Postprint: Analysis of the Coupling Process and Mechanism between Urbanization and Ecological Environment in Kazakhstan

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Date: 2021-08-02T00:00:00+00:00

Abstract

Against the backdrop of the Belt and Road Initiative, exploring the complex relationship between urbanization and the ecological environment in Kazakhstan holds significant importance. By employing the entropy-weighted coefficient of variation method and multi-objective fuzzy membership functions to conduct comprehensive measurements of urbanization and the ecological environment in Kazakhstan respectively and construct comprehensive indices, the dynamic coupling relationship between urbanization and the ecological environment was analyzed based on an improved Tapio decoupling analysis model, and its static coupling relationship was examined using threshold analysis. The results indicate: (1) High values of comprehensive urbanization in Kazakhstan are primarily distributed in the oil extraction areas of the west and the industrial zones of the central and northeastern regions, while low values are mainly distributed in the southern region and parts of the north characterized by agricultural economies. (2) High values of the comprehensive ecological environment level are distributed in Nur-Sultan and Almaty, which are dominated by the service sector and exhibit high ecological environment protection responsiveness, whereas low values are mainly distributed in the western oil and gas extraction areas with relatively active carbon emissions. (3) From 2000–2015, the dynamic coupling relationship between urbanization and the ecological environment in Kazakhstan was primarily characterized by strong decoupling, weak decoupling, strong negative decoupling, recessive decoupling, and expansive negative decoupling states; through summarizing and inducing the coupling mechanism, it is found that ecological environment protection responsiveness, the stage of urbanization, total agricultural water consumption, and the international external economic environment are the main driving factors influencing the coupling relationship between urbanization and the ecological environment in Kazakhstan.

Full Text

Coupling Process and Mechanism of Urbanization and Ecological Environment in Kazakhstan

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Abstract: Against the backdrop of the Belt and Road Initiative, exploring the complex relationship between urbanization and the ecological environment in Kazakhstan holds significant importance. This study employs the coefficient of variation method supported by entropy technology and multi-objective fuzzy membership functions to comprehensively measure urbanization and ecological environment in Kazakhstan, constructing comprehensive indices. Based on an improved Tapio decoupling analysis model, we analyze the dynamic coupling relationship between urbanization and ecological environment, and use threshold analysis to examine their static coupling relationship. The results indicate that: (1) High values of comprehensive urbanization in Kazakhstan are mainly distributed in the oil extraction areas in the west and the industrial areas in the central and northeastern regions, while low values are primarily concentrated in the southern and some northern regions characterized by agricultural economies. (2) High values of the ecological environment comprehensive level are found in Nur-Sultan and Almaty, which are dominated by the service industry and demonstrate high responsiveness to ecological environmental protection, whereas low values are mainly distributed in the western oil and gas extraction areas with relatively active carbon emissions. (3) From 2000 to 2015, the dynamic coupling relationship between urbanization and ecological environment in Kazakhstan mainly exhibited states of strong decoupling, weak decoupling, strong negative decoupling, declining decoupling, and expansion negative decoupling. (4) Through summarizing the coupling mechanism, we find that the responsiveness of ecological environmental protection, the stage of urbanization, total agricultural water consumption, and the international external economic environment are the main driving factors influencing the coupling relationship between urbanization and ecological environment in Kazakhstan.

Keywords: ecological environment; comprehensive urbanization; coupling process; decoupling model; Kazakhstan

1 Study Area Overview

Kazakhstan is located in northern Central Asia, bordering Turkmenistan, Uzbekistan, and Kyrgyzstan to the south, Russia to the north, China to the east, and the Caspian Sea to the west. Kazakhstan comprises 14 states and

2 municipalities (Almaty and Nur-Sultan). The 14 states include: Akmola, Kostanay, Pavlodar, and North Kazakhstan in the north; Karaganda in the center; East Kazakhstan in the east; Aktobe, Atyrau, West Kazakhstan, and Mangystau in the west; and Almaty, Zhambyl, South Kazakhstan, and Kyzylorda in the south. Kazakhstan has a total area of 2.72 million km^2, accounting for 60.11% of Central Asia' s land area. In 2018, its permanent population was 18.038 million and its GDP was $159.47 billion, representing 25.30% and 27.8% of Central Asia' s five countries, respectively. Since 2000, the development of oil, natural gas, and mineral resources has attracted over $40 billion in foreign investment, accounting for approximately 70% of the country' s total industrial output value (about 25% of GDP). Overall, Kazakhstan is a region with relatively advanced urbanization and relatively developed economic growth in Central Asia.

[Figure 1: see original paper]

2 Data and Methodology

2.1 Data Sources and Indicator System

Socioeconomic and ecological environment data for Kazakhstan from 2000 to 2015 at the state scale were obtained from the *Kazakhstan Population Statistical Yearbook*, *Kazakhstan Environmental Protection and Sustainable Development Statistical Yearbook*, *Kazakhstan Regional Statistical Yearbook*, *Kazakhstan Industrial Statistical Yearbook*, and *Kazakhstan Economic Statistical Yearbook*. Missing data for individual years were interpolated using adjacent years. Per capita income levels were converted to US dollars using the official exchange rate from the World Bank database. Per capita ecological land data were calculated using European Space Agency land use data. Per capita available freshwater resources were estimated based on national-scale available freshwater resources and basin water resources in Kazakhstan, with basin water resources referenced from relevant foreign literature.

Drawing upon existing research on urbanization and ecological environment indicator systems, and based on a thorough understanding of urbanization theory and connotation, this study constructs a comprehensive evaluation system suitable for Kazakhstan. For the comprehensive urbanization indicator system, we selected population urbanization, economic urbanization, social urbanization, and spatial urbanization as primary indicators, and chose 12 secondary indicators from four dimensions. For the comprehensive ecological environment indicator system, we drew upon the PSR (Pressure-State-Response) framework, selecting 9 secondary indicators from three dimensions to construct the ecological environment comprehensive evaluation index system (Table 1). As Kazakhstan' s economic development mainly relies on energy resource extraction and export, with manufacturing accounting for a relatively low proportion and contribution to economic development, this study added the indicator "manufacturing value added as a proportion of GDP" to the economic urbanization subsystem to objectively reflect the degree of industrial structure optimization during urbanization while avoiding the impact of energy industries on economic urbanization levels.

2.2 Methodology

2.2.1 Indicator Preprocessing and Weight Calculation Multi-objective fuzzy membership function standardization. Given that raw indicator data have large dimensional differences and different units, making them incomparable, they must be nondimensionalized. To avoid affecting standardization results due to excessively large differences between maximum and minimum values of some data, this study employs multi-objective fuzzy membership function standardization. The formulas are detailed in the literature.

For positive indicators, the membership formula is:

$$s_{\lambda ij} = \frac{1}{1 + \left(\frac{x_{\lambda ij} - pn}{pn - mn}\right)^2} \quad \text{when } x_{\lambda ij} < pn$$

$$s_{\lambda ij} = 1 \quad \text{when } pn \leq x_{\lambda ij} \leq pn^+$$

For negative indicators:

$$s_{\lambda ij} = \frac{1}{1 + \left(\frac{x_{\lambda ij} - pn}{pn - mn}\right)^2} \quad \text{when } x_{\lambda ij} > pn$$

$$s_{\lambda ij} = 1 \quad \text{when } pn^- \leq x_{\lambda ij} \leq pn$$

where $s_{\lambda ij}$ is the standardized value of the jth indicator for the ith study area in year λ; $x_{\lambda ij}$ is the actual value; mn is the threshold for the urbanization comprehensive index grading standard; and pn is the threshold for the specific indicator grading standard. This study divides the urbanization (or ecological environment) comprehensive index into five levels: low, relatively low, medium, relatively high, and high, with corresponding threshold intervals of $[0, 0.2)$, $[0.2, 0.4)$, $[0.4, 0.6)$, $[0.6, 0.8)$, and $[0.8, 1.0]$. The pn values are determined by referencing relevant domestic and foreign literature and development experience from developed countries and regions, with specific methods detailed in the literature.

Weight calculation. To eliminate bias from single objective weighting methods and avoid subjectivity and errors from subjective weighting methods, this study combines entropy weighting and coefficient of variation methods to calculate weights for greater accuracy and reliability. The formulas are detailed in the literature.

The comprehensive weight of the jth indicator for urbanization (or ecological environment) is:

$$w_j = \frac{w'_j + u'_j}{2}$$

where w'_j and u'_j are the weights from the entropy method and variation coefficient method, respectively.

The development index of the ith state' s urbanization (or ecological environment) subsystem is:

$$UI_i = \sum_{j=1}^{n} w_j \cdot s_{ij}$$

where w_j and u_j are the entropy weight and variation weight of the jth indicator, respectively; and UI_i is the urbanization (or ecological environment) subsystem development index for the ith state calculated by combining both methods.

2.2.2 Decoupling Model Decoupling theory, first proposed by the Organisation for Economic Co-operation and Development (OECD), describes the breaking of links between economic growth and resource consumption or environmental pollution. Its application and development have gradually received widespread attention. Based on the Tapio model, this study constructs a decoupling model for regional comprehensive urbanization and ecological environment pressure in Kazakhstan:

$$\varepsilon_{tk} = \frac{\Delta EPI_{tk}}{\Delta UI_{tk}} = \frac{EPI^e_{tk} - EPI^s_{tk}}{EPI^s_{tk}} \Big/ \frac{UI^e_{tk} - UI^s_{tk}}{UI^s_{tk}}$$

where ε_{tk} is the decoupling state in period tk; ΔEPI_{tk} is the change rate of the ecological environment pressure index in period tk; EPI^s_{tk} and EPI^e_{tk} are the ecological environment pressure indices at the beginning and end of period tk, respectively; ΔUI_{tk} is the change rate of the comprehensive urbanization index in period tk; and UI^s_{tk} and UI^e_{tk} are the comprehensive urbanization indices at the beginning and end of period tk, respectively.

Based on the growth rates of ecological environment and urbanization levels and the decoupling index ε_{tk}, the decoupling states between urbanization and ecological environment systems are classified as shown in Table 2.

3 Results

3.1 Spatial-Temporal Evolution Characteristics

3.1.1 Spatial-Temporal Evolution of Comprehensive Urbanization Level in Kazakhstan From 2000 to 2015, Kazakhstan' s comprehensive urbanization level showed significant growth. In 2000, the comprehensive urbanization level was mainly medium and relatively low, with median values distributed in central and northeastern regions including Karaganda, Pavlodar, and East Kazakhstan states. From 2005 onward, Atyrau, West Kazakhstan, Aktobe, Pavlodar, and Karaganda states successively entered the relatively high urbanization level stage, while South Kazakhstan and Almaty states developed relatively slowly, remaining at the low urbanization level stage for an extended period. The remaining states successively entered the medium urbanization level stage.

As shown in Figure 2, higher values of comprehensive urbanization in Kazakhstan are mainly distributed in the old industrial areas in the central region, the oil extraction areas in the western region, and the heavy industrial area of Pavlodar in the northeast. Lower urbanization values are mainly distributed in South Kazakhstan, North Kazakhstan, and Almaty states. Southern Kazakhstan is dominated by grasslands and mountains with mild climatic conditions suitable for fruit and vegetable cultivation, while the northern region is relatively cold and serves as an important grain production area. Kazakhstan' s grain largely comes from Kostanay state, with grain production of 5.0–5.2 million tons in 2015. As Kostanay state focuses on agricultural development with relatively scarce mineral resources, its regional economic development level is generally below the national average, with relatively limited infrastructure and human resources. Therefore, its comprehensive urbanization level was relatively low in the early period from 2000 to 2005. With industrial development, its urbanization level gradually entered the medium stage from 2006 onward. Almaty city, as Kazakhstan' s most complete and largest industrial city, and Nur-Sultan, as the capital, have generally limited radiating and driving effects but obvious trickle-down effects, resulting in relatively low comprehensive urbanization levels in Almaty and Akmola states.

[Figure 2: see original paper]

3.1.2 Spatial-Temporal Evolution of Ecological Environment Level in Kazakhstan Kazakhstan' s ecological environment index fluctuated significantly over time, with relatively small overall increases (Figure 3). Due to large differences in climate, aridity, land use types, and area among administrative units, the comprehensive ecological environment levels vary considerably. Because they are dominated by the service industry with low industrial pollution and water pressure, and have high pollutant treatment and purification rates and good ecological environment response measures, Nur-Sultan and Almaty cities have ecological environment levels higher than the average of all states, placing them in the first tier. East Kazakhstan, Almaty, and North Kazakhstan states have ecological environment status levels at relatively high or high levels (0.6–1.0), ecological environment pressure at relatively low or low levels, and ecological environment response at medium or relatively high levels, resulting in good comprehensive ecological environment levels and placing them in the second tier. Mangystau, Atyrau, Pavlodar, and Karaganda states are in the fourth tier. In recent years, Karaganda state has intensified environmental governance, reducing air pollution emissions from 4.33 billion m^3 to 1.4154 billion m^3, with its comprehensive ecological environment level continuously improving. Pavlodar state has maintained air pollution emissions at around 800,000 tons since 2000, with its comprehensive ecological environment level remaining at 0.4–0.5. In Mangystau, Atyrau, and other regions, wasteland accounts for as much as 66.44% and 85.97% of the area, respectively, with grassland coverage also relatively low, resulting in poor baseline ecological environment conditions. Combined with air pollution emissions from the oil and gas industry, the comprehensive ecological environment quality is poor. The remaining states fall into the third tier, with ecological environment levels showing fluctuating changes.

[Figure 3: see original paper]

3.2 Dynamic Coupling Between Urbanization and Ecological Environment in Kazakhstan

Figures 4 and Table 3 show the spatial-temporal evolution trends and calculation results of the decoupling status between urbanization and ecological environment in Kazakhstan. From the annual changes between 2000 and 2015, the dynamic changes in the decoupling relationship between urbanization and ecological environment in Kazakhstan states mainly manifested as strong decoupling, weak decoupling, strong negative decoupling, declining decoupling, and expansion negative decoupling states. These five states accounted for 100% of the statistical periods, with strong and weak decoupling states accounting for 65.9% of the total, significantly higher than the remaining states combined. This is because the change amplitude of urbanization was higher than that of the ecological environment pressure comprehensive index, and as both urbanization subsystems and ecological environment subsystems in each state showed fluctuating changes, their dynamic relationship also exhibited unstable changes over time.

Overall, strong decoupling is widely distributed in three types of regions: First, regions where urbanization speed changes are not substantial and ecological environment responsiveness is good, such as Akmola, Aktobe, and West Kazakhstan states. As urbanization development speed remains within the carrying capacity of the ecological environment, environmental governance and protection efforts exceed environmental degradation with urbanization development. Second, regions with relatively high proportions of agricultural output value, such as Kostanay, South Kazakhstan, and East Kazakhstan states, which originally had low urbanization levels. During the initial stage of urbanization, industrial pollution pressure is relatively small, while agricultural water pressure decreases, resulting in a strong decoupling state. Third, regions with relatively fast urbanization development speed but high ecological environment responsiveness, such as Karaganda state, which entered the high ecological environment response stage in 2005, with ecological environmental protection investment, pollutant recycling utilization rate, and detoxification purification rate all ranking among the top in Kazakhstan.

Strong negative decoupling is mainly distributed in Mangystau state, concentrated between 2000 and 2005, attributed to reduced population urbanization levels caused by population migration and decreased oil and gas exports due to economic crisis.

[Figure 4: see original paper]

3.3 Static Coupling Relationship Between Urbanization and Ecological Environment in Kazakhstan

Drawing on existing research and considering Kazakhstan' s actual conditions, this study classifies the spatial coupling types of comprehensive urbanization and ecological environment levels in each state (classification criteria shown in Table 4). The spatial coupling types are divided into four categories: HH (high urbanization, high ecology), HL (high urbanization, low ecology), LH (low urbanization, high ecology), and LL (low urbanization, low ecology).

3.3.1 HH Type: High Urbanization and High Ecology Both urbanization and ecological environment comprehensive levels are high, with well-coordinated urbanization and ecological environment systems, representing key development areas for the future. This type is widely distributed in western, eastern, and northern Kazakhstan, including Akmola and Kyzylorda states. The total number of HH-type administrative units is 6 and remains relatively stable, accounting for 27.8% of all administrative units in Kazakhstan. These regions have good ecological environment resource baselines and moderate ecological environment responsiveness. Pressure from both water use and industrial pollution is relatively small, indicating significant development potential.

3.3.2 HL Type: High Urbanization but Lagging Ecology Urbanization has reached a relatively high stage, but the ecological environment level lags behind. This type is mainly distributed in central industrial areas and western oil extraction areas of Kazakhstan, represented by Karaganda, Pavlodar, West Kazakhstan, and Atyrau states. Considering per capita GDP, manufacturing proportion, and industrial structure, Karaganda, Pavlodar, and West Kazakhstan states are in the middle-to-late stage of industrialization with low service industry proportions, resulting in high ecological environment pressure. Combined with relatively weak ecological environment resource baselines, their ecological environment levels lag behind.

3.3.3 LH Type: Lagging Urbanization but High Ecology Urbanization development is relatively lagging, but ecological environment resources are abundant and industrial water use and pollution pressures are relatively small, representing regions where the economy can be prioritized for development in the future. This type is mainly distributed in southern and northern Kazakhstan, represented by North Kazakhstan, South Kazakhstan, and Zhambyl states. According to Table 4, these regions are mainly in the middle stage of industrialization, but both industrialization and urbanization levels are relatively low. Emerging industries can be cultivated in the future to drive economic and urbanization development.

3.3.4 LL Type: Lagging Urbanization and Ecology Both urbanization and ecological environment levels are relatively lagging. This type is mainly distributed in the central industrial areas of Kazakhstan (Karaganda, Pavlodar states) and western oil extraction areas. Although these regions have relatively abundant energy and mineral resources, their ecological resource endowments are weak, water resources are relatively scarce, and urbanization levels are in the primary and middle stages with lagging industrial development, low per capita income, and relatively poor infrastructure conditions.

[Figure 5: see original paper]

3.4 Coupling Mechanism Analysis

Based on domestic and international literature and using Kazakhstan as an example, this study preliminarily analyzes the interaction relationships and mechanisms between urbanization subsystems and ecological environment systems and their elements (Figure 6), drawing the following conclusions.

[Figure 6: see original paper]

3.4.1 Climate, Water Resources, and Energy Resources Jointly Affect Population Urbanization Levels Uneven population distribution is usually closely related to regional historical economic development characteristics and is simultaneously affected by natural climate conditions. More than half of Kazakhstan' s territory is occupied by deserts and semi-deserts. In addition to economic development factors, Kazakhstan' s population distribution is also influenced by climate, aridity, and water scarcity. Therefore, natural climate conditions historically laid the foundation for uneven population distribution within the country' s territory. However, in many cases, unfavorable natural climate conditions can be compensated by economic factors, most notably the abundant mineral resources (oil, natural gas, metals, coal, etc.) in certain regions that attract large populations, while population redistribution affects population urbanization levels in each region.

3.4.2 Industrial Structure and Scale Affect the Boundary and Intensity of Economic Urbanization' s Impact on Ecological Environment In 2015, pollutant emissions from Karaganda and Pavlodar states accounted for 48.9% and 16.6% of Kazakhstan' s total emissions, respectively, with per capita pollutant emissions significantly higher than other regions. This is mainly influenced by economic and industrial structure. Karaganda state hosts numerous large heavy industries, coal and steel enterprises, metallurgical enterprises, and power stations, resulting in substantial pollutant emissions. Pavlodar state is a major industrial center in Kazakhstan, focusing on bauxite mining, alumina and aluminum production, thermal power generation, oil refining, and mechanical engineering, also resulting in relatively high pollutant emissions. Throughout 2000–2015, industrial waste emissions in Kazakhstan were mainly concentrated in Karaganda, Pavlodar, and East Kazakhstan states, which can be explained by regional industrial type differences. The main waste problems in eastern Kazakhstan (including Pavlodar and East Kazakhstan states) stem from toxic waste generated by the mining and metallurgical sectors, with power plants and metal ore dressing plants in Almaty city also producing certain dust and waste. The coal mining, metallurgical, and chemical industries in Karaganda state are high-pollution sectors, so pollution in these areas is mainly manifested as industrial waste. In western regions, the large-scale oil and natural gas industry mainly impacts the ecological environment through carbon emissions and solid/liquid waste. Therefore, differences in industrial structure (sectoral differences) affect resource consumption, pollution types, and emission intensity, thereby influencing the capacity to damage the ecological environment, while industrial scale further intensifies the impact strength of different industries on the ecological environment.

3.4.3 Ecological Environment Pressure System Indirectly Affects Regional Economic Urbanization Development Regions with relatively active oil and gas resource extraction face high-intensity carbon emissions, thereby affecting climate change and creating chain reactions that influence regional economic urbanization development. For arid regions, water resources are an important factor affecting urbanization development. Research over the past 20 years indicates that climate change will exacerbate water resource shortages in Kazakhstan and the entire Central Asian region. Due to desertification and rapid melting of mountain glaciers, water shortage problems in Central Asia will become increasingly severe. It is projected that by the end of this century, glaciers in Central Asia will completely disappear, significantly impacting water resource supply in the region. Long-term predictions indicate that available water resources in Central Asia will be greatly reduced. Water resource shortages and increasing water demand will intensify water competition among various economic sectors at regional and national levels, thereby affecting regional economic development. According to research by the World Resources Institute (WRI), Kazakhstan will face extremely high water stress by 2040, ranking among the countries with the highest water stress globally. Therefore, Kazakhstan should adopt sustainable development strategies as soon as possible to promote coordinated development between ecological environment and regional economy.

4 Conclusions

This study constructs comprehensive indices for urbanization and ecological environment, and based on the Tapio decoupling analysis model, analyzes the static and dynamic coupling relationships between urbanization and ecological environment in Kazakhstan, drawing the following conclusions:

1. High values of comprehensive urbanization in Kazakhstan are mainly distributed in the oil extraction areas in the west, the industrial area of Karaganda in the central region, and Pavlodar in the northeast. These regions have abundant mineral resources (oil and gas reserves) and are key areas for oil and gas development and heavy industry. Low urbanization values are mainly distributed in southern and some northern regions of Kazakhstan characterized by agricultural economies.

2. From the perspective of annual changes from 2000 to 2015, the dynamic changes in the decoupling relationship between urbanization and ecological environment in Kazakhstan states mainly manifested as strong decoupling, weak decoupling, strong negative decoupling, declining decoupling, and expansion negative decoupling states. Under the influence of industrial structure and ecological environment responsiveness, the dynamic coupling relationship continued to change from 2000 to 2015.

3. Preliminary analysis of the coupling mechanism reveals that Kazakhstan' s climate, water resources, and energy resources jointly affect population urbanization levels; industrial type and scale affect the boundary and intensity of economic urbanization' s impact on the ecological environment; and the ecological environment pressure system indirectly affects regional economic urbanization development.

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Note: Figure translations are in progress. See original paper for figures.