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Spatiotemporal characteristics and driving mechanism of the coupling coordination degree of urbanization and ecological environment in Kazakhstan

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Abstract: When viewed against the backdrop of globalization and the Belt and Road Initiative (BRI), Central Asia has ushered in new development opportunities. However, problems of ecological environment as a consequence of urbanization have begun to act as a constraint on the economic development of the region. the coupling coordination degree between the urbanization and ecological environment in Kazakhstan was analyzed by the coupling coordination degree model. The main controlling factors affecting its development were explored using a geographical detector. Several main conclusions can be drawn. (1) Kazakhstan's urbanization level, ecological environment level, and the coupling coordination degree between urbanization and ecological environment are all on the rise. (2) In terms of the comprehensive urbanization index, the western and eastern states have higher values than the southern and northern states. The spatial distribution pattern of the ecological environment index revealed high values in the eastern and western regions and low values in the central region. (3) The coupling coordination degree among the states of Kazakhstan is mostly at a low-moderate level. The spatial distribution shows that the coordination level of the east, middle, and west of the country is higher than that of south and north. (4) Indicators such as GDP per capita, social fixed asset investment per capita, employment in industry and services (% of total employment), and the number of college students per 10,000 people are important urbanization factors that affect the coupling coordination degree of urbanization and ecological environment. Indicators of farmland areas per capita, availability of water resources per capita, ecological land per capita and forest coverage in the ecological environment subsystem are important ecological environmental factors that affect the degree of coordination between urbanization and ecological environment in Kazakhstan. The interaction of the main elements in the two subsystems has a strong synergy.

Keywords: Kazakhstan; comprehensive urbanization; ecological environment; synergistic effects; Belt and Road Initiative; geographical detector

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1 Introduction

Central Asia is located at the junction between Europe and Asia and is a transportation hub for the Eurasian continent. The ancient Silk Road traverses Central Asia, and modern Central Asia is also the strategic core area of the Silk Road Economic Belt (Mao, 2013; Liu *et al*., 2018). Central Asia is the primary location through which China has opened-up to the West. China and Central Asia have mutual interests in terms of security, economy, and energy. In-depth cooperation with Central Asia is an important development direction for China in the future, and is also the only way to promote the prosperity of western China and Central Asia (Wuzhati *et al*., 2014).

Since the beginning of the new century, Central Asia has ushered in new development opportunities. Both economic development and urbanization levels are increasing in the region. According to the law of global urban expansion, the urbanization levels of the five Central Asian countries will continue to increase. However, Central Asia, which lies deep in the middle of the Eurasian continent, is the main body of the Eurasian inland arid zone. It is one of the most arid regions in the world and the carrying capacity of the environment is very limited (Cowan, 2007). As urbanization has advanced, the scale and intensity of resource utilization and environmental degradation has continued to expand and increase. The process of regional urbanization may be constrained by a restriction of resource availability and an environmental "threshold.” The neglect of these regional resource and environmental issues will inevitably become an obstacle to urbanization development. The occurrence of the maritime crisis is an example of this.

For ecologically fragile areas, such as arid areas, the coordinated development of urbanization and the ecological environment is essential for regional sustainable development. Kazakhstan, which accounts for 68% of Central Asia’s land area, has developed from a major agricultural economy to a major energy and mineral resource development country in recent years. The pace of social and economic development has accelerated. It has entered a rapid industrialization track before the other four countries, and the speed of urbanization has also accelerated. From an urbanization development model led by traditional industrialization, the urbanization rate of Kazakhstan has long ranked first among the five Central Asian countries, reaching more than 50%. According to the general law of urbanization development in various countries around the world, when a country’s urbanization level reaches 40% to 60%, it is considered to be urbanized. Economic development in Kazakhstan has entered the golden period, and the country is also facing a period with the frequent occurrence of “urban diseases” (Ma, 2020). Therefore, Kazakhstan can be used as a model for the development of urbanization in the five Central Asian countries. It is of great significance to regard Kazakhstan as a key area for studying the coordinated development of urbanization and the ecological environment in Central Asia.

2 Literature review

The process of urbanization has caused increasingly serious negative effects worldwide, leading to a far-reaching impact on ecological environment (Fang *et al*., 2019b). Studies of the interaction and coupling of urbanization and the ecological environment are currently a research hot spot and represent the frontier of our current understanding of the human–environment relationship and sustainability science (Reid *et al*., 2010; Kates *et al*., 2013; Fang *et al*., 2019a). Most previous studies of the impact of urbanization on ecological environment have focused on internal factors (Buyantuyev *et al*., 2010), the ecological environmental response in rapidly urbanizing areas (Wang *et al*., 2013), the constraints of ecological environment on urbanization (Bao and Fang, 2009), and the relationship between urbanization and ecological environmental systems (Qiao and Fang, 2005; Zhang *et al*., 2016). In terms of theoretical research on the coupling of urbanization and ecological environment, international studies have mainly focused on the pressure-state-response (PSR) model (Berger and Hodge., 1998), environmental Kuznets curve (Grossman and Krueger., 1995), ecological footprint theory (Rees and Wackernagel, 1996), decoupling theory (OECD, 2002), and telecoupling theory (Liu *et al*., 2007). Chinese researchers have also conducted theoretical research work and have proposed the theory of the “society-economy-nature” compound ecosystem (Ma and Wang, 1984), and the theory of the coupling circle of urbanization and ecological environment (Fang *et al*., 2019a). In recent years, studies have been undertaken on the interaction and coupling of urbanization and ecological environment, including the coupling mechanism and a regularity analysis (Huang and Fang, 2003), a coupled dynamic simulation (Cui *et al*., 2019), and theoretical and empirical research on the conceptual framework of a “coupling cube” (Liu *et al*., 2019). Research has shown that the interaction between urbanization and ecological environment has complex one-to-one, one-to-many, and many-to-many relationships (Fang, 2004). Researchers have studied this issue from different angles, focusing on the interactive coupling between urbanization and water resources and water environmental systems (Yang and Liu, 2014; Cao *et al*., 2019), and the interactive coupling between urbanization and land resource systems (Yang *et al*., 2011; Zheng *et al*., 2013), the interaction and coupling between urbanization and atmospheric environment (Kyrkilis *et al*., 2007), the interaction and coupling between urbanization and energy consumption and carbon emissions (Fan and Li, 2011; Guan *et al*., 2013; Wang and Cheng, 2020), and the interaction and coupling of urbanization, ecosystems, and biodiversity (Estoque and Murayama, 2013; Li *et al*., 2019). In general, the existing research has focused on one-to-one and one-to-many interactive coupling analyses between urbanization and ecological environment, with little research on the many-to-many elements, i.e., an overall interactive coupling analysis of the urbanization system and the ecological environmental system.

Although there has been little empirical research on urbanization and the impact on ecological environment in many countries, a large number of multi-scale studies, including the state (Liu *et al*., 2005; Zhang and Jiao, 2015), local administrative units (Fan *et al*., 2015), urban agglomerations and metropolitan areas (Liu *et al*., 2018; Zhao *et al*., 2020), as well as other typical areas such as watersheds (Du, 2014) and oases in arid areas (Tang *et al*., 2014), have been conducted in China. Most developed countries have gone through the stage of rapid urbanization and development, while most developing countries are still in the initial stage of urbanization development, and the ecological environmental problems have not been adequately addressed. Most countries will experience urbanization development, and will therefore require protection of the ecological environment. However, Central Asia faces particularly severe problems due to its fragile ecological environment. Studies of these problems have mostly focused on those caused by urbanization or human activities, especially the damage to the water environmental system (Deng and Chen 2017; Yang *et al*., 2017), land use (Kuang *et al*., 2014) and ecosystems (Vakhlamova *et al*., 2014; Jiang *et al*., 2017). A few researchers have begun to pay attention to Central Asia, including one-to-one research on urbanization and ecological environment (Xiong and Yang, 2015).

In summary, researchers have studied the interaction and coupling of urbanization and ecological environment in China, but fewer such studies have been conducted elsewhere in the world. Much research has been conducted on the "one-to-one" and "two-element" interactive coupling between urbanization and ecological environment, with fewer studies on the coordination of "multi-element" coupling. As the first country in Central Asia to transform its economy, Kazakhstan is now experiencing rapid urbanization. How to manage the conflict between urbanization and the ecological environment has become an important issue regarding social development in this region. Therefore, this study applied data for both human and natural elements in Kazakhstan to research the processes of dynamic change in urbanization and ecological environment of Kazakhstan at province and national scales, and the coupling coordination degree between these two complex systems were assessed by constructing a coupling coordination degree model. A geographical detector was used to analyze the interaction between urbanization and various elements of the complex system in Kazakhstan, with the main control factors affecting the coordination degree being quantitatively identified. Finally, corresponding countermeasures and suggestions are proposed, which will provide a scientific reference for the coordination and sustainable development of urbanization and ecological environment in arid regions such as Kazakhstan and Central Asia, and ensure the prosperity and development of the "Belt and Road" region.

3 Research area, data sources, and an evaluation index system

3.1 Study area and data sources

Kazakhstan lies in the northern part of Central Asia, which borders on Turkmenistan, Uzbekistan, and Kyrgyzstan to the south, Russia to the north, China to the east, and the Caspian Sea to the west. It covers an area of 272.49 km^2 and comprises 68% of the Central Asian region. Kazakhstan is located in the middle latitudes of the northern hemisphere (north temperate zone), covering 15 degrees of latitude from 40°N to 55°N and 35 degrees of longitude from 50°E to 85°E. It has a population of approximately 72.5 million, with 55% of the population living in urban areas. It contains many ecological zones, but the principal biomes are, in the order of increasing aridity: steppe, semi-desert, and desert. About 60% of Kazakhstan's territory (179.9 million ha) is desert (Kirsten, 2004). It consists of various geomorphological types and has distinctive regional topographical features. Most of its territory consists of plains and lowlands, with the lowest point being in the western part of the Karagieh Basin at 132 m below sea level. The northeastern and southeastern parts consist of the Altai and Tianshan Mountains, of which the highest point is located in the central border of the Khan Tengri, with an altitude of 6995 m. The central part consists of the Kazakh Hills, which have a general height of 300–500 m, with the highest point being 1565 m. Kazakhstan has an abundance of mineral and fossil fuel resources, and ranks 11th in the world in terms of proven oil and gas reserves. Since 1993, the development of oil, gas, and minerals has attracted more than 40 billion USD in foreign investment, accounting for about 57% of the country's total industrial output (about 13% of its GDP). In 2017, Kazakhstan had a permanent population of 18.038 million and a GDP of 159.47 billion USD, accounting for 25.30% and 60.11%, respectively, of the totals among the five Central Asian countries.

Administratively, the territory of Kazakhstan is divided into 14 regions, consisting of districts and settlements. In addition, two cities, Almaty and Nur-Sultan, are classified as having republican significance. Considering its geographical location and socio-economic characteristics, the Kazakhstan region has traditionally been referred to as five macro areas: northern (Akmolinskaya, Kostanaiskaya, Pavlodarskaya, Severo-Kazakhstanskaya), central (Karagandinskaya), eastern (Vostochno-Kazakhstanskaya), western (Aktubinskaya, Atyrauskaya, Mangistauskaya, Zapadno-Kazakhstanskaya), and southern (Almatinskaya, Yuzhno-Kazakhstanskaya, Kyzylordinskaya, Zhambylskaya).

Socio-economic and environmental data for the Kazakhstan region at the oblast scale (from 2000 to 2017) and country scale (from 1992 to 2018) were used in this study, all of which were obtained from the official website of the Kazakhstan statistics bureau[1] (The State Statistics Bureau of Kazakhstan, http://stat.gov.kz/) and the World Bank Open Data (https://data.worldbank.org.cn). World Development Indicators (WDI) is the main database for World Bank development data. This study used European Space Agency (ESA) 1992–2015 data (data source, http://maps.elie.ucl.ac.be/CCI/viewer/download.php) for global land cover (ESA Glob Cover) as the basis for the measurement of built-up and natural land.

3.2 The evaluation index system

To determine the coordination degree between urbanization and ecological environment in Central Asia, an indicator system for urbanization and ecological environment was constructed based on previous literature (Du *et al*., 2020; Ma, 2020). A comprehensive evaluation system suitable for urbanization and ecological environment in Central Asia was constructed based on the principles of science, maneuverability, a systematic structure, independence, generality, foresightedness, and data accessibility. The results are shown in Tables 1 and 2. Urbanization is a function of urban population growth (population urbanization), economic growth (economic urbanization), the expansion of urban space (spatial urbanization), and the improvement of people's living standards and quality (social urbanization). Population urbanization and spatial urbanization are physically apparent, while economic urbanization is the foundation and driving force of the process, and improvement in the quality of urban living standards is the ultimate goal of urbanization. The ecological environmental index used in the study covered the ecological environmental status, ecological environmental attributes, ecological environmental pressure, and ecological environmental responses.

4 Research methods

The commonly used weighting methods mainly include the expert investigation method (Delphi method), the analytic hierarchy process (AHP), the binomial coefficient method, the principal component analysis method, the entropy method, the deviation and mean square

[1] Due to the availability of data, we only obtained relevant data at the state scale for Kazakhstan from 2000 to 2017, while the data obtained at the national scale are from 1992 to 2018.

Table 1 Index system for urbanization.

First-level index	Weight	Basic-level index	Entropy weight	Coefficient of variation weight	Comprehensive weight
Population urbanization	0.108	Urban population (% of total)	0.499	0.543	0.521
		Employment in industry and services (% of total employment)	0.501	0.457	0.479
Spatial urbanization	0.504	Urban population density (person/km^2)	0.469	0.429	0.451
		Percentage of built-up areas in total land area (%)	0.431	0.396	0.416
		Number of built-up areas per 10,000 people (km^2)	0.040	0.086	0.059
		Density of road network per 10,000 people (km^2)	0.061	0.090	0.074
Economic urbanization	0.247	GDP per capita (USD)	0.258	0.254	0.257
		Industry and services, value added (% of GDP)	0.027	0.067	0.043
		Gross industrial output value per capita (USD)	0.393	0.352	0.374
		Per capita social fixed assets investment	0.322	0.327	0.326
Social urbanization	0.140	Per capita income and consumption expense	0.293	0.284	0.290
		Number of public buses per 10,000 people	0.281	0.295	0.289
		Number of college students per 10,000 people	0.132	0.182	0.156
		Number of professional doctors per 10,000 people	0.293	0.238	0.265

Table 2 Index system for ecological environment.

First-level index	Weight	Basic-level index	Entropy weight	Coefficient of variation weight	Comprehensive weight
Ecological environmental status	0.357	Renewable internal freshwater resources per capita (m^2)	0.374	0.292	0.332
		Arable land area (ha per person)	0.304	0.344	0.325
		Cereal production per capita (metric kg)	0.323	0.363	0.344
Ecological environmental attributes	0.170	Forest area (% of land area)	0.637	0.624	0.631
		Ecological land per capita (m^2)	0.363	0.376	0.369
Ecological environmental pressure	0.363	Emissions of solid pollutants (kg per capita)	0.346	0.319	0.332
		Emissions of liquid and gaseous pollutant substances (kg per capita)	0.319	0.322	0.321
		Emissions of free air pollutants, from non-stationary sources (kg per capita)	0.335	0.359	0.347
Ecological environmental response	0.110	Running expenses for ecological environmental protection (thousand tenge)	0.438	0.261	0.346
		Removal rate of pollutants (%)	0.233	0.234	0.238
		Recycling rate of pollutants (%)	0.329	0.505	0.416

error method, the multi-objective programming method, and the projection tracking model. The entropy method has been widely used to define index weights in geography and environmental science and reflects the validity of information provided by the index. It reflects the original information of the index and improves the objectivity of the evaluation.

As the original data were not comparable due to the large differences of dimensional and units, standardization of the data range was used to make data being dimensionless. The original index was therefore divided into two: the positive index and negative index. The larger the positive index, the more favorable it was for the development of the system (conversely, the larger the negative index, the more unfavorable it was). To eliminate the deviation of a single objective weighting method and to avoid the arbitrariness and error of the subjective weighting method, the entropy method and variation coefficient method were combined in this study to ensure the accuracy and reliability of the results.

$$\begin{cases} S_{ij} = \dfrac{x_{ij} - \min\{x_{ij}\}}{\max\{x_{ij}\} - \min\{x_{ij}\}} (\text{the index is positive}) \\ S_{ij} = \dfrac{\max\{x_{ij}\} - x_{ij}}{\max\{x_{ij}\} - \min\{x_{ij}\}} (\text{the index is negative}) \end{cases} \tag{1}$$

where x_{ij} is the value of the jth indicator in the ith oblast; and $\max\{x_{ij}\}$ and $\min\{x_{ij}\}$ represent the maximum and minimum values of the jth index in the ith country, respectively.

The calculated weights of urbanization and ecological environmental system evaluation indexes are shown in Tables 1 and 2. The comprehensive weight of the indicators was calculated as follows:

$$W_i = \frac{\left(w_{1i*}w_{2i}\right)^{1/2}}{\sum_{i=1}^{n}\left(w_{1i*}w_{2i}\right)^{1/2}} \tag{2}$$

where w_{1i} and w_{2i} are the entropy weight and variation coefficient weight; and W_i is the comprehensive weight.

4.1 Comprehensive evaluation model

The subsystems of population urbanization, economic urbanization, social urbanization, and spatial urbanization; and ecological environmental status, ecological environmental attributes, ecological environmental pressure, and ecological environmental response were calculated using the linear weighting method.

The evaluation of the index values of urbanization and ecological environmental system was calculated as follows:

$$u(x) = \sum_{i=1}^{n} w_i * x_i \,, \; e(y) = \sum_{j=1}^{m} w_j * y_j \tag{3}$$

$$U(x) = \sum_{i=1}^{n} W_i * f(x),\; E(y) = \sum_{j=1}^{m} W_j * g(y) \tag{4}$$

where $u(x)$ and $e(y)$ are the comprehensive evaluation values of urbanization and ecological environmental system, respectively; x_i and y_j are the standardized values of the urbanization and ecological environmental evaluation indicators; w_i and w_j represent the comprehensive weights for the assessment of urbanization and ecological environmental indicators respectively; and W_i and W_j represent the weight of urbanization and ecological environment respectively. For Central Asia, the development of urbanization seems to be as important as ecological environmental quality. The values of w_i and w_j are therefore equal.

4.2 An urbanization and ecological environmental coordination model

Coupling refers to the phenomenon in which two (or more) systems are affected by the var-

various interactions between them and the outside world. The coupling degree model (5), which depicts the relationship between a pair of parameters, is widely used to study the interaction between urbanization and ecological environment.

$$T = \left\{ \frac{f(U)g(E)}{\left(\left(f(U) + g(E)\right)1/2\right)^2} \right\}^{1/2} \tag{5}$$

We further constructed the coupling coordination degree model for urbanization and ecological environment to identify the degree of coordination between the coupling of urbanization and ecological environment, namely:

$$C=\alpha f(U) +\beta g(E) \tag{6}$$

$$D=\sqrt{C\ T} \tag{7}$$

where C is the coupling degree between urbanization and ecological environment ($C \in (0, 1)$); $f(U)$ is the urbanization subsystem; and $g(E)$ is the ecological environmental subsystem; D is the coupling coordination degree between urbanization and ecological environment; T represents the comprehensive reconciliation index of urbanization and ecological environment; α and β represent the contribution of urbanization and ecological environment, respectively. For Central Asia, we assumed that the development of urbanization is as important as the quality of ecological environment, and therefore the values α and β are equal.

Table 3 Classification of the synergistic development of urbanization and ecological environment.

Primary division of developmental stages		Secondary division of developmental stages	Tertiary division of developmental stages		Code
Uncoordinated	0<D≤0.2	Severe imbalance	E(y)–U(x)>0.1	Uncoordinated; urbanization is blocked	I1
			|E(y)–U(x)|≤0.1	Balanced development	I2
			E(y)–U(x)<–0.1	Uncoordinated; ecological environment is blocked	I3
	0.2<D≤0.4	Moderate imbalance	E(y)–U(x)>0.1	Low-level coordination; urbanization is blocked	II1
			|E(y)–U(x)|≤0.1	Balanced development	II2
			E(y)–U(x)<–0.1	Low-level coordination; ecological environment is blocked	II3
Transition period	0.4<D≤0.6	Low coordination	E(y)–U(x)>0.1	Basic coordination; urbanization is blocked	III1
			|E(y)–U(x)|≤0.1	Balanced development	III2
			E(y)–U(x)<–0.1	Basic coordination; ecological environment is blocked	III3
	0.6<D≤0.8	Moderate coordination	E(y)–U(x)>0.1	High-level coordination; urbanization is blocked	IV1
			|E(y)–U(x)|≤0.1	Balanced development	IV2
			E(y)–U(x)<–0.1	High-level coordination; ecological environment is blocked	IV3
Highly coordinated period	0.8<D≤1	Advanced coordination	E(y)–U(x)>0.1	Uncoordinated; urbanization is blocked	V1
			|E(y)–U(x)|≤0.1	Balanced development	V2
			E(y)–U(x)<–0.1	Uncoordinated; ecological environment is blocked	V3

The coupling degree between urbanization and ecological environment can be divided into three main stages of development, each of which can be further divided into four sub-categories (Li *et al*., 2012). In Table 3, E(y) represents ecological environment, U(x) represents urbanization, and D is the coupling coordination degree.

4.3 Geographical detector

Geographical detectors were originally applied to assess the environmental risks to health (Wang *et al*., 2010). They can be used as a statistical method for detecting spatial differentiation and to explain the driving forces behind it (Wang and Xu, 2017). Geographical detectors have less constraints than other models in terms of hypothesis formulation (Hu *et al*., 2011) and can analyze both numerical and qualitative data. They can also analyze the effects of two factors interacting with dependent variables. They have therefore been widely used to analyze the evolution of geographical elements and the differentiation of geographical space. The core idea of a factor detector is that geographical elements always exist in specific spatial locations, and the environmental factors affecting their development are spatially different. If a certain environmental factor has a significant spatial consistency with regard to the change of a geographical element, the environmental factor would be decisive for the occurrence and development of that geographical element (Wang *et al*., 2010).

5 Results

5.1 Evolution of the coupling coordination degree between urbanization and ecological environmental systems at the national scale in Kazakhstan

In this study, the original data at the national scale for Kazakhstan were standardized, and the trends of the coupling degree and coupling coordination degree between urbanization and ecological environment were calculated according to the coupling degree and coupling coordination degree formulas, respectively (Figure 1). From 1992 to 2018, the coupling degree presented an inverted "U"-shaped curve of "slow growth–stable growth–fast decline," and the coupling coordination degree maintained a continuous rising trend. A very close interaction between urbanization and ecological environment was identified in Kazakhstan. According to the changes in the coupling coordination degree, the development could be divided into three stages. (1) There was a relatively slow urbanization in the stage from 1992 to 2005. Due to a plenty of energy resources and through urban expansion, there was eventually rapid growth in population agglomeration, which increased the urbanization level. However, resource exploitation and industrial development during this stage generated enormous pressure on the ecological environment. (2) From 2005 to 2013, there was a period of concern for the ecological environment. After experiencing extensive economic growth, Kazakhstan introduced a number of environmental policies that focused on the promotion of high-quality urban development. This resulted in a slow decline in the coupling degree and a continuous increase in the coupling coordination degree. (3). From 2013 to 2018, the ecological environment had a limiting effect on the rate of urbanization, leading to a decrease in urbanization and a decrease in the coupling coordination degree between urbanization and ecological environment.

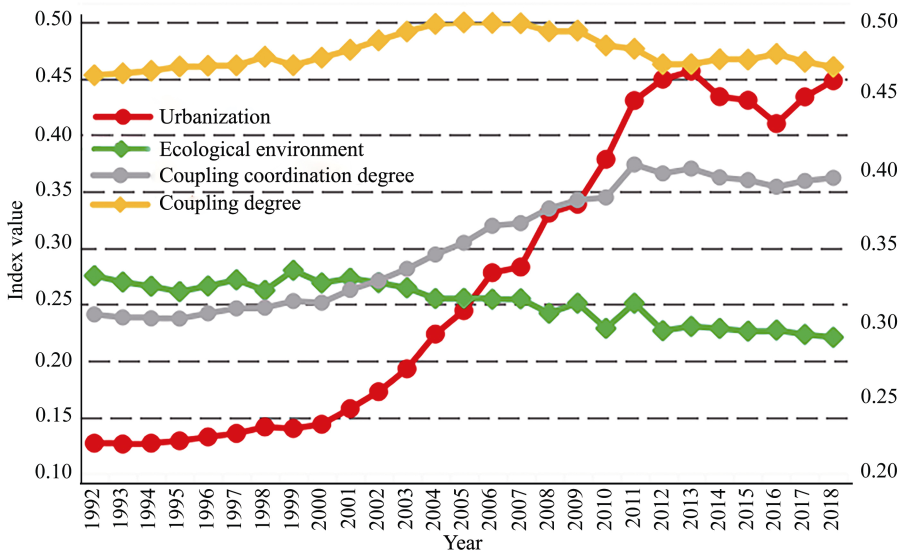


Figure 1 Urbanization and ecological environmental systems indexes and trends for the coupling coordination degree at the national scale in Kazakhstan

5.2 Spatiotemporal evolution of the urbanization and ecological environmental systems and their interactions within the oblasts of Kazakhstan

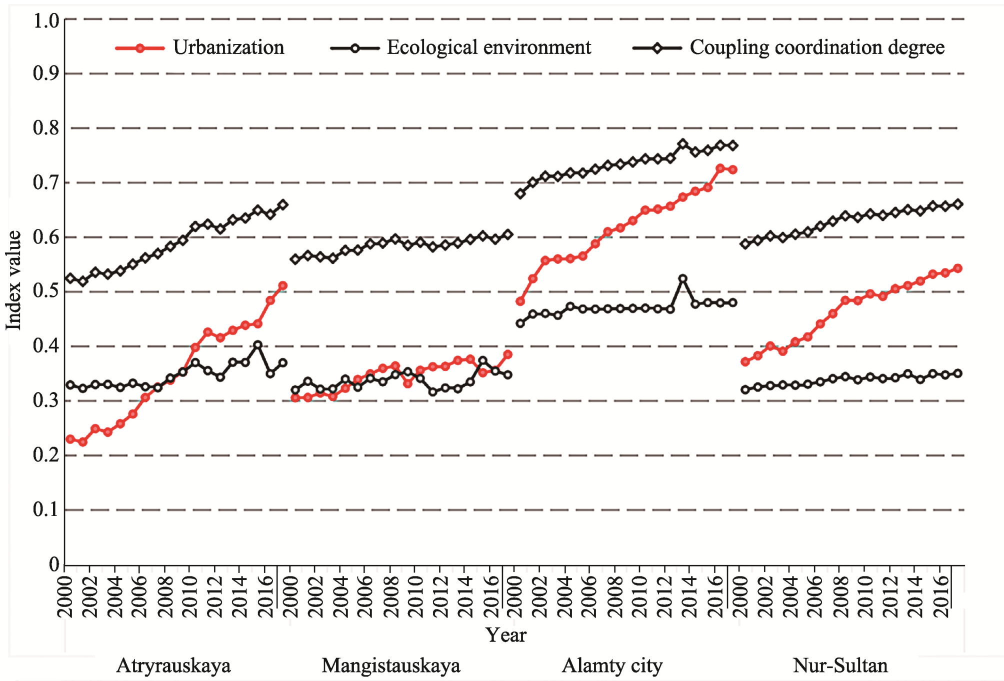
5.2.1 The spatiotemporal evolution of the comprehensive urbanization index within the oblasts of Kazakhstan

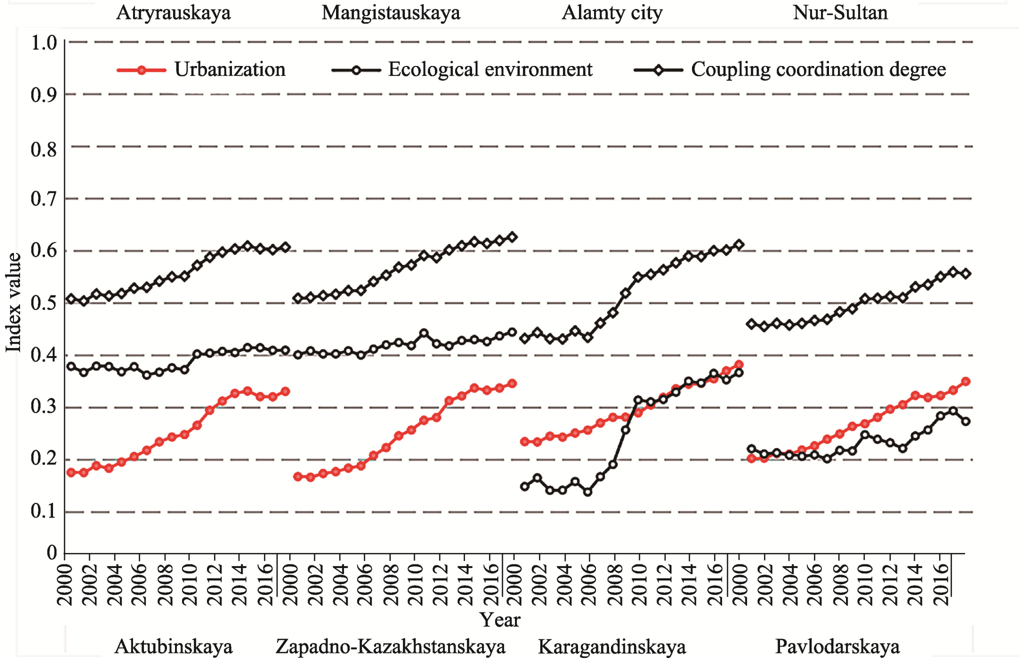
A statistical chart (Figure 2) for the years 2000–2017 was constructed to analyze the interaction between urbanization and ecological environment within the oblasts of Kazakhstan. The comprehensive urbanization index of various administrative regions in Kazakhstan increased over time. When the average annual level of urbanization in each administrative unit was compared, Almaty city (0.48–0.72) comprised the first echelon within the country. Nur-Sultan city[2] (0.37–0.54), Atyrauskaya (0.22–0.51), and Mangistauskaya (0.30–0.40) comprised the second echelon, which indicated that these units had an absolute advantage in terms of their urbanization level. Karagandinskaya (0.23–0.38), Pavlodarskaya (0.20–0.35), Zapadno-Kazakhstanskaya (0.17–0.35), and Aktubinskaya (0.17–0.33) comprised the third echelon. Yuzhno-Kazakhstanskaya (0.10–0.27), Severo-Kazakhstanskaya (0.08–0.22), Akmolinskaya (0.11–0.24), Zhambylskaya (0.12–0.22), and Almatinskaya (0.07–0.21) comprised the fourth echelon.

As shown in Figure 3, during the study period, the comprehensive urbanization index of all regions of Kazakhstan displayed an upward trend. In terms of spatial differentiation, the areas with higher levels of comprehensive urbanization were mainly distributed in provinces such as Atyrauskaya and Zapadno-Kazakhstanskaya in the west, which have an abundance of mineral resources (oil and gas reserves). Atyrauskaya is the province with the largest oil production and produces most of the crude oil in Kazakhstan. In 2017 it produced and condensate 42.39 million tons of crude oil (about 49.2% of the country's total output), and ex-

[2]Nur-Sultan was renamed in 2019, having originally being named Astana. For consistency, this paper uses the new name of Nur-Sultan.

tracted 20.92 billion m^3 of natural gas (about 40% of the national output). Its level of urbanization is relatively high and its industrial base of oil and gas exploration has driven regional economic development. The areas with low levels of urbanization are mainly distributed in parts of the south and north, such as Yuzhno-Kazakhstanskaya and Zhambylskaya in the south and Severo-Kazakhstanskaya and Kostanaiskaya in the north. These areas are mainly grassland and mountainous areas. The southern climatic conditions are mild and suitable for the development of the fruit and vegetable industry. The north is relatively cold and is an important grain-producing area. A quarter of Kazakhstan's grain comes from





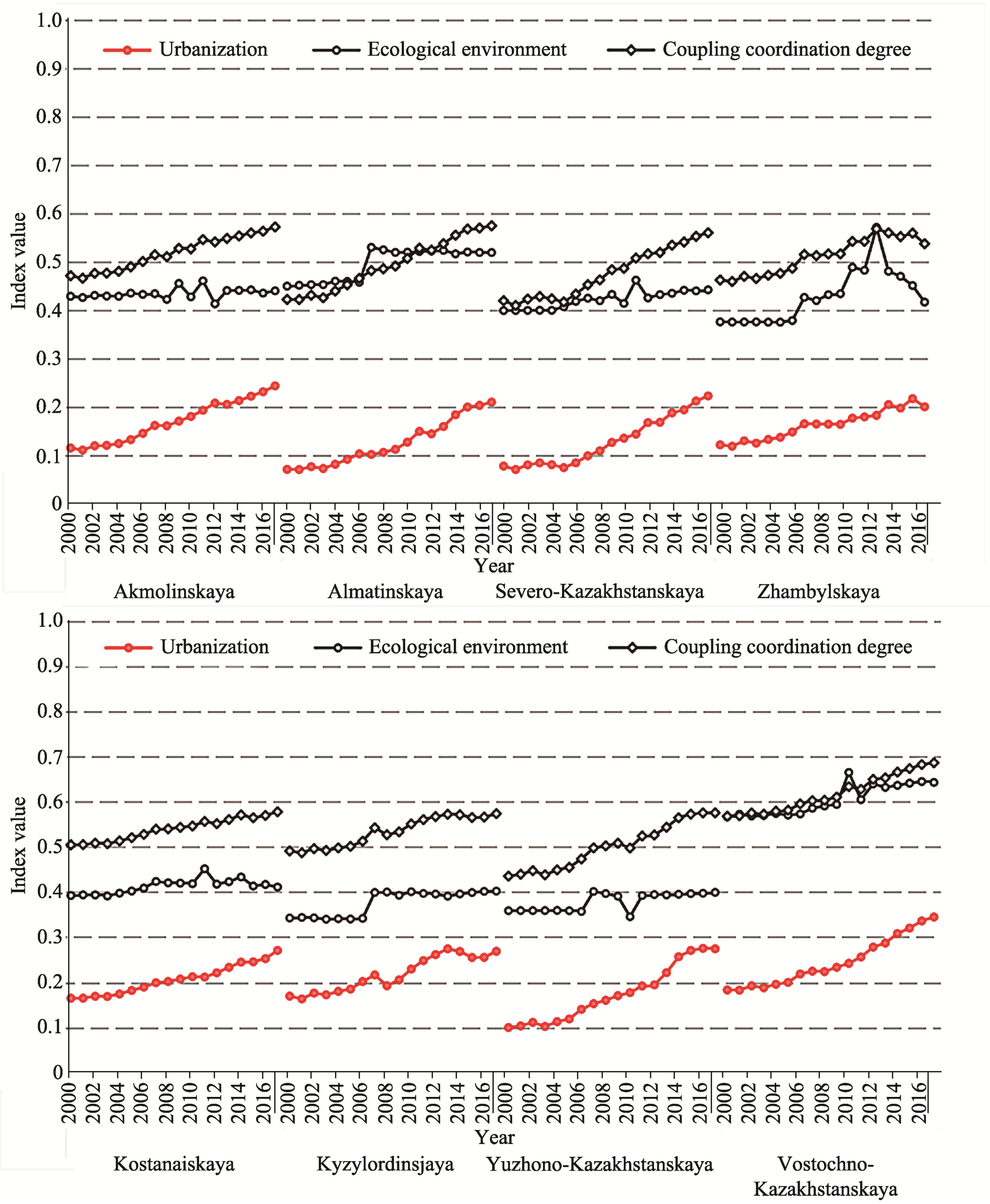


Figure 2 Urbanization and ecological environmental systems index values and trends for the coupling coordination degree within the oblasts of Kazakhstan

Kostanaiskaya. In 2017 and 2018, the grain output was 5.2 and 5 million tons, respectively. Because Kostanaiskaya is mainly engaged in agricultural development, its level of economic development is generally lower than the average national level. With relatively scarce mineral resources, infrastructure, and human resources, the overall level of urbanization is low. In the central and northeastern parts of the country, including Karagandinskaya, Pavlodarskaya, and Zapadno-Kazakhstanskaya, there is an intermediate level of urbanization. The climate of this region is of continental climatic type, which is cold and dry. Agricultural development is limited in this region, but due to its abundant mineral resources and the indus-

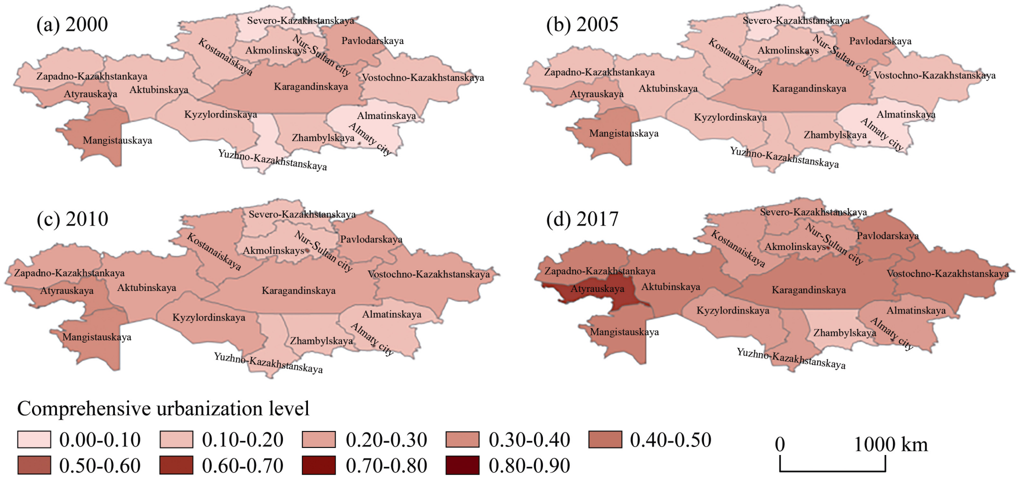


Figure 3 Spatiotemporal evolution of the comprehensive urbanization index within the oblasts of Kazakhstan from 2000 to 2017

trial facilities left over from the Soviet era, there are very favorable conditions for industrial development. Karagandinskaya is rich in non-ferrous metals and is the transit point of the Central Asia's oil pipeline and the Eurasian railway, while Pavlodarskaya is an important industrial base (Xing *et al*., 2015). The states around Almaty, Kazakhstan's largest and most industrialized city, and the capital city of Nur-Sultan have low levels of urbanization. Almaty and Nur-Sultan have little effect on promoting the urbanization of surrounding regions.

5.2.2 The spatiotemporal evolution of the comprehensive ecological environment index within the oblasts of Kazakhstan

Over time, the comprehensive ecological environment index of all regions of Kazakhstan displayed a fluctuating upward trend, indicating that Kazakhstan's overall ecological environment level has improved, but the overall increase has been small (Figure 2). In terms of its spatial distribution, the comprehensive index of ecological environment values was high in the east and west, and low in the central part of the country, where it is lowlying, with low ecological environmental quality (Figure 4). Overall, the comprehensive index of ecological environment values for Vostochno-Kazakhstanskaya in the east and Almatinskaya in the southeast were much higher than those of the other regions, because the eastern and southeastern parts of Kazakhstan contain mountains and valleys and have a good ecological foundation. Except for the Karagandinskaya and Pavlodarskaya regions, the comprehensive ecological environment index was consistent with the ecological background. The ecological conditions of the Karagandinskaya and Pavlodarskaya regions are considered to be moderately good, but the comprehensive ecological environment index values were the lowest among all regions of the country. This was mainly because they are industrial and mining areas, where development has occurred from industrial production such as metallurgy, coal, petroleum processing, and machinery manufacturing. Industrial development has caused environmental pollution. However, in recent years, Karagandinskaya's comprehensive ecological environment index has increased significantly, rising rapidly from 0.148 in 2000 to 0.314 in 2009, and finally reaching 0.367 in 2017.

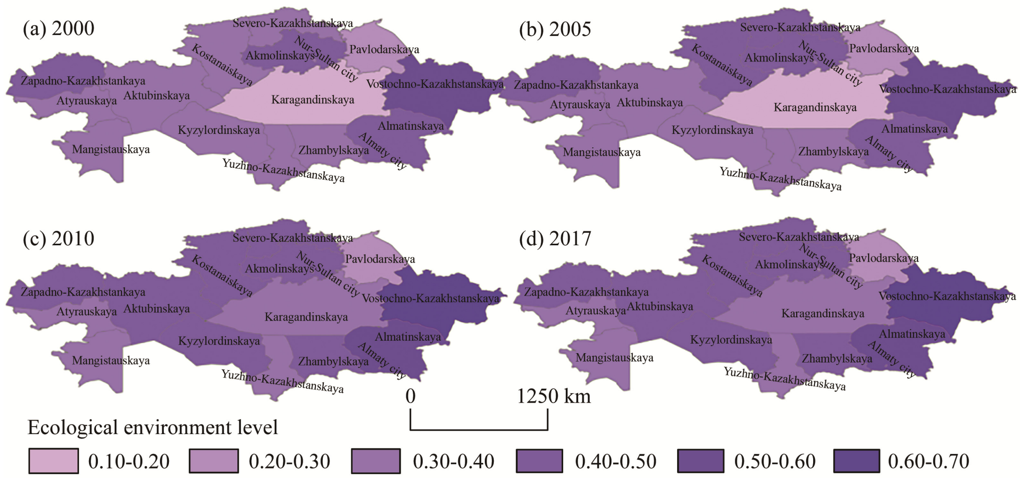


Figure 4 Spatiotemporal evolution of the comprehensive ecological environment index within the oblasts of Kazakhstan from 2000 to 2017

5.2.3 Spatiotemporal evolution of the interaction between the urbanization system and the ecological environmental system within the oblasts of Kazakhstan

The coupling coordination degree between the urbanization and ecological environment can be used to reflect not only the correlation between systems but also the size of the system index (Wang *et al*., 2019). For those oblasts where the relationship between urbanization and ecological environment was not in harmony, the exploitation of resources and urban development was more restricted. The coupling coordination degree between urbanization and ecological environment within the oblasts of Kazakhstan from 2000 to 2017 was calculated to characterize the correlation and coordination of urbanization and ecological environment (Table 4), and to summarize the stage of development in each region.

In terms of the spatiotemporal differentiation of the coupling coordination degree between urbanization and ecological environment in Kazakhstan, the states mainly had a low-moderate level of coordination and were at the stage of transformation and development. In terms of spatial distribution, the coordination level of the east, middle, and west of the country was higher than that of the south and north (Figure 5). This spatial distribution pattern indicated that the coordination degree between the coupling of the urbanization and ecological environmental systems had the characteristics of an area based on industrial development rather than an area based on agricultural development. Topographically, the coupling coordination degree in the plains area was higher than that in the mountains. Over time, most of Kazakhstan's eastern, central, and western states changed from a low to medium level of coordinated development (Table 5), while most of the northern and southern states were still at a low level of coordinated development, but they changed over time from being dominated by the ecological environment to experiencing urbanization and development. With the introduction of developmental policies in Kazakhstan, much attention has been given to sustainable development, and most regional coordination policies have been gradually upgraded. Almaty, the largest metropolis not only in Kazakhstan but also in the whole of Central Asia, has always been at a stage of moderate coordination. Almaty, the city with the

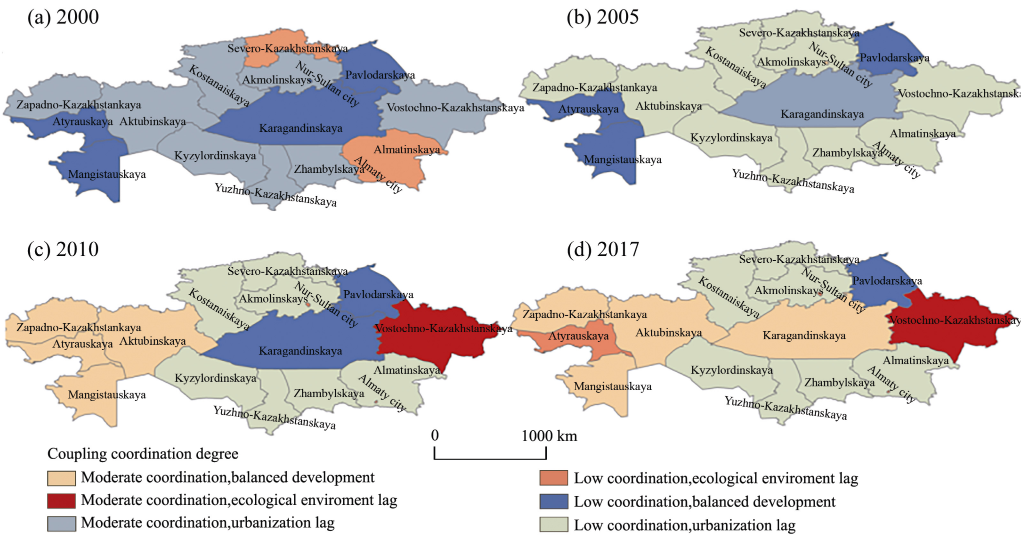


Figure 5 Spatiotemporal evolution of the coupling coordination degree within the oblasts of Kazakhstan from 2000 to 2017

Table 4 Summary of the coupling coordination degree of urbanization and ecological environment within the oblasts of Kazakhstan from 2000 to 2017

Region	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Akmolinskaya	0.471	0.466	0.476	0.476	0.480	0.490	0.500	0.514	0.510	0.528	0.527	0.546	0.541	0.548	0.553	0.560	0.563	0.572
Aktubinskaya	0.508	0.504	0.517	0.513	0.518	0.528	0.530	0.542	0.550	0.551	0.572	0.587	0.597	0.603	0.609	0.604	0.602	0.607
Almatinskaya	0.400	0.422	0.431	0.425	0.439	0.452	0.465	0.482	0.485	0.491	0.507	0.528	0.524	0.537	0.555	0.568	0.570	0.574
Atyrauskaya	0.524	0.519	0.535	0.532	0.538	0.550	0.562	0.570	0.583	0.594	0.619	0.624	0.615	0.632	0.635	0.649	0.641	0.659
Zapadno-Kazakhstanskaya	0.509	0.510	0.514	0.516	0.523	0.524	0.541	0.553	0.568	0.572	0.591	0.587	0.601	0.609	0.617	0.614	0.619	0.626
Zhambylskaya	0.462	0.459	0.470	0.465	0.472	0.476	0.486	0.515	0.513	0.516	0.516	0.542	0.542	0.568	0.560	0.552	0.559	0.537
Karagandinskaya	0.432	0.443	0.431	0.431	0.446	0.434	0.461	0.481	0.518	0.549	0.555	0.563	0.577	0.589	0.589	0.600	0.601	0.612
Kostanaiskaya	0.504	0.505	0.508	0.507	0.513	0.520	0.528	0.539	0.540	0.543	0.546	0.556	0.551	0.560	0.571	0.564	0.569	0.577
Kyzylordinskaya	0.491	0.487	0.496	0.492	0.498	0.501	0.512	0.542	0.527	0.533	0.551	0.560	0.567	0.572	0.571	0.565	0.566	0.573
Mangistauskaya	0.559	0.566	0.564	0.561	0.576	0.576	0.588	0.589	0.597	0.585	0.590	0.582	0.586	0.589	0.596	0.602	0.596	0.605
Yuzhno-Kazakhstanskaya	0.435	0.439	0.447	0.438	0.449	0.455	0.473	0.498	0.502	0.508	0.497	0.524	0.526	0.543	0.564	0.572	0.575	0.575
Pavlodarskaya	0.460	0.455	0.461	0.458	0.461	0.466	0.468	0.483	0.489	0.508	0.509	0.512	0.510	0.530	0.535	0.550	0.559	0.556
Severo-Kazakhstanskaya	0.400	0.409	0.423	0.428	0.423	0.417	0.433	0.452	0.462	0.483	0.486	0.507	0.516	0.519	0.534	0.541	0.552	0.560
Vostochno-Kazakhstanskaya	0.568	0.569	0.575	0.572	0.579	0.581	0.595	0.602	0.603	0.610	0.633	0.627	0.649	0.653	0.665	0.673	0.682	0.686
Nur-Sultan city	0.587	0.594	0.602	0.599	0.605	0.609	0.620	0.629	0.639	0.636	0.643	0.640	0.645	0.650	0.648	0.657	0.656	0.660
Almaty city	0.679	0.700	0.711	0.711	0.718	0.717	0.724	0.731	0.733	0.738	0.743	0.743	0.744	0.771	0.756	0.759	0.768	0.768

Table 5 Classification table of the coupling coordination degree of urbanization and ecological environment within the oblasts of Kazakhstan from 2000 to 2017 (for details of the codes used here refer to Table 3)

Region	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Akmolinskaya	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1
Aktubinskaya	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III2	IV2	IV2	IV2	IV2	IV2
Almatinskaya	II1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1
Atyrauskaya	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	IV2	IV2	IV2	IV2	IV2	IV2	IV3	IV3
Zapadno-Kaza-khstanskaya	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	IV1	IV1	IV2	IV2	IV2	IV2
Zhambylskaya	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1
Karagandinskaya	III2	III2	III3	III3	III2	III3	III3	III2	III2	III2	III2	III2	III2	III2	III2	III2	IV2	IV2
Kostanaiskaya	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1
Kyzylordinskaya	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1
Mangistauskaya	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	IV2	III2	IV2
Yuzhno-Kaza-khstanskaya	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1
Pavlodarskaya	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2	III2
Severo-Kazakhstanskaya	II1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1	III1
Vostochno-Kazakhstanskaya	III1	III1	III1	III1	III1	III1	III1	IV1	IV1	IV1	IV1	IV1	IV1	IV1	IV1	IV1	IV1	IV1
Nurs-Sultan city	III2	III2	IV2	III2	IV2	IV2	IV3	IV3	IV3	IV3	IV3	IV3	IV3	IV3	IV3	IV3	IV3	IV3
Almaty city	IV2	IV2	IV2	IV3	IV2	IV2	IV3	IV3	IV3	IV3	IV3	IV3	IV3	IV3	IV3	IV3	IV3	IV3

highest coupling coordination degree, is not only the largest city in Kazakhstan, but is also the most competitive city in Central Asia. It has a high concentration of human resources, a strong financial foundation, a complete education system and a developed infrastructure. The coupling of rapid economic growth and the Almaty municipal government's heavy investment in environmental protection in recent years resulted in the coupling coordination degree being much higher than the state average and it continues to remain stable.

5.3 The dominant factors influencing the degree of coordination between Kazakhstan's urbanization and ecological environmental systems

Geographical spatial factors affect the spatial differentiation of the interaction between urbanization and ecological environment. Based on the calculated coupling coordination degree between urbanization and ecological environment in Kazakhstan, we conducted an equal-isolation and decentralized treatment for 25 indicators of the urbanization and ecological environmental systems. We then input these results into geographical detector software to calculate the q values affecting the coupling coordination degree between urbanization and ecological environment. Other than the number of professional doctors per 10,000 people and the recycling and re-use rate of waste materials, all other indicators passed the test at a significance level of 0.05. Specifically, in the urbanization subsystem, the indicators of GDP per capita, social fixed asset investment per capita, employment in industry and services (% of total employment), and the number of college students per 10,000 people were found to be important factors in the coupling coordination degree in Kazakhstan, with q values that were much higher than the average. The GDP per capita is an important indicator of regional economic development, and indicates the level of economic growth and urbanization. Urbanization leads to higher economic productivity due to its positive externalities and economies of scale. A higher GDP can attract more innovative talent, and thus promote the establishment of innovative industries without causing high levels of pollution. Research, funding, and educational programs that favor green technology companies are currently flourishing, which will boost the market for green technologies, and thus improve environmental performance. An increasing number of college students will lead to industrial innovation and attract talents to the region, which will promote the high-quality development of regional urbanization. Urbanization promotes the development of service industries because it bridges the gap between intermediary organizations and clients. An outstanding business location, with high-quality talents in an environment in which productivity flourishes will increase the total investment in regional fixed assets, which is in turn a positive factor. These were considered to be important driving forces behind the sustainable and coordinated development of the region.

In the ecological environment subsystem, indicators such as farmland areas per capita, availability of water resources per capita, ecological land per capita, and forest coverage were found to be important factors in the coupling coordination degree in Kazakhstan. In oases of arid areas, the influence of water resources on urbanization was the most decisive factor. An uncontrolled escalation of urbanization tends to result in a deterioration of water systems (Zhang *et al*., 2012; Liu *et al*., 2014), and water resources are particularly important for Kazakhstan. With the rapid development of the petroleum and mining industries in recent years, the availability of water resources has declined. For example, the total amount of renewable water resources in Akmolinskaya decreased from 133,000 million m^3 in 2001 to 54 million m^3 in 2016. In the northern part of Kazakhstan, there are large areas of savanna, which play a vital role in regional and global carbon storage (Propastin *et al*., 2008; Eisfelder *et al*., 2012). Therefore, the protection of land and forest resources plays an important indirect driving role in the interaction between urbanization and ecological environment.

This research on Kazakhstan revealed that the interaction between urbanization and ecological environmental factors had a strong influence on the overall degree of coordination, and they also have a strong synergy. Only the pollutant recovery rate index (i.e., the recycling rate of pollutants) and the value added of industry and services (i.e., % of GDP) were independent of each other, and the interaction between urbanization and ecological environment for these parameters was not significant. Table 6 lists the interactions where the two-factor interaction q value was greater than 0.7. It can be seen that the q value of the interaction factor increased significantly after these interactions. Employment in industry and services (% of total employment) interacted most frequently with the other factors. Employment in industry and services (% of total employment) interacted with the per capita air pollutant index to have the greatest comprehensive impact on the coupling coordination degree of urbanization and ecological environment. To some extent, employment in industry and services (% of employment) reflected the vitality of regional productivity, and some heavy industries and service industries inevitably produced air pollution. Factors such as the number of college students per 10,000 people, GDP per capita, and social fixed asset investment per capita, interacted with other factors multiple times. This shows that economic and social development, and industrial transformation and upgrading have played an important role in promoting the coordinated development of Kazakhstan's urbanization and ecological environmental systems.

Table 6 Dominant interaction factors affecting the harmony between urbanization and ecological environment in Kazakhstan

Dominant interaction factor	*q*	Dominant interaction factor	*q*	Dominant interaction factor	*q*
Employment in industry and services (% of total employment) ∩ GDP per capita	0.709	Cereal production per capita ∩ Urban population (% of total)	0.717	Recycling rate of pollutants ∩ Employment in industry and services (% of total employment)	0.713
Employment in industry and services (% of total employment) ∩ Gross industrial output value per capita	0.703	Cereal production per capita ∩ Employment in industry and services (% of total employment)	0.752	Emissions of liquid and gasiform pollutant substances ∩ Employment in industry and services (% of total employment)	0.787
Employment in industry and services (% of total employment) ∩ Social fixed asset investment per capita	0.705	Ecological land per capita ∩ GDP per capita	0.743	Emissions of solid pollutants ∩ Employment in industry and services (% of total employment)	0.762
Employment in industry and services (% of total employment) ∩ Number of public buses per 10,000 people	0.704	Ecological land per capita ∩ Employment in industry and services (% of total employment)	0.731	Emissions of free air pollutants, divergent from stationary sources ∩ Employment in industry and services (% of total employment)	0.803
Employment in industry and services (% of total employment) ∩ Number of built-up areas per 10,000 people	0.758	Forest areas (% of land area) ∩ Employment in industry and services (% of total employment)	0.788	Emissions of liquid and gasiform pollutant substances ∩ Gross industrial output value per capita	0.751
Per capita income and consumption expenses ∩ Employment in industry and services (% of total employment)	0.721	Forest area (% of land area) ∩ GDP per capita	0.758	Emissions of liquid and gasiform pollutant substances ∩ Social fixed asset investment per capita	0.753
Number of public buses per 10,000 people ∩ Employment in industry and services (% of total employment)	0.750	Forest area (% of land area) ∩ Urban population (% of total)	0.748	Emissions of free air pollutants from non-stationary sources ∩ Gross industrial output value per capita	0.717
Number of college students per 10,000 people ∩ GDP per capita	0.731	Forest area (% of land area) ∩ Number of college students per 10,000 people	0.729	Emissions of free air pollutants from non-stationary sources ∩ social fixed asset investment per capita	0.711
Number of college students per 10,000 people ∩ social fixed asset investment per capita	0.711	Forest area (% of land area) ∩ Arable land area (hectares per person)	0.716	Emissions of free air pollutants from non-stationary sources ∩ Urban population (% of total)	0.717
Number of college students per 10,000 people ∩ Number of public buses per 10,000 people	0.720	Running expenses for environmental protection ∩ Urban population	0.756	Emissions of free air pollutants from non-stationary sources ∩ Urban population (% of total)	0.704
Number of college students per 10,000 people ∩ Employment in industry and services	0.783	Running expenses on environmental protection ∩ Employment in industry and services	0.739		
Number of college students per 10,000 people ∩ Per capita income and consumption expenses	0.712	Running expenses on environmental protection ∩ Number of college students per 10,000 people	0.751		
Number of college students per 10,000 people ∩ Number of public buses per 10,000 people	0.784	Purification rate of pollutants ∩ Employment in industry and services	0.726		

6 Conclusions and discussion

6.1 Conclusions

In this study, a comprehensive evaluation index system for urbanization and ecological environment in Central Asia was constructed. Taking Kazakhstan as a case study, the spatio-temporal changes of the coupling degree and coupling coordination degree between the comprehensive index of urbanization and ecological environment at the national and state scales were analyzed. A geographical detector model was used to identify the main factors controlling the interaction between urbanization and ecological environment in Kazakhstan. The conclusions can be drawn as follows:

(1) The coupling degree between urbanization and ecological environment in Kazakhstan at the national scale displayed an inverted "U" shaped curve, indicating a pattern of "slow growth - stable growth - fast decline," while the coupling coordination degree displayed a continuous upward trend.

(2) In recent years, the coupling of urbanization and ecological environment of Kazakhstan has shown an upward trend. For states with a high level of industrialization, the level of urbanization was significantly higher than that of states with a high level of agricultural production. From a spatial perspective, the comprehensive urbanization index values for the western and eastern states were higher than those of the southern and northern states. In terms of the ecological environment, the comprehensive ecological environment index values for each state fluctuated and increased over the study period, but the increases were not large. The comprehensive ecological environment index presented a spatial distribution pattern of being high in the east and west and low in the central region. Except in Karaganda and Pavlodar, the comprehensive ecological environment index was mainly determined by the ecological background.

(3) Overall, the interaction between urbanization and ecological environmental system in the states of Kazakhstan had a relatively low level of coordination, but it displayed a positive development trend. The spatial distribution showed that the coordination level of the east, middle, and west of the country was higher than that of the south and north. The states with good industrialization development were in a moderately well-coordinated state, while in the states where agriculture was the main activity urbanization and ecological environment were poorly coordinated and there was a lack of economic development. The coordination degree in Almaty was the largest in the country.

(4) The investigation and identification of the main factors that affected the coordination degree between urbanization and ecological environment were determined based on a geographic detector model. The indicators of GDP per capita, social fixed asset investment per capita, employment in industry and services (% of total employment), and the number of college students per 10,000 people were important urbanization factors that affected the coupling coordination degree of urbanization and ecological environment in Kazakhstan. The indicators of farmland areas per capita, availability of water resources per capita, ecological land per capita, and forest coverage were important environmental factors that affected the coordination degree between the coupling of urbanization and ecological environment in Kazakhstan. The interaction of each element in the two subsystems had a greater impact on the coupling coordination degree than any single element, and also had a strong synergy.

6.2 Discussion

The ecological environment in Central Asia is fragile, with several prominent ecological problems. The industrial structure is dominated by agriculture and basic energy-based industries, and urbanization is severely restricted by ecological environmental conditions. Kazakhstan has the largest area and total economic output among the five Central Asian countries, as well as the highest level of urbanization and industrialization. The coordinated development of urbanization and protection of ecological environment has had a demonstrable effect on the sustainable development of Central Asia and arid regions elsewhere in the world. This study found that in the past ten years, Kazakhstan has shown a healthy and coordinated developmental trend between urbanization and protection of ecological environment. Some successful developments have occurred, but some problems still exist. Therefore, the following suggestions are proposed for the future development of Kazakhstan.

(1) Kazakhstan is still facing the problem of a lack of urbanization. It is necessary to accelerate the urbanization of the population, space, society, and economy, and narrow the gap between the various subsystems. To achieve a breakthrough in population urbanization, the transformation of the agricultural population from agriculture-based states to urban populations should be actively promoted to improve the population urbanization rate. The rate of infrastructure construction should be increased to improve the population carrying capacity of cities. Ecologically efficient industries should be promoted to replace traditional low-ecological efficient industries and production methods. An accelerated program of industrial upgrading would transform economic development patterns.

(2) Kazakhstan's industry is dominated by traditional oil and gas exploitation, and the ecological environment has been seriously damaged. Therefore, it is necessary to strengthen the environmental protection of resources, improve the efficiency of resource utilization, and gradually increase the carrying capacity of the local ecological environment. Increased investment in environmental protection is necessary, including the establishment of sewage treatment plants and sewage recycling facilities to relieve the pressure on water resources. It is also necessary to expand the area of vegetation cover, including forest areas, and to develop and use land rationally, whilst also remediating damaged land resources.

(3) The opportunity offered by the “Belt and Road” construction project should be seized to further accelerate the transformation and upgrading of the country’s industrial structure. The industrial chain could be extended in terms of the traditional petrochemical industry by progressing from crude oil extraction to deep processing. The development potential of renewable energy should be exploited to develop clean energy. The introduction of professional talent is needed together with an improvement in the level of education. High-tech industries should be cultivated and developed, and tertiary industry should be developed in an appropriate manner.

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