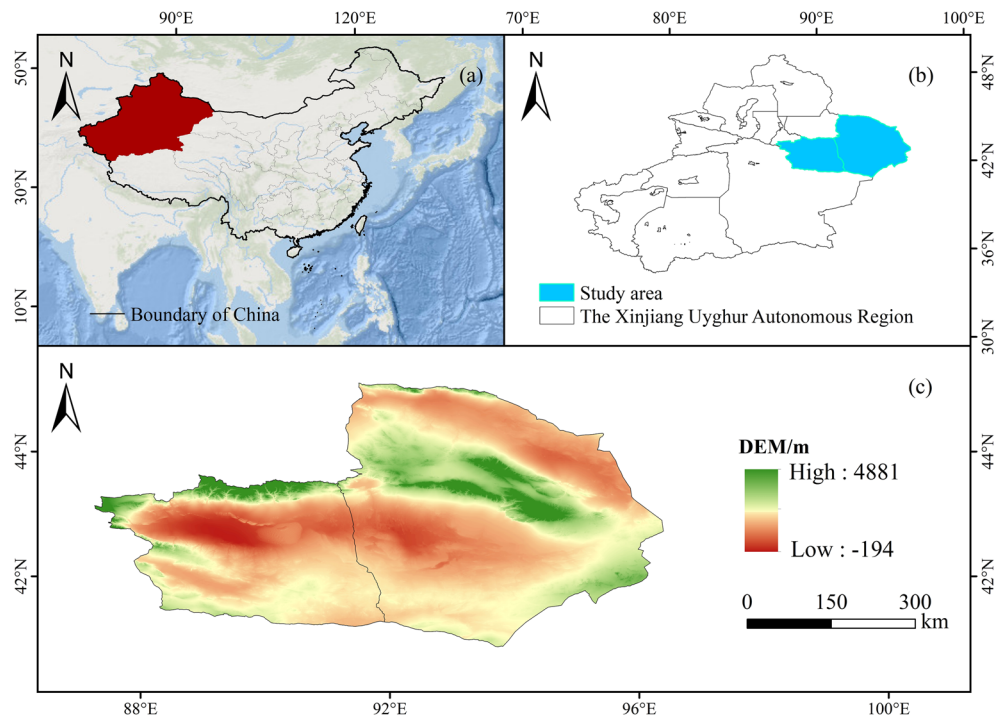


Figure 2. Map of the study area (mapping based on the ArcGIS10.2 software can be obtained from the following link, <https://support.esri.com/en/download/2093>).

Remotely sensed ecological indices

Note that China's Ministry of Ecology and Environment's Normative Environment Index (EI) is prone to subjective bias³¹. Xu²² proposed the RSEI, which uses four indicators (greenness, humidity, dryness, and heat) to characterize the ecological environment of a region. Furthermore, PCA can be employed to prevent the subjective bias in the weighting results due to human error.

Regularizing these indicators to unify their magnitudes between [0, 1] is crucial before performing the principal component transformation. Allowing for customization for each indicator, the regularization formula is as follows:

$$NI_i = \frac{I - I_{min}}{I_{max} - I_{min}} \quad (1)$$

where NI_i is the value of an indicator after regularization, and I_i is the value of the indicator in Quadrant i .

Next, PC1, the first principal component, was computed using the four regularized indicators. For high PC1 values to indicate favorable ecological conditions, PC1 needs to be further calculated to obtain RSEI0. This was achieved by using Eq. (2) shown below:

$$RSEI0 = 1 - \{PC1 [F(NDVI, WET, LST, NDBSI)]\} \quad (2)$$

To facilitate metrics and the comparisons of indicators, RSEI0 was regularized using the following equation:

$$RSEI = \frac{(RSEI0 - RSEI0_{min})}{(RSEI0_{max} - RSEI0_{min})} \quad (3)$$

The RSEI values were in the range of 0–1. The quality of the ecology was indicated by how close the RSEI value was to 1, with values closer to 1 portraying good quality³².

Comprehensive evaluation index: comprehensive development index (CDI).

The CDI for the PWEE subsystems of the Tuha region was computed using a linear weighting method³³.

$$U_i = \sum_{j=1}^m w_j \cdot x_{ij} \quad (4)$$

Coupled coordination degree model (CCDM)

The coordination effect of the PWEE subsystems was measured using the CCDM. The CCDM consisted of two components: the coupling and coordination degree models. The coupling degree model (CDM) was achieved using the following equations³⁴:

$$C = \sqrt[4]{\frac{U_a \times U_b \times U_c \times U_d}{\frac{U_a + U_b + U_c + U_d}{4}}} \quad (5)$$

where C is the coupling degree, U_a , U_b , U_c , and U_d are the CDIs of the PWEE subsystems, respectively. The degree of coupling indicates how strongly the PWEE subsystems interact with each other or how dependent they are on one another during the development process.

The phenomenon of 'pseudo-coordination' can arise when a system's coupling degree is high, despite the subsystem portraying a low development level, if the CDM of only the one subsystem is applied. To objectively reflect the coupling coordination degree (CCD) of the PWEE system, it is important to consider this circumstance and further introduce the coordination degree model³¹. This was achieved using the following equations:

$$T = \alpha \times U_a + \beta \times U_b + \gamma \times U_c + \delta \times U_d \quad (6)$$

$$D = \sqrt{C \times T} \quad (7)$$

where D denotes the CCD, T is the CDI of the PWEE systems, and α , β , γ , and δ are the reference coefficients of the PWEE subsystems. We assumed that each subsystem to be equally significant for this research.

In this study, we divided the degree of coupled coordination into 10 levels (Table 1), drawing on the distinctions employed by previous studies³⁵.

CCD value	Categories	CCD value	Categories
$0 \leq \text{CCD} \leq 0.1$	Extreme disorder	$0.5 < \text{CCD} \leq 0.6$	Marginal coordination
$0.1 < \text{CCD} \leq 0.2$	Serious disorder	$0.6 < \text{CCD} \leq 0.7$	Low coordination
$0.2 < \text{CCD} \leq 0.3$	Moderate disorder	$0.7 < \text{CCD} \leq 0.8$	Moderate coordination
$0.3 < \text{CCD} \leq 0.4$	Low disorder	$0.8 < \text{CCD} \leq 0.9$	Good coordination
$0.4 < \text{CCD} \leq 0.5$	Marginal disorder	$0.9 < \text{CCD} \leq 1.0$	High coordination

Table 1. Classification of coupling coordination degree (CCD).

Scissor difference

The scissor difference can be used to determine the differences in the evolutionary rates between two systems³⁶. The difference in evolutionary trends between the PWEE systems can be judged and analyzed by analyzing the angle θ of the projected trajectories, constituted by the rates of change between the systems on a two-dimensional (2D) plane³⁷. The tangent slopes of the curves $F'(x)$, $F'(y)$, $F'(z)$, and $F'(w)$ of the PWEE system can be used to express the evolutionary rates $V(x)$, $V(y)$, $V(z)$, and $V(w)$, respectively, of each system, which can be expressed as follows:

$$V(x) = F'(x) = \frac{dx}{dt}, V(y) = F'(y) = \frac{dy}{dt}, V(z) = F'(z) = \frac{dz}{dt}, V(w) = F'(w) = \frac{dw}{dt} \quad (8)$$

$$\begin{aligned} \theta_1 &= \arctan \left| \frac{F'(x) - F'(y)}{1 + F'(x)F'(y)} \right|, \left(0 \leq \theta < \frac{\pi}{2}\right); \theta_4 = \arctan \left| \frac{F'(y) - F'(z)}{1 + F'(y)F'(z)} \right|, \left(0 \leq \theta < \frac{\pi}{2}\right) \\ \theta_2 &= \arctan \left| \frac{F'(x) - F'(z)}{1 + F'(x)F'(z)} \right|, \left(0 \leq \theta < \frac{\pi}{2}\right); \theta_5 = \arctan \left| \frac{F'(y) - F'(w)}{1 + F'(y)F'(w)} \right|, \left(0 \leq \theta < \frac{\pi}{2}\right) \\ \theta_3 &= \arctan \left| \frac{F'(x) - F'(w)}{1 + F'(x)F'(w)} \right|, \left(0 \leq \theta < \frac{\pi}{2}\right); \theta_6 = \arctan \left| \frac{F'(z) - F'(w)}{1 + F'(z)F'(w)} \right|, \left(0 \leq \theta < \frac{\pi}{2}\right) \end{aligned} \quad (9)$$

where $F'(x)$, $F'(y)$, $F'(z)$, and $F'(w)$ denote the annual trends of the population, water resource, economy, and ecosystem subsystems, respectively; θ is the angle of two tangents to the curves of evolutionary rates V at given moment, with smaller θ values indicating smaller differences between the trends of evolutionary rates V .

By considering the interactive coercive relationship of the PWEE system in the Tuha, the evolutionary state of each subsystem under the influence of itself and another subsystem can be discussed. The cyclic dynamic coupling process among the system can be judged by analyzing the angle φ of the projection trajectory constituted by the rate of change of the PWEE system in the 2D plane (as the perspective of the coupling model)³⁸.

$$\begin{aligned} \varphi_1 &= \arctan \left(\frac{f'(x)}{f'(y)} \right), (-\pi < \varphi < \pi); \varphi_4 = \arctan \left(\frac{f'(y)}{f'(z)} \right), (-\pi < \varphi < \pi) \\ \varphi_2 &= \arctan \left(\frac{f'(x)}{f'(z)} \right), (-\pi < \varphi < \pi); \varphi_5 = \arctan \left(\frac{f'(y)}{f'(w)} \right), (-\pi < \varphi < \pi) \\ \varphi_3 &= \arctan \left(\frac{f'(x)}{f'(w)} \right), (-\pi < \varphi < \pi); \varphi_6 = \arctan \left(\frac{f'(z)}{f'(w)} \right), (-\pi < \varphi < \pi) \end{aligned} \quad (10)$$

Results

Statuses of the population, water resources, and economy subsystems

Evaluation indicator system

To analyze the status of the subsystems, it is essential to construct a sensible evaluation indicator system³⁹. Based on the principles of science, stability, and data availability^{40–42}, we constructed an index system based on earlier research^{43–46} and integrated the characteristics of the PWEE system by following professional consultation. Finally, a set of indicator systems was determined to assess the degree of CDI among the population, water resources, and economy (PWE) subsystems (Table 2).

Population, water resources, and economy (PWE) system development scenario

The entropy method was used to calculate each indicator's weight, and the CDI of each subsystem was computed using the linear weighting method. Figure 3a illustrates the interannual CDI trend for the PWE systems from 2005 to 2020. Overall, all three subsystems performed well.

The population subsystem CDI increased by 5.94% (on average) annually, from 0.27 in 2005 to 0.68 in 2020. The population subsystem displayed a decreasing trend, followed by a fluctuating increasing trend. Before 2009, the population-subsystem development index fell; however, after 2010, there was a significant increase in the index, with a 10.36% yearly growth on average. This implies that Tuha succeeded in enhancing its population quality and optimizing its population structure in the latter half of the study period. The economic subsystem increased at an average yearly rate of 11.35%, from 0.12 in 2005 to 0.67 in 2020. The development accelerated in 2009–2014 and slowed down in 2015, but maintained a growing pattern. The social instability in Xinjiang in 2008 may have contributed to considerable fluctuations in the CDI of the region's economy and population subsystems in 2009. The CDI of the Tuha water resource subsystem portrayed significant changes between 2005 and 2020, with an overall upward trend. The CDI of the PWE system shows a fluctuating increase, with the lowest value (0.21) occurred in 2005, and the highest value (0.65) in 2020 (Fig. 3b).

Development of the 'ecology' subsystem

Results of PCA

The PCA results were obtained by standardizing, synthesizing, and transforming the WET, NDVI, NDBSI and LST indicators for each year. The contribution rates of PC1 for the four years considered in this study (2005, 2010, 2015, and 2020) were 81.91, 76.52, 79.64, and 79.39%, respectively (Table 3), demonstrating that PC1 concentrated most of the characteristics. Consequently, we determined the RSEI using the data obtained from PC1⁴⁷.

Subsystem	Subsystem weight (w)	Dimension	Indicator [code]	Unit	Property	Entropy (ej)	Redundancy factor (gj)	Indicator weight (wj)
Population [A]	0.251	Scale [A1]	Total population [A11]	people	+	0.914	0.086	0.033
			Density of population [A12]	people/km ²	+	0.933	0.067	0.026
		Structure [A2]	Urbanization rate [A21]	%	+	0.838	0.162	0.063
			Urban registered unemployment rate [A22]	%	+	0.956	0.044	0.017
		Quality [A3]	Number of students per 10,000 population [A31]	people	+	0.874	0.126	0.049
			Number of health technicians per 10,000 population [A32]	people	+	0.839	0.161	0.063
Water resources [B]	0.364	Endowment [B1]	Annual precipitation [B11]	mm	+	0.911	0.089	0.035
			Total water resources [B12]	Billion m ³	+	0.946	0.054	0.021
			Production of water modulus [B13]	10,000 m ³ /km ²	+	0.898	0.102	0.040
			Water resources per capita [B14]	m ³	-	0.947	0.053	0.021
		Stresses [B2]	Per capita water consumption [B21]	m ³	-	0.911	0.089	0.035
			Water consumption per 10,000 GDP [B22]	m ³	-	0.957	0.043	0.017
			Sewage Discharge [B23]	10,000 m ³	-	0.909	0.091	0.035
			Area of green space [B24]	hectares	+	0.898	0.102	0.040
			Water-resources utilization rate [B25]	%	-	0.937	0.063	0.024
		Policy response [B3]	Total investment in environmental pollution control [B31]	10,000 CNY	+	0.801	0.199	0.078
			Sewage treatment rate [B32]	%	+	0.954	0.046	0.018
		Economy [C]	0.385	Scale [C1]	GDP [C11]	10,000 CNY	+	0.893
Local general public budget revenues [C12]	10,000 CNY				+	0.890	0.110	0.043
GDP per capita [C13]	CNY				+	0.900	0.100	0.039
Structure [C2]	Proportion of primary sector [C21]			%	-	0.947	0.053	0.021
	Proportion of secondary sector [C22]			%	+	0.946	0.054	0.021
	Proportion of tertiary sector [C23]			%	+	0.951	0.049	0.019
Abilities [C3]	GDP growth rate [C31]			%	+	0.941	0.059	0.023
	Per capita disposable income of urban residents [C32]			CNY	+	0.879	0.121	0.047
	Total exports and imports [C33]			10,000 USD	+	0.764	0.236	0.092
	Average wage of employed staff [C34]			CNY	+	0.904	0.096	0.038

Table 2. Evaluation indicators of the PWE systems. GDP, Gross domestic product; CNY, Chinese Yen; USD, United States Dollar.

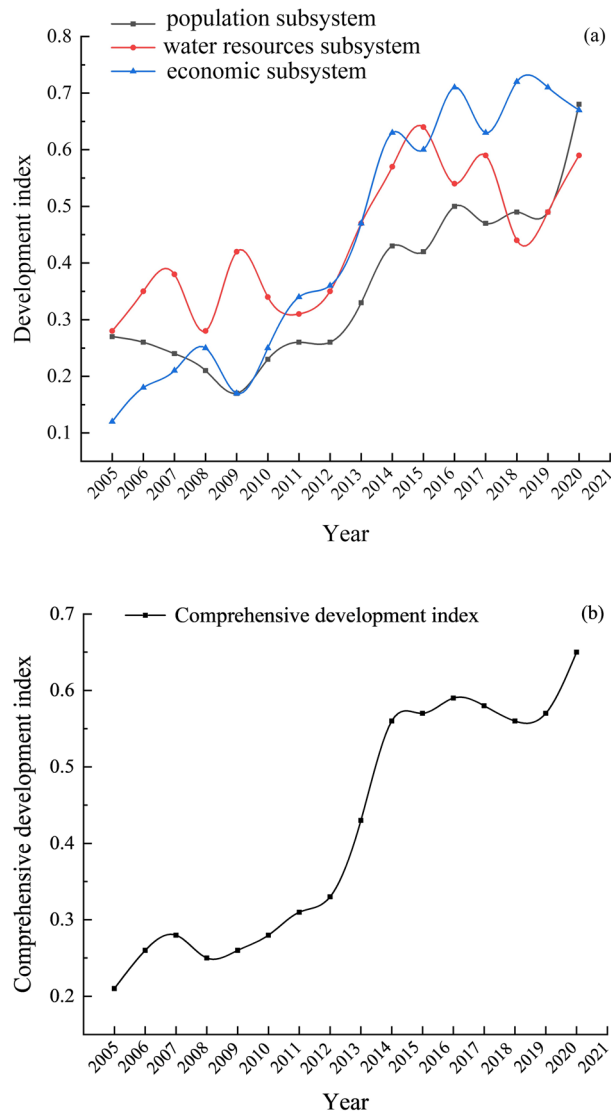


Figure 3. The CDI of the PWE subsystems (a); the CDI of the PWE system (b) in Tuha, 2005–2020.

Ecological quality of the Tuha region

Figure 4 portrays the Tuha region's RSEI statistics for 2005–2020. The study area was randomly sampled and statistically analyzed for determining the RSEI values. The mean RSEI values are shown as squares in Fig. 4e. The multi-year mean value of the RSEI was 0.28, and the five-year mean values were 0.29, 0.28, 0.28, and 0.26. These values suggest that the average environmental quality was below the average. The region's overall environmental quality indicated a deteriorating tendency from 2000 to 2020, although the change was slight and the overall level was low.

To gain a deeper understanding of the environmental-quality distribution features, we considered five grades (bad, poor, moderate, good, and excellent) based on the RSEI, at 0.2 intervals⁴⁸. From 2005 to 2020, the overall environmental quality was poor. In 2005, 2010, 2015, and 2020, the areas with poor grades accounted for 52.38, 49.36, 47.73, and 42.67%, respectively; the overall change was not substantial (Table 4).

There was a noticeable spatial difference in the environmental quality of the study area; it was higher in the central region and lower in the north and south. Owing to the low rainfall and fragile environment in large areas, generally, the state of the environment was poor, accounting for 48.04% on average (mostly in the north and south of the underutilized land). The average percentage of the total area that had moderate or better environmental quality was 14.80%, which was primarily limited to farmlands, oases, and the central mountainous regions.

Spatio-temporal changes in ecological quality

The differential-change test aims to examine the change in the RSEI in two stages. In this research, through the ENVI5.3 platform, the RSEI values of any two different years in the same area were used as a difference operation; because the RSEI values were between [0,1], after performing the difference operation, the final interval was [-1,1]. Therefore, eight levels were defined, which are quantified as levels 1–8²⁷: L1 [-1.0, -0.4), L2 [-0.4, -0.2),

Year	Indicators	PC1	PC2	PC3	PC4
2005	WET	0.053	-0.137	-0.809	0.569
	NDVI	0.267	0.956	-0.090	0.078
	NDBSI	-0.059	0.003	0.571	0.819
	LST	-0.960	0.258	-0.105	0.003
	Percentage variance (%)	81.91	12.92	4.12	1.04
2010	WET	0.100	-0.181	-0.618	0.758
	NDVI	0.249	0.956	-0.112	0.104
	NDBSI	-0.134	0.053	0.752	0.643
	LST	-0.954	0.223	-0.199	0.016
	Percentage variance (%)	76.52	16.24	5.90	1.34
2015	WET	-0.064	0.036	0.997	0.011
	NDVI	-0.536	-0.844	-0.004	0.002
	NDBSI	0.002	0.002	-0.011	1.000
	LST	0.842	-0.534	0.074	0.000
	Percentage variance (%)	79.64	18.07	2.29	0.00
2020	WET	-0.062	0.030	-0.939	-0.336
	NDVI	-0.420	-0.904	0.027	-0.078
	NDBSI	0.049	0.069	0.335	-0.939
	LST	0.904	-0.421	-0.070	-0.009
	Percentage variance (%)	79.39	17.02	3.30	0.29

Table 3. Results of the PCA.

L3 [-0.2, -0.1], L4 [-0.1, 0.0], L5 [0.0, 0.1], L6 [0.1, 0.2], L7 [0.2, 0.4], and L8 [0.4, 1.0]. Grades 1–8 were defined as follows: significant decrease, substantial decrease, significant decrease, slight decrease, slight increase, significant increase, substantial increase, and significant increase, respectively, distinguished by different colors.

Figure 5 portrays the results of ecological-quality change detection, wherein the overall spatial distribution pattern of the ecological quality status did not change significantly. From 2005 to 2010, the area of deterioration in environmental quality (28.03%) was smaller than the area of improvement (71.97%), which indicated that during this time, the state of the ecosystem was improving; the majority of environmental improvements occurred in the eastern and western regions of Tuha, a less populous area. The percentage of areas with enhanced environmental quality (59.90%) was still greater than the percentage of degraded environmental areas (40.10%) between 2010 and 2015. However, the difference was small, which may be related to the rapid advancement of socio-economic growth in the region. Notably, degraded environmental quality fields accounted for 22.74% of the entire region (between 2015 and 2020). During 2005–2020, 11.61% of the areas experienced degraded environmental quality, owing to increased concerns about ecological protection.

Analysis of coupled coordination of the PWEE system

According to Table 1, the coupled coordination effect of PWEE system was at a lower tier as shown in Fig. 6, with the CCD fluctuating and increasing from 0.28 to 0.58. From 2005 to 2012, the CCD gradually increased, and it increased rapidly after 2012. This may be a result of Tuha's accelerated population and economic growth after 2012, gradual recovery of the ecological subsystem, stabilization of the water resources subsystem, and further enhancement of the coordination between the four subsystems.

There were two phases in the coupled coordination level of the PWEE: between 2005 and 2012, the coupled coordination level was dominated by low disorder; after 2013, it transitioned from low disorder to the stage of marginal coordination and maintained this status (Table 5). In general, owing to the rapid expansion of the population and economy, along with the improvement and conservation of the environment's ecology and water resources, the coordinated development trend became more apparent³. The CCD level increased from low disorder to marginal coordination; in the future, it may develop toward low and moderate coordination.

Discussion

Coupling process of the growth rate of the PWEE system based on scissor analysis

We used the scissor-difference analysis method to analyze the differences in the changes of the PWEE system, to better explore the differences in the development process of the subsystems³⁵.

As shown in Fig. 7a, the scissors difference between the evolution rates of population and water resources subsystems showed a downward trend from 2005 to 2008, then a rapid increase in 2008, a rapid decrease after 2008, and a fluctuating decreasing trend after 2010. The scissors difference between the evolution rates of the population and economy subsystems exhibited a fluctuating decreasing trend from 2005 to 2019, and a rapid increase after 2019. Furthermore, the scissors difference in the evolution rates of the population-ecosystem, economy-ecosystem, and water resources-ecosystem systems exhibited an 'M' type fluctuation trend, and that of the

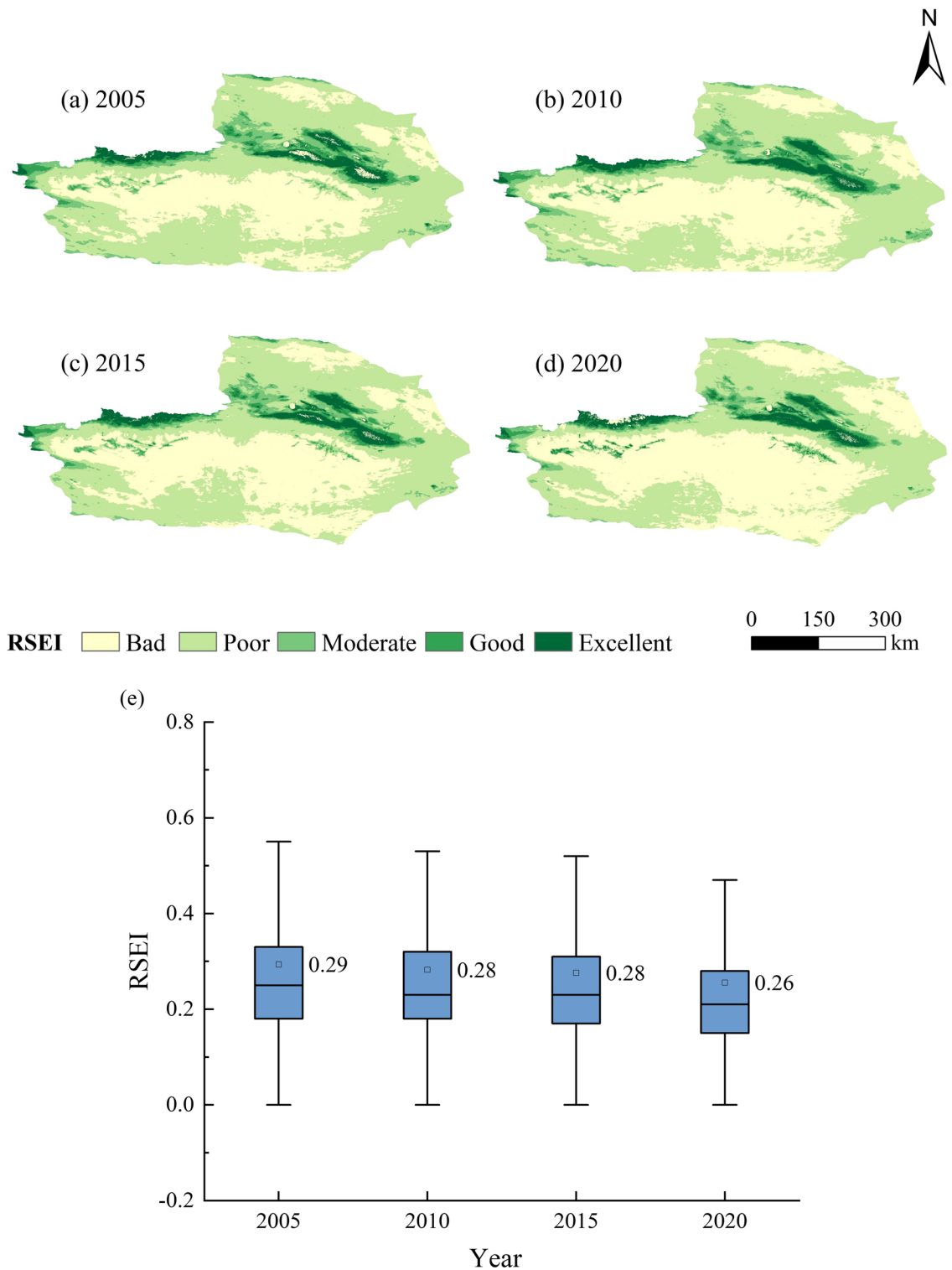


Figure 4. Spatial distribution of RSEI in: 2005 (a), 2010 (b), 2015 (c), 2020 (d), and statistical distribution (e) in Tuha, 2005–2020 (mapping based on the ArcGIS10.2 software can be obtained from the following link, <https://support.esri.com/en/download/2093>).

water resources-economy system exhibited a left-high and right-low ‘M’ type fluctuation trend. For 2005–2020, we note a consistent fluctuating tendency in the general progression of the PWEE system.

The scissors difference between the evolution rates of the PWEE system suddenly increased after 2009, followed by a drastic fluctuation, whereas the scissors between the population-economy, population-ecosystem, water resources-ecosystem, and economy-ecosystem systems did not change drastically, portraying stable fluctuating trends. In terms of fluctuation trends, the ‘water resource’ system experienced a relatively large adjustment

RSEI grade	2005		2010		2015		2020	
	Area/10,000 km ²	%	Area/10,000 km ²	%	Area/10,000 km ²	%	Area/10,000 km ²	%
Bad	7.17	31.64	7.97	35.11	8.54	37.65	9.89	44.27
Poor	11.88	52.38	11.20	49.36	10.83	47.73	9.53	42.67
Moderate	1.77	7.79	1.71	7.52	1.44	6.34	1.13	5.03
Good	0.93	4.09	0.96	4.21	0.89	3.92	0.81	3.64
Excellent	0.93	4.1	0.86	3.8	0.99	4.36	0.98	4.38
Total	22.67	100	22.69	100	22.68	100	22.34	100

Table 4. Statistics of the remote sensing ecological index (RSEI) level in Tuha, 2005–2020.

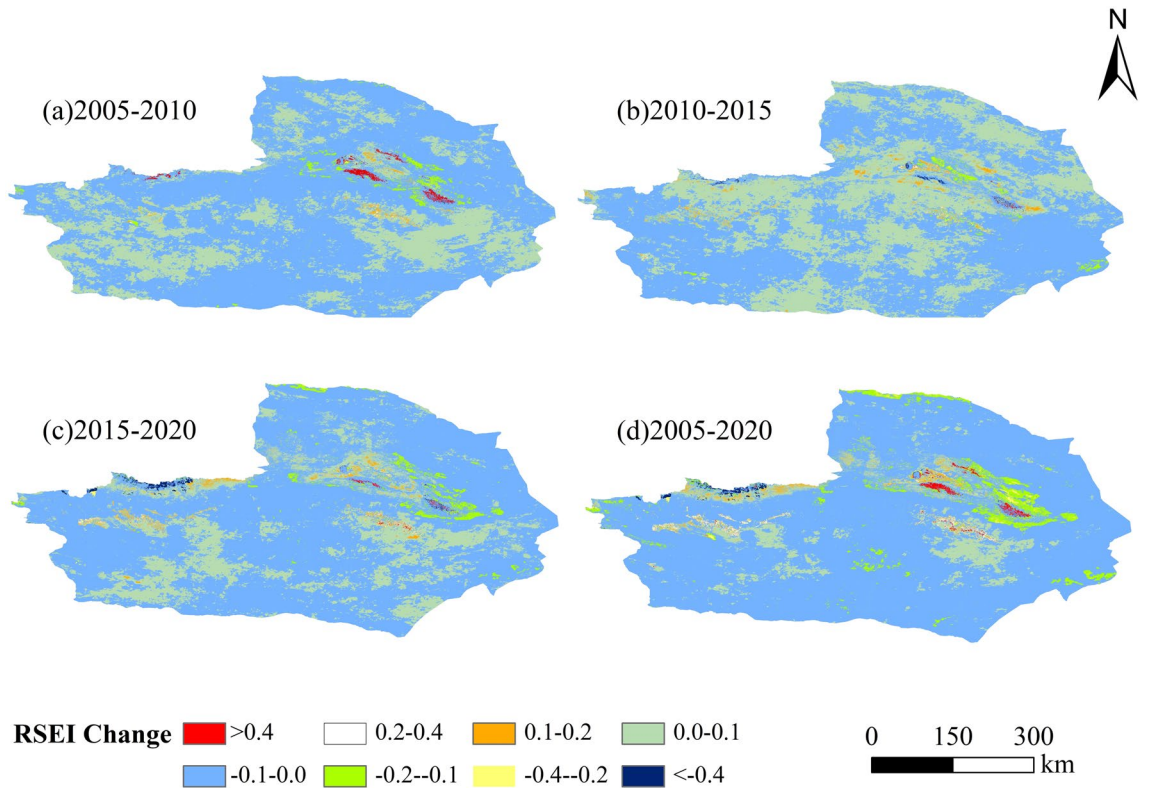


Figure 5. Detection map of RSEI changes in Tuha, 2005–2020 (mapping based on the ArcGIS10.2 software can be obtained from the following link, <https://support.esri.com/en/download/2093>).

in 2009, and this drastic change gradually affected the other subsystems; this was further confirmed by the upward trend in the growth rates of the other subsystems that occurred after 2009 (Fig. 7b).

Dynamic coupling analysis

The PWEE composite system of the Tuha region is still in a disordered stage, as evidenced by the overall evolution characteristics of the PWEE system coupling angle (Fig. 7c); this indicates that its angle range is in a drastic fluctuation situation, and that the coupling-angle changes in the PWEE systems from 2005 to 2020 were all greater than 100°. This may be strongly connected to the sluggish growth of ecosystems, populations, water resources, and economic systems in the region, without any regard to environmental constraints³.

In 2005–2007, 2009–2012, and 2015–2018, the coupling angle of the population and water-resources system indicated a low-level coordinated symbiosis ($-90^\circ < \beta \leq 0^\circ$), indicating that the population and water-resources systems interact with each other, and the contradiction of the constraints and limitations of the water-resources system on the population system is not yet prominent. In 2008, 2013, and 2019, the coupling angle of the population-water resources system appeared in the primary coordinated development stage ($0^\circ < \beta \leq 45^\circ$) and reached the co-development stage ($45^\circ < \beta \leq 90^\circ$) in 2014 and 2020, indicating that the fluctuating changes in the water resource system’s growth rate were evident contradictions in the constraints and limitations imposed on the population subsystem. The coupling angle of the population-economy system in 2005–2016 portrayed a fluctuating upward trend, portraying a primary coordinated development stage, indicating that the economy

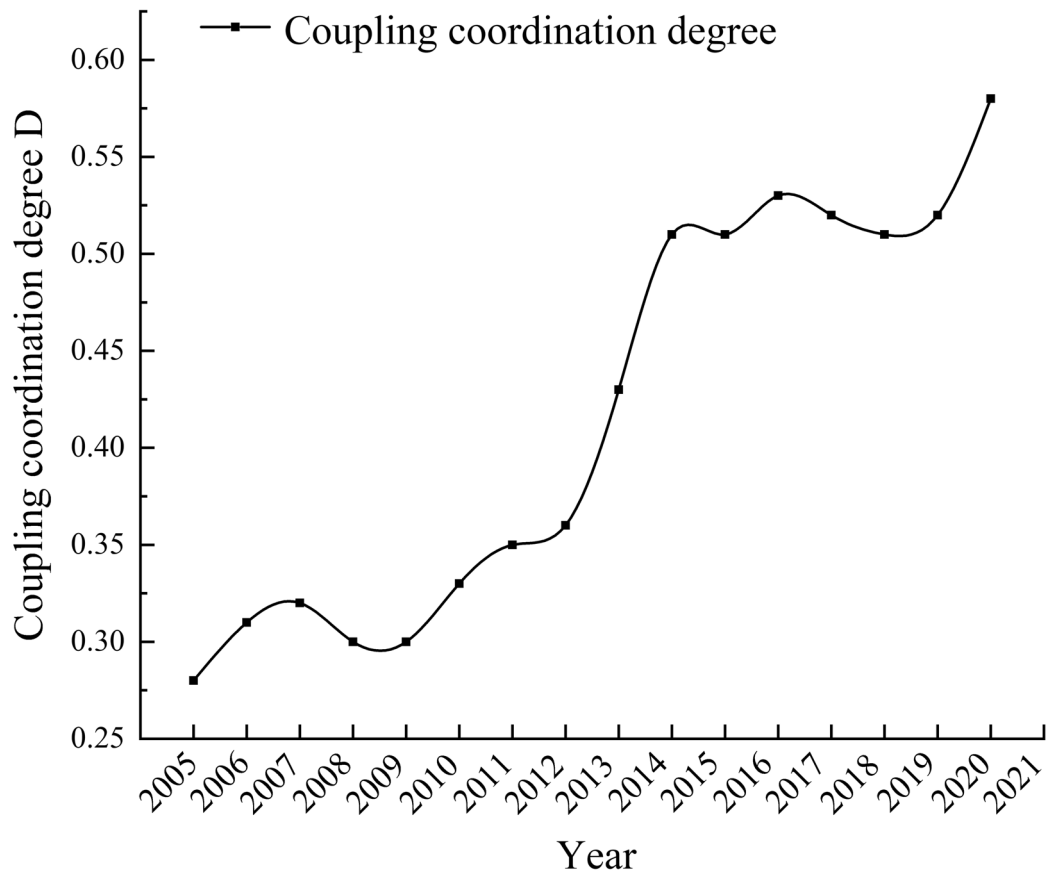


Figure 6. The CCD of the PWEE system (c) in Tuha, 2005–2020.

Year	Qualitative	Primary limitations	Year	Qualitative	Primary limitations
2005	Moderate disorder	Economic development lag	2013	Marginal disorder	Ecological lag
2006	Low disorder	Economic development lag	2014	Marginal coordination	Ecological lag
2007	Low disorder	Economic development lag	2015	Marginal coordination	Ecological lag
2008	Moderate disorder	Population development lag	2016	Marginal coordination	Ecological lag
2009	Moderate disorder	Economic development lag	2017	Marginal coordination	Ecological lag
2010	Low disorder	Economic development lag	2018	Marginal coordination	Ecological lag
2011	Low disorder	Population development lag	2019	Marginal coordination	Ecological lag
2012	Low disorder	Population development lag	2020	Marginal coordination	Ecological lag

Table 5. CCD level of the PWEE system in Tuha, 2005–2020.

system had an apparent influence on the population system. After 2016, the coupling angle of the population-economy system portrayed a sharp decline, showing a sharp decline in the demographic and economy subsystems' growth rates, the contradiction of the mutual constraints was revealed. The fluctuating changes in the coupling angle between the water-resources and economy subsystems from 2005 to 2011, the rapid decline after a short co-development phase in 2012 and 2013, and the sharp decline to a low-level coordinated symbiosis phase indicated that the water resource system's growth rate first accelerated rapidly, followed by a decline; the contradiction of the mutual constraints and limitations between the water resources and economy systems first strengthened and then weakened. The coupling angles of population-ecosystem, water resource-ecosystem, and economy-ecosystem systems all fluctuated sharply between the low-level coordinated symbiosis and co-development stages; the peaks and troughs were in line with the changes growth rate of the population, water resources, and economy subsystems. This indicated that the ecosystems were developing slowly but were drastically affected by the other three subsystems; notably, they portrayed a lag in the evolution of the coupling angles with the population and economy subsystems.

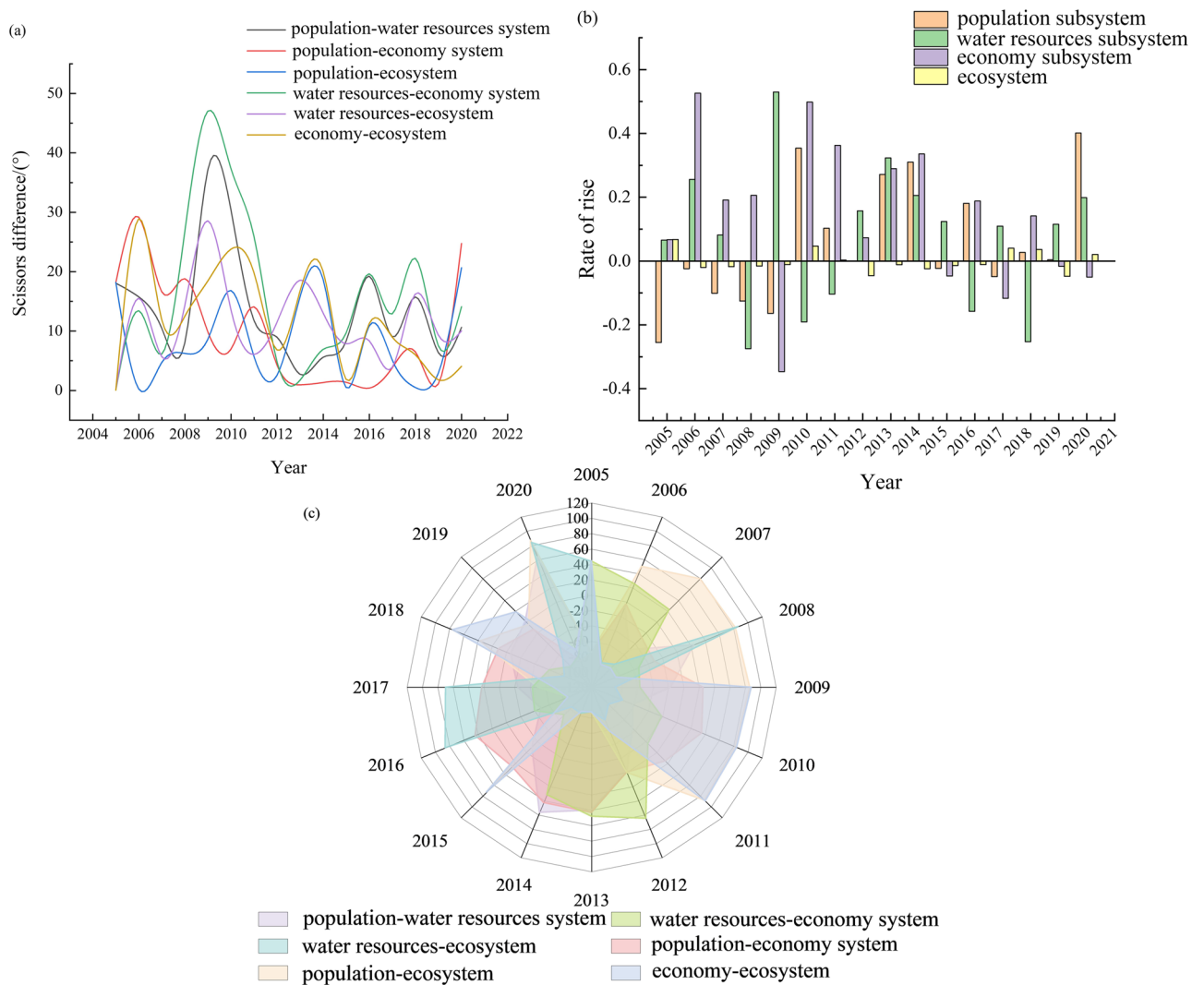


Figure 7. Trends of scissors differential (a); trends of growth rate (b) and trends of coupling model angle (c) of the PWEE system in Tuha, 2005–2020.

Comparison with the previous literature

1. Construction of a four-dimensional PWEE system. The construction of the indicator system in this study draws on the widely used pressure-state-response (PSR) framework⁴⁹ in related research. However, this study takes more into account the economic development and resource characteristics of the study area^{50–52}, and constructs a four-dimensional PWEE system. Compared to the two-dimensional system of urbanization and ecological environment⁵³, or the three-dimensional system of economy, society, and ecology⁵⁴, the PWEE system is better able to explain the complex issues of urban system incoordination.
2. Methods for Evaluating Ecological and Environmental Quality. The RSEI method, as an ecological environment assessment index system based on remote sensing technology, has been widely applied in evaluating ecological and environmental quality^{55–57}. It has proven effective and stable for such evaluations. The research results of this study indicate that the RSEI values in the Tuha region from 2005 to 2020 exhibited a general decreasing trend (Fig. 4), which is consistent with existing research findings^{58–60}.
3. Coupling analysis results. The coupling coordination degree model (CCDM) and coupling angle model (CAM) are widely used in the study of system complexity and coupling effects^{36,61,62}, which are prevalent in many studies. They help us effectively explore relationships between subsystems within complex systems and aid in formulating efficient management and decision-making strategies. Our research findings indicate that the CCD in the Tuha region from 2005 to 2020 ranged between 0.28 and 0.58 (Fig. 6), showing a fluctuating upward trend, which is consistent with previous research findings in this region^{54,63}.

Limitations and outlook

In this research, we constructed a set of complex indicator systems (PWEE) applicable to the coupled and coordinated study of arid city integrated system. And applying the typical arid area of the Tuha region as an example, we investigated the integrated development status, CCD changes, and dynamic coupling process. Future research on PWEE coupling coordination in cities in arid zones can use the index system of this work as a reference, and this paper's research methodology and conclusions can provide lessons for the coupled and coordinated development of urban in other arid regions.

There are some limitations in this study. First, taking data accessibility into account, the indicator system built in this research is not sufficiently thorough. Second, some of the missing socio-economic statistics in the indicator system are supplemented by linear interpolation, which may lead to uncertainty in the results. Furthermore, due to limitations in the study methodology, the dynamic coupling of PWEE system has not been sufficiently examined. Future research can further center on a detailed examination of the dynamic coupling between PWEE system, and the prediction of the coupling coordination.

Conclusion and policy implications

Conclusion

This study analyses the PWEE system for the Tuha region, calculates the CCD during 2005–2020 (using the CCDM), and analyses the dynamic coupling process of the system based on the scissors difference and CAM methods.

1. From 2005 to 2020, Tuha's population, water resources, and economy subsystems displayed a fluctuating rising trend; the Xinjiang region's social stability and policy drive were the main causes of the fluctuating rise and fall of the CDI. The ecological and environmental quality was clearly denoted by the RSEI, which had a multi-year average of 0.28. This indicates that Tuha's average state of the environment is poor, and that the overall trend is declining. The quality of the environment has not changed significantly.
2. The coupled coordination effect of the PWEE system of the Tuha region has been at a low level during 2005–2020, with the CCD ranging from 0.28 to 0.58 (with a fluctuating upward trend). The level of CCD increased from mildly dysfunctional to barely coordinated, and that the PWEE-system interactions do not have a significant impact. Notably, in the future, the system may develop to portray primary and moderate coupling coordination.
3. The evolution of the PWEE subsystem with each other from 2005 to 2020 portrayed a persistent fluctuating trend, and the changes in the coupling-angle between the PWEE subsystems were all over 100°. This phenomenon may be intimately associated with the slow growth of the ecosystem subsystem. At the early stage of the study, there were no notable limitations between the various systems. The differences in the development process of various subsystems of the PWEE system were analyzed using the scissors difference method. Furthermore, in the early stage, there were no evident limitations between the systems: with the city's development, the influences of population, water resources, and economy subsystems on the ecosystem subsystem were revealed. However, the ecological support capacity was not observed until the late stage of the study. In summary, the PWEE composite system of the region remains in the disordered development stage; thus, it is important to protect the environment of the region.

Policy implications

Based on the above research results regarding the comprehensive development evaluation, coupling coordination, and dynamic coupling characteristics of the PWEE system in the Tuha region, policy recommendations are proposed to achieve coordinated development of urban systems in the region:

1. Water scarcity is a critical resource issue that cannot be avoided and is unlikely to be completely resolved in the short term in the Tuha region. Although substantial human and material resources have been invested to weaken its constraints on regional development, it remains crucial to persistently implement policies to improve water resource management efficiency, such as strengthening legislative guarantees for water management, promoting water-saving irrigation technologies, improving the water pricing mechanism, strengthening groundwater abstraction management, and enhancing public awareness of water conservation. However, relying solely on local water resources cannot meet the long-term development needs of the Tuha region, and it may be necessary to solve the water shortage problem by diverting water from external sources.
2. The research found that although water scarcity has always been a prominent developmental constraint in the study area, it has received considerable attention and investment over time. The comprehensive development level of the water resource subsystem has improved overall, while since 2013, the primary constraint on coupling coordination has been the ecological lag. In addition to water resource protection, more attention should be given to the protection of the ecological environment, such as the restoration of natural ecosystems (grasslands, wetlands, deserts), and the guidance of sustainable industries. The Tuha region should vigorously carry out research on oasis hydrology, water-soil balance, saline-alkali land improvement, and ecological restoration. Furthermore, there should be an increase in investment in eco-tourism, green energy, and other industries, aiming to optimize the industrial structure.

Data availability

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

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Competing interests

The authors declare no competing interests.

Additional information

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