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Interplay of Urbanization and Ecological Environment: Coordinated Development and Drivers

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Abstract: The interplay between urbanization and ecological environmental efficiency has gained increasing significance in the context of sustainable development, as rapid urban growth poses challenges to resource consumption, greenhouse gas emissions, and the overall ecological well-being of urban areas. Understanding and analyzing the coordinated development of urbanization and ecological environmental efficiency, as well as assessing the influence of drivers on this relationship, is crucial for developing effective policies and strategies that promote environmentally sustainable urban development. This study establishes an urbanization index based on four key aspects: economy, society, population, and ecology. This investigation focuses on 30 provinces in China spanning from 2011 to 2020. The following methods are applied: global Malmquist–Luenberger productivity index, entropy method, TOPSIS model, coupled coordination degree model, panel-corrected standard error (PCSE), and feasible generalized least squares (FGLS) models. The empirical results demonstrate a favorable level of coordinated development between urbanization and the ecological environment overall, with more pronounced regional evolution trends. The trade openness, energy structure, and digitalization level play significant roles in effectively promoting the coordinated development of urbanization and the ecological environment to varying extents. The growth of trade openness and digitalization level promote coordinated development between urbanization and the ecological environment by 0.125 and 0.049, respectively. However, the increase in the energy structure decreases it by 0.509. These results have significant implications for policymakers, urban planners, and stakeholders, emphasizing the need for a balanced approach that prioritizes ecological environmental protection in urbanization efforts. This study underscores the importance of sustainable urban development strategies to ensure long-term ecological and environmental sustainability.

Keywords: sustainable development; urbanization; governance; infrastructure; quality of life

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1. Introduction

China has undergone a remarkable surge in urbanization, with the urbanization rate increasing from 17.92% to 65.22% between 1978 and 2022. However, scholars [1,2] outline that this rapid urbanization has led to various challenges, including resource depletion, environmental degradation, imbalanced spatial expansion of cities, and a severe urban–rural divide. Past studies [3–5] show that to address these issues, there is a need to modernize the urbanization strategy by integrating the concept of ecological civilization into the process. Considering the findings [6–8], this strategy should promote green, circular, low-carbon development, emphasize the efficient and sustainable utilization of land, water, energy, and other resources, and strengthen environmental protection and ecological restoration. This approach emphasizes the efficient and sustainable utilization of resources, environmental protection, and ecological restoration. However, it is important to assess whether the new urbanization strategy effectively contributes to improving the ecological environment and to understand the overall characteristics and spatial patterns of its impact on ecological environmental efficiency.

This research aims to comprehensively understand and analyze the coordinated development of urbanization and ecological environmental efficiency while also assessing the influence of drivers on this relationship. This understanding is crucial for the development of effective policies and strategies that promote environmentally sustainable urban development. This study employs a diverse set of methodologies to accomplish its objectives: the global Malmquist–Luenberger productivity index to evaluate ecological environmental efficiency; the entropy method and TOPSIS model to assess the urbanization index; and panel-corrected standard error (PCSE) and feasible generalized least squares (FGLS) models to measure the influence of drivers on the coordination between urbanization and ecological environmental efficiency. Additionally, this study utilizes nuclear density methods to analyze the evolutionary trend and coordination between urbanization and the ecological environment over time. By adopting these approaches, the research aims to provide comprehensive insights into the interplay of urbanization and ecological environmental efficiency. The findings of this study hold significant implications for policymakers, urban planners, and stakeholders, emphasizing the necessity of a balanced approach that prioritizes ecological environmental protection in urbanization efforts. Ultimately, this research aims to foster environmentally sustainable urban development by integrating these insights and recommendations.

This paper has the following structure: literature review—analysis of the theoretical background on urbanization effect on ecological environmental efficiency; materials and methods—describing variables and sources for analysis and the methods and instruments to check the research hypothesis; results—explaining the results of the analysis; discussion and conclusions—exploring the core findings, outlining the policy implication, limitations, and further directions for investigations.

2. Literature Review

Urban planners and sociologists have expressed concerns about the relationship between ecological environmental efficiency and urbanization. They have introduced concepts such as "pastoral cities" [9], "satellite towns" [10], "eutopia" [11], "organic planning" [12], and "organic evacuation" [13]. Scholars [14–18] acknowledge three coupling states between urbanization and the ecological environment. First, there could be a positive coupling where urbanization promotes improvements in ecological environmental quality through scale effects and technological progress resulting from population and industry agglomeration and distribution [19–22]. Second, a negative coupling could occur where urbanization poses challenges to sustainable development, as it results in heightened resource and energy consumption, elevated greenhouse gas emissions, and degradation of the ecological environment. These factors hinder the long-term sustainability of cities [23–27]. Third, there exists a dynamic coupling between urbanization and the ecological environment. Scholars [28–31] outline that this relationship is not a simple linear one but rather follows patterns such as double exponentials, inverted U-shaped curves (environmental Kuznets curve), or S-shaped curves, illustrating the interaction and mutual influence between urbanization and the ecological environment as they progress from low to high levels.

It should be noted that different disciplines have examined the impact of urbanization on the ecological environment from various perspectives. Environmental science [32–35] focuses on studying pollution, destruction, and protection of groundwater, climate change, air quality, and soil during the urbanization process to understand the ecological and environmental effects. Ecology [20,36,37] measures the impact of urbanization by assessing changes in biodiversity resulting from urban development. Systematics comprehensively analyzes the ecological and environmental effects of urbanization, considering aspects such as resources, environment, system, economy, and society [38–41].

Scholars [42–44] examine the impact of environmental regulation on urbanization from two angles: technology and industry. On the one hand, the effects of environmental regulation on urbanization have been studied in terms of technological innovation, with many researchers suggesting that environmental regulations can effectively drive technological advancements and progress [45–49]. On the other hand, scholars have investigated the impact of environmental regulation on industrial transfers, transformations in industrial structure, upgrades, and agglomeration from an industrial perspective [50–54].

The scientific community [55–58] conducts extensive research on the relationship between urbanization and ecological environmental efficiency, producing valuable insights that serve as a reference for further studies in this field. However, most of the existing research focuses on exploring the coupling relationship between urbanization and the ecological environment and analyzing the ecological and environmental effects of urbanization from individual disciplinary perspectives. This study aims to address the lack of in-depth discussion on whether the urbanization process affects the efficiency of the ecological environment and whether it hampers ecological environment improvement, as well as to investigate the underlying mechanisms involved. Over the past few decades, China has rapidly urbanized and has also prioritized the construction of ecological civilization.

Considering the above, the analysis of the coordination between urbanization and the ecological environment over time requires further exploration, particularly in terms of understanding the specific mechanisms and processes involved. In addition, there is a lack of in-depth discussion on whether the urbanization process affects the efficiency of the ecological environment and hampers ecological environment improvement. In addition, the multidimensional aspects of ecological environmental efficiency in relation to urbanization require comprehensive analysis. Existing studies have often focused on limited aspects, neglecting the multidimensional nature of the issue. There is a need to bridge the knowledge gap by considering the evolutionary trend and coupling between urbanization and the ecological environment.

3. Materials and Methods

3.1. Research Model

To analyze the coupling and coordination level between urbanization and ecological environmental efficiency, this study employs the coupling and coordination degree model. The model is expressed as follows:

(1) The comprehensive development model is utilized to assess the development level of both urbanization (U_1) and the ecological environment (U_2).

(2) The coupled coordination degree model (1) consists of two components: the coupling degree model and the coordination degree model. The coupling degree model (2) is employed to quantify the level of interaction between multiple systems, while the coordination degree model (3) is used to assess the degree of coordinated development between these systems.

$$D = \sqrt{C \times T}, \tag{1}$$

where D is the coupling and coordination degree between new urbanization and the ecological environment. If D is higher, the relationship between the new urbanization and ecological environment is better; T is the comprehension coordination evaluation index:

$$T = \alpha \times U_1 + \beta \times U_2; \tag{2}$$

where α and β are weighting coefficients (0.5).

C is the coupling degree of urbanization and ecological environment, and the value range is [0, 1]:

$$C = \frac{2\sqrt{U_1 U_2}}{U_1 + U_2}. \tag{3}$$

The coupling and coordination degree between urbanization and the ecological environment, as identified in study [59], is classified into seven phases and three intervals (Table 1).

Table 1. Coupled coordination degree stage division.

D	Coupling Coordination Phase	Coupling Coordination Interval
0.900~1.000	Quality coordination	
0.800~0.899	Good coordination	Accept
0.700~0.799	Intermediate coordination	
0.650~0.699	Primary coordination II	
0.600~0.649	Primary coordination I	Forced to accept
0.500~0.599	Forced coordination	
0.000~0.499	Disorder coordination	Not accept

The kernel density estimation method was employed to analyze the distribution of the comprehensive index measuring the efficiency of the coupled coordination degree between urbanization and the ecological environment in China:

$$f(x) = \frac{1}{Nh}\sum_{i=1}^{N} K\left(\frac{X_i - x}{h}\right) \quad (4)$$

where N is the numeral of observations; X_i is the independently and identically distributed annotations; x is the mean of the observations; $K(\cdot)$ is the kernel density function; and h is the bandwidth. The lesser the bandwidth is, the more accurate the estimation is.

$$K(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) \quad (5)$$

The panel data model is employed to analyze the driving factors that influence the coupling and coordination between new urbanization and the ecological environment:

$$D_{i,t} = \alpha + \beta \sum Z_{i,t} + \varepsilon_{i,t} \quad (6)$$

where $D_{i,t}$ is the coupled coordination degree between urbanization and the ecological environment in China; $Z_{i,t}$ are the set of driving factors; and $\varepsilon_{i,t}$ are random error items.

To analyze panel data that include both time series and cross-sectional observations, it is crucial to consider the unique characteristics of this data type. Tests, such as the Wooldridge test for autocorrelation in panel data, the Modified Wald test for groupwise heteroskedasticity, and Pesaran's test of cross-sectional independence, were conducted to assess the data's characteristics and determine the appropriate specification and econometric method. Heteroskedasticity refers to situations where the variance in errors varies across different observations, while autocorrelation occurs when errors within a time series are correlated over time. By adjusting the standard errors, the PCSE model effectively accounts for these issues, resulting in more reliable and efficient coefficient estimation. The feasible generalized least squares (FGLS) model proves particularly valuable when correlations exist not only over time but also across different cross-sectional units. By simultaneously incorporating these correlations, the FGLS model provides a more comprehensive understanding of the data structure and enables more robust parameter estimation. This method takes into account the potential dependencies between observations, leading to more accurate and reliable statistical inference.

3.2. Data and Variable Description

Considering past studies [60–65], the urbanization index (U_1) incorporates 17 second-level level indicators from four key aspects: population urbanization, economic urbanization, social urbanization, and ecological environment urbanization (Table 2).

Table 2. Construction of the urbanization index.

Variable	Calculation Method	Unit
	Population urbanization	
Urbanization rate	The urbanization rate of permanent residents	%
Density of population	Urban population density	square kilometer
Employment status	Registered urban unemployment rate	%
Employment structure	The share of employment in secondary and tertiary industries	%
Population education	The average number of students per 100,000 institutions of higher learning	Person
	Economic urbanization	
Economic development level	GDP per capita	Yuan/person
Economic structure	The added value of the tertiary industry accounted for GDP	%
Government receipts	General public budget revenue	100 million
Investment level	Investment in the fixed assets	100 million
Residents' income	Disposable income of urban residents per capita	Yuan/person
	Social urbanization	
Public service	The share of education expenditure in government expenditure	%
	Number of health technicians per thousand people	1000 people
Infrastructure	Public transport vehicles per 10,000 people	vehicle
	Urban road area per capita	square meter
Quality of life	Public library collections per capita	volume
	Telephone penetration	%
	Ecological environment urbanization	
Garbage disposal	The harmless treatment rate of household garbage	%
Ecological foundation	Green coverage rate of the built-up area	%
Sewage treatment	Daily urban sewage treatment capacity	10,000 m^3
Air quality	Total industrial sulfur dioxide emissions	Ten thousand tons

This study applies the entropy-based TOPSIS method to assess the urbanization index [53]. The entropy method calculates the weight based on the variability among indicators, meaning that a higher entropy weight indicates a greater dispersion of data within the index. The advantage of the entropy method is that it objectively determines the weight of the index based on the information reflected by the indicators [54]. The specific operational steps are outlined below:

Step 1: Assessment of the entropy weight of each index.

Normalize the initial index:

$$r_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}} \tag{7}$$

where x_{ij} are the individual index values, $i = 1, 2, 3, \ldots, m$; $j = 1, 2, 3, \ldots, n$.

Assessment of the index entropy value:

$$e_i = -\frac{\sum_{j=1}^{n} r_{ij} * Inr_{ij}}{Inn} \tag{8}$$

where e_i is the $i -$ th index entropy value.

Assessment of the index weight:

$$\omega_i = \frac{1 - e_i}{\sum_{i=1}^{m} (1 - e_i)} \tag{9}$$

Step 2: Establish the TOPSIS comprehensive evaluation model.

Using the normalized matrix obtained when calculating the entropy weight:

$$Z = \begin{bmatrix} z_{11} & \cdots & z_{1m} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nm} \end{bmatrix} \quad (10)$$

$$z_i^+ = max\{z_{1i}^+, z_{2i}^+, \ldots\ldots z_{mi}^+\} z_i^- = min\{z_{1i}^-, z_{2i}^-, \ldots\ldots z_{mi}^-\} \quad (11)$$

Calculate the distance between each index z_i^+ and z_i^- on different evaluation objects. The formula is as follows:

$$Dist_i^+ = \sqrt{\sum_{j=1}^{m} \omega_j \left(z_j^+ - z_{ij}\right)^2} \quad (12)$$

$$Dist_i^- = \sqrt{\sum_{j=1}^{m} \omega_j \left(z_j^- - z_{ij}\right)^2} \quad (13)$$

where ω_j is the entropy weight of the jth index

Step 3: Calculate the score of each indicator.

$$s_i = \frac{Dist_i^-}{Dist_i^- + Dist_i^+} \quad (14)$$

The value range of s_i is 0 to 1, and the closer the score is to 1, the higher the urbanization development level in the region; otherwise, the development level is low.

This study utilized the global Malmquist–Luenberger productivity index to assess ecological efficiency in China. This index combines the concepts of the Malmquist and Luenberger productivity indexes to provide a comprehensive assessment of productivity changes. The index captures both efficiency change, which refers to the ability to use resources effectively, and technological change, which represents changes in the production frontier or best practices. By considering both factors, it offers a more holistic measure of productivity changes. Additionally, the Malmquist–Luenberger productivity index is capable of handling multiple inputs and outputs simultaneously, enabling a comprehensive analysis of productivity changes across various dimensions. This makes it well suited for evaluating the performance of complex systems, such as China, with diverse production processes. This index measures the efficiency of the ecological environment while considering undesired outputs:

$$U_{2t,t+1} = \frac{1 + R_G\left(x_{it}, y_{it}, z_{it}; g_x, g_y, g_z\right)}{1 + R_G\left(x_{i(t+1)}, y_{i(t+1)}, z_{i(t+1)}; g_x, g_y, g_z\right)} \quad (15)$$

where U_2 is the total efficiency index of the ecological environment; x, y, and z are the input, expected output, and unexpected output, respectively; t is the period; and i is the region.

Based on previous studies [66–68], in model (15), x_{it} (input variables) are the following: coal consumption, total water supply, built-up area, urban employment, and fixed asset investment. The output variable (y_{it}) is the index comprising GDP, while z_{it} (unexpected output) is carbon dioxide discharge, sulfur dioxide discharge, and industrial wastewater discharge. The Malmquist–Luenberger productivity index allows the incorporation of all selected variables simultaneously. Including environmental variables as unexpected output into model (15) enables a more environmentally conscious assessment of productivity changes. This helps to identify areas where improvements can be made in terms of resource usage and environmental impact.

The industrial structure, energy structure, environmental regulation, and digitalization level are identified as crucial driving factors that impact the coupling and coordination between new urbanization and the ecological environment. The industrial structure (Instr—

the share of the secondary industry in regional GDP, %) refers to the composition and characteristics of industries within urban areas, with a focus on their resource consumption and environmental impact [69]. The energy structure (Ens—the proportion of coal consumption in total energy consumption) pertains to the sources of energy used in urban areas and their efficiency, emphasizing the transition to cleaner and more sustainable energy sources [70]. Trade openness (Open—the share of foreign direct investment above a designated size in regional GDP) facilitates the exchange of goods, services, and knowledge between regions, which can lead to the transfer of environmentally friendly technologies and practices. Regions can access cleaner and more sustainable production methods, reducing their environmental impact and promoting ecological efficiency. Environmental regulation (Er) involves the policies and regulations in place to mitigate the negative environmental impacts of urbanization and promote sustainable practices. This study constructs a comprehensive index system of environmental regulation (Er) based on the entropy-based TOPSIS method (Formulas (7)–(14)) to reflect the intensity of environmental regulation more accurately in each province. Based on previous studies [50–54], common indicators were chosen to describe environmental regulation: industrial wastewater discharge volume (10 thousand tons) [71], industrial sulfur dioxide emissions (10 thousand tons) [71], industrial smoke (powder) dust emissions (10 thousand tons) [72], and the amount of pollutant discharge fee (10 thousand tons) [71]. Last, the digitalization level (Dig—internet penetration rate) signifies the integration of digital technologies in urban systems, enabling data-driven decision making and smart solutions for efficient resource management and environmental monitoring. By considering these driving factors, policymakers and urban planners can develop strategies and interventions that foster coordinated and sustainable development between new urbanization and the ecological environment.

This paper utilizes panel data from 30 Chinese provinces spanning the period from 2010 to 2020 (excluding Xizang, Hong Kong, Macao, and Taiwan). The data for each index variable are collected from various sources, including the China Statistical Yearbook [71], China Environmental Statistical Yearbook [72], and the statistical yearbooks of each province [73].

4. Results

As shown in Table 3, the environmental ecological efficiency exhibits a range of 3.885 among the 300 observed values, with the highest efficiency reaching 0.033. On the other hand, the new urbanization index ranges from 0.157 to 0.639, indicating a relatively small difference and implying the rapid development of China's urbanization. Moreover, noticeable differences can be observed in the economic development level, industrial structure, trade openness, environmental regulation, and energy structure.

Table 3. Descriptive statistics.

Variable	Symbol	Mean	Std.	Min	Max
Ecological environmental efficiency	GML	1.048	0.270	0.033	3.885
Urbanization index	Nurb	0.325	0.101	0.157	0.639
Industrial structure	Instr	1.219	0.696	0.518	5.297
Trade openness	Open	0.274	0.290	0.008	1.464
Environmental regulation	Er	0.004	0.004	0.000	0.031
Energy structure	Ens	0.033	0.023	0.004	0.095
Digital infrastructure	Dig	6.534	0.916	3.728	8.266

The calculation of the coupling and coordination level between urbanization and ecological environmental efficiency is presented in Table 4. The variation range of the coupling coordination is 0.754, with the highest observation efficiency reaching 1.099 among the 300 observations.

Table 4. Results of the coupling and coordination degree of urbanization and ecological environment efficiency.

Province	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Beijing	0.76	0.84	0.86	0.85	0.87	1.00	0.89	0.88	0.92	0.91
Tianjin	0.76	0.76	0.73	0.75	0.61	1.00	0.74	0.83	0.75	0.87
Hebei	0.69	0.71	0.71	0.71	0.73	0.75	0.77	0.79	0.78	0.80
Shanghai	0.82	0.81	0.85	0.83	0.85	0.87	1.00	0.88	0.95	0.91
Jiangsu	0.77	0.80	0.82	0.80	0.84	0.86	0.88	0.88	0.89	0.92
Zhejiang	0.77	0.78	0.79	0.80	0.82	0.84	0.85	0.86	0.87	0.87
Fujian	0.70	0.73	0.75	0.75	0.78	0.78	0.80	0.81	0.83	0.83
Shandong	0.73	0.75	0.78	0.78	0.79	0.83	0.83	0.84	0.83	0.85
Guangdong	0.77	0.79	0.81	0.80	0.83	0.85	0.87	0.88	0.90	0.90
Hainan	0.50	0.69	0.69	0.71	0.66	0.94	0.78	0.72	0.75	0.74
Shanxi	0.65	0.69	0.68	0.69	0.70	0.72	0.74	0.78	0.74	0.76
Anhui	0.68	0.71	0.71	0.72	0.74	0.75	0.77	0.79	0.82	0.81
Jiangxi	0.69	0.70	0.71	0.71	0.72	0.74	0.76	0.77	0.33	0.80
Henan	0.70	0.71	0.72	0.73	0.75	0.78	0.80	0.80	0.83	0.82
Hubei	0.69	0.71	0.73	0.74	0.76	0.79	0.79	0.81	0.82	0.78
Hunan	0.68	0.69	0.71	0.72	0.73	0.75	0.77	0.78	0.81	0.82
Guangxi	0.67	0.69	0.69	0.70	0.73	0.74	0.76	0.77	0.77	0.78
Nei Monggol	0.67	0.68	0.69	0.70	0.70	0.74	0.71	0.75	0.74	0.75
Chongqing	0.67	0.70	0.72	0.70	0.74	0.75	0.75	0.77	0.80	0.77
Sichuan	0.69	0.71	0.71	0.72	0.73	0.76	0.78	0.80	0.81	0.81
Guizhou	0.61	0.64	0.66	0.67	0.68	0.72	0.71	0.73	0.76	0.75
Yunnan	0.65	0.68	0.67	0.68	0.69	0.72	0.74	0.74	0.80	0.77
Xizang	0.73	0.74	0.74	0.74	0.73	0.76	0.78	0.79	0.79	0.80
Shaanxi	0.62	0.66	0.66	0.68	0.69	0.71	0.72	0.76	0.74	0.75
Gansu	0.63	0.56	0.80	0.58	0.78	0.68	0.70	0.72	0.73	0.74
Qinghai	0.59	0.65	0.63	0.66	0.69	0.71	0.74	0.76	0.77	0.82
Ningxia	0.68	0.66	0.69	0.70	0.70	0.72	0.76	0.74	0.77	0.75
Xinjiang	0.67	0.69	0.69	0.70	0.73	0.74	0.76	0.77	0.77	0.78
Liaoning	0.52	0.53	0.50	0.50	0.67	0.65	0.60	0.59	0.58	0.70
Jilin	0.37	0.42	0.41	0.44	0.46	0.56	0.51	0.45	0.50	0.63
Heilongjiang	0.44	0.42	0.42	0.42	0.53	0.57	0.51	0.48	0.48	0.64

The results presented in Table 4 indicate that from 2011 to 2020, the average level of coupling and coordination between China's urbanization development and the ecological environment has remained consistently high. However, notable differences are observed among the eastern, western, and northeast regions, indicating varying degrees of coupling and coordination in these areas (Figure 1).

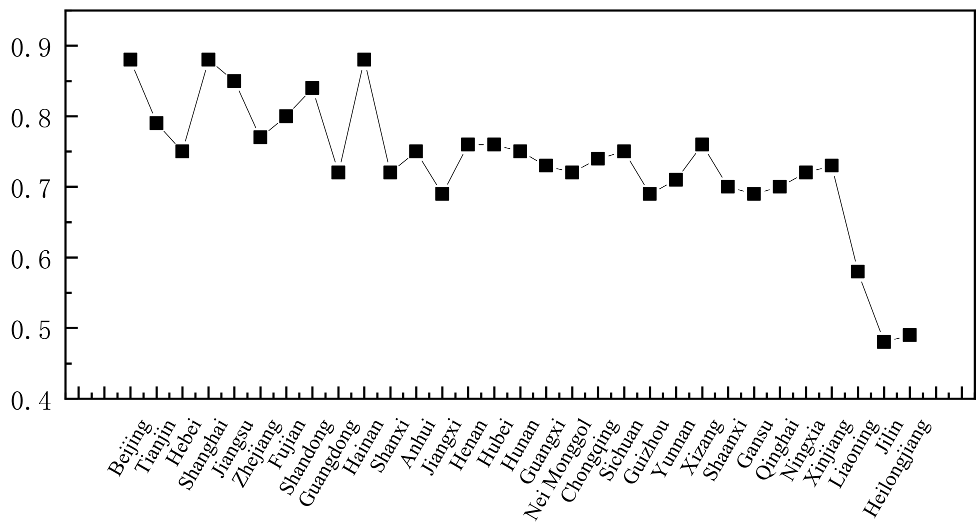
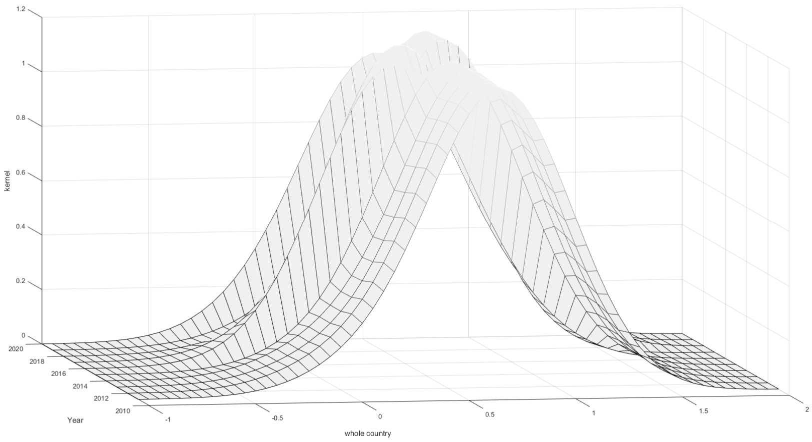


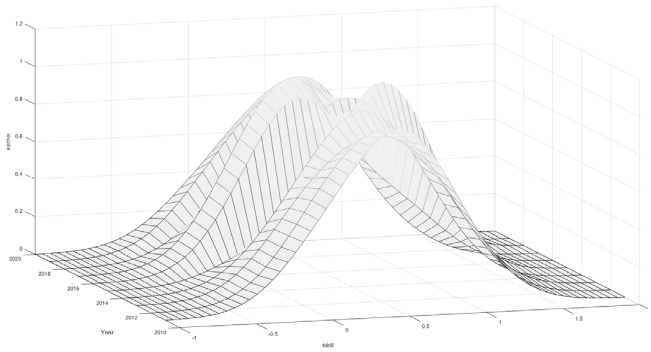
Figure 1. The average value of the coupling and coordination degree of urbanization and ecological environment efficiency in 30 provinces in China.

According to Figure 1, the eastern region demonstrates a high level of coupling and coordination between urbanization and ecological environment efficiency. In contrast, the central region maintains an intermediate level, while the northeast region shows a primary level.

The results obtained through the kernel density estimation method (Figure 2a) demonstrate an increasing trend in the coupling and coordination degree between urbanization and ecological environment efficiency over time. The overall pattern reveals a prominent peak, indicating that China is actively prioritizing ecological and environmental protection in its urbanization efforts, aligning with national policies. However, upon closer examination of the four regions individually (Figure 2b–e), it becomes evident that there are substantial variations in the coordinated development of urbanization and the ecological environment.



(**a**)



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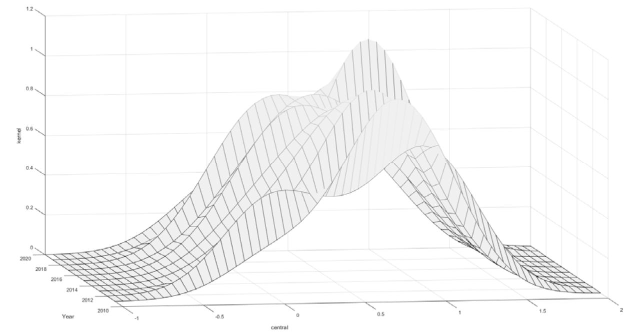

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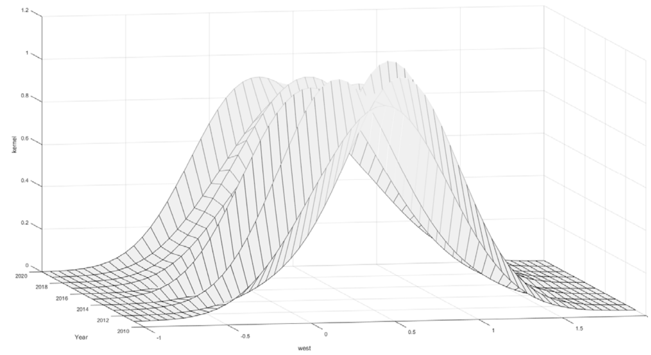

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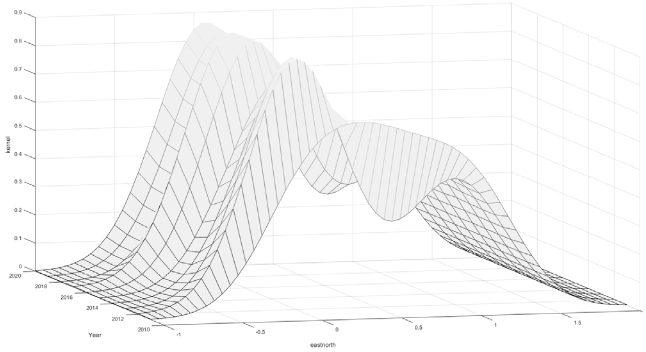

(**e**)

Figure 2. National and four major regional evolution trends. (**a**) Whole country; (**b**) East; (**c**) Central; (**d**) West; (**e**) East–north.

In the eastern region, the strong coupling between urbanization and ecological environment efficiency indicates that urban development in this area has been carefully planned with ecological considerations in mind. Strategies such as green infrastructure, sustainable urban planning, and the adoption of eco-friendly technologies have likely been implemented. As urbanization progresses, there is a simultaneous emphasis on protecting the environment, resulting in a positive influence on ecological environmental protection. The central region, although not as well integrated as the eastern region, still exhibits some degree of coordination between urban development and ecological protection. Efforts to protect the environment exist but may not be as comprehensive or effectively implemented due to competing development priorities. Despite this, the positive relationship indicates progress in balancing urbanization and environmental protection. In contrast, the primary level of coupling between urbanization and ecological environment efficiency in the northeast region suggests minimal coordination between urban development and environmental protection efforts. Urbanization in this area appears to have been carried out without sufficient consideration for ecological concerns, potentially leading to negative environmental impacts. This lack of coordination may stem from factors such as rapid urbanization, inadequate environmental regulations, or a focus on short-term economic gains without long-term sustainability considerations. Overall, the findings highlight the importance of well-planned urbanization that incorporates ecological environment protection measures. When urban development considers ecological factors, it positively influences environmental protection. Conversely, unplanned or poorly coordinated urbanization can have adverse effects on the ecological environment. Therefore, policymakers and urban planners in regions with lower levels of coupling should prioritize integrating ecological considerations into urban development, aiming for a sustainable and balanced approach that benefits both urbanization and environmental protection.

The results of Pesaran's test indicate a test statistic of 5.332 and a probability value of 0.000 (Table 5), suggesting strong evidence of cross-sectional dependence in the panel data. The Modified Wald test reveals a test statistic of 47,800.90, with a probability value of 0.0000, indicating the presence of significant groupwise heteroskedasticity in the panel data. Furthermore, the Wooldridge test demonstrates a test statistic of 9.258 and a probability value of 0.0049, indicating the presence of autocorrelation in the panel data, although to a lesser extent compared to the other two tests.

Table 5. Panel data tests: Wooldridge test for autocorrelation, Modified Wald test for groupwise heteroskedasticity, and Pesaran's test of cross-sectional independence.

Test	Statistic	Probability
Pesaran's test of cross-sectional independence	5.332	0.000
Modified Wald test for groupwise heteroskedasticity	47,800.90	0.0000
Wooldridge test for autocorrelation	9.258	0.0049

Table 6 provides the findings from the PCSE (panel-corrected standard error) and FGLS (feasible generalized least squares) models, which examine the influence of various drivers on the coordination between urbanization and ecological environmental efficiency.

The results suggest that certain factors significantly impact the coupling and coordination between new urbanization and the ecological environment. Specifically, the variables of trade openness (Open), energy structure (Ens), and digitalization level (Dig) demonstrate statistically significant effects. Trade openness, as indicated by the coefficients of 0.125 (PCSE) and 0.108 (FGLS), shows a positive relationship with the coupling and coordination between urbanization and ecological environmental efficiency. This implies that greater openness to trade contributes to enhanced coordination between urbanization and the ecological environment. Similarly, the energy structure variable (Ens) displays a negative relationship with a statistically significant impact. The coefficients of −0.509 (PCSE) and −0.595 (FGLS) suggest that a lower proportion of coal consumption in total energy consumption positively affects the coordination between urbanization and ecological environmental efficiency. Additionally, the digitalization level (Dig) exhibits a positive and statistically significant relationship with a coefficient of 0.049 in both the PCSE and FGLS models. This indicates that a higher internet penetration rate contributes to the coordination and coupling between urbanization and the ecological environment. However, the variables of industrial structure (Instr) and environmental regulation (Er) do not show statistically significant effects on the coordination between urbanization and ecological environmental efficiency.

Table 6. The results of the PCSE and FGLS models.

Variable	PCSE		FGLS	
	Coefficient	Probability	Coefficient	Probability
Instr	−0.007	0.313	0.002	0.623
Open	0.125	0.000	0.108	0.000
Er	1.349	0.394	0.435	0.554
Ens	−0.509	0.029	−0.595	0.000
Dig	0.049	0.000	0.049	0.000
const	0.422	0.000	0.409	0.000
Wald chi2	413.96	0.000	876.69	0.000
R-squared	0.479		–	

5. Discussion

The findings of this study regarding the coupling and coordination level between urbanization and ecological environmental efficiency align with previous investigations in the field. The average level of coupling and coordination between China's urbanization development and the ecological environment remained consistently high from 2011 to 2020, which is in line with the conclusions reached by previous studies [74–76].

Notable differences among the eastern, western, and northeast regions, indicating varying degrees of coupling and coordination, are also consistent with the research conducted by [74–76]. The comparative analysis with previous studies reinforces the importance of well-planned urbanization that incorporates ecological environment protection measures. The positive relationship between coupling and ecological environment efficiency highlights the need for policymakers and urban planners to integrate ecological considerations into urban development, as emphasized in [49,50].

The findings outline the importance of considering ecological environmental protection and efficiency as essential components of China's long-term urbanization strategy. Such conclusions were also attained by scholars [3,5]. Considering previous studies [3,5], the realization of new urbanization is crucial for the country's development, but it should be accompanied by strengthened measures to protect and enhance the ecological environment. This implies that policymakers and urban planners should prioritize sustainable practices and incorporate ecological considerations into urban development plans.

The empirical results show that driving factors (trade openness, energy structure, digitalization level) positively affect the coupling coordination degree between urbanization and ecological environmental efficiency. The obtained results are consistent with previous studies [77–79]. Thus, trade openness is an important aspect to consider, as it reflects the degree of integration of a region's economy with the global market. Increased trade openness led to a higher volume of trade activities, which has implications for environmental sustainability. However, considering the studies [70,77], a higher level of trade openness results in greater environmental pressures if environmental regulations and monitoring systems are not effectively implemented. Scholars [20,51,80] outline that urbanization is often accompanied by an increased demand for energy, particularly in rapidly developing regions. Higher electricity consumption indicates greater energy requirements for urban infrastructure, industries, and households. Managing electricity consumption and transitioning to cleaner and more sustainable energy sources are critical aspects of promoting ecological environmental efficiency in the context of urbanization. A higher level of internet penetration promotes coordination between urbanization and ecological environmental efficiency by facilitating the exchange of information, enhancing collaboration among stakeholders, and fostering citizen engagement. By leveraging the power of the internet, policymakers and urban planners can effectively integrate ecological considerations into urban development, leading to a more sustainable and balanced approach that benefits both urbanization and environmental protection [81,82].

The results of this study contribute to the existing knowledge on the coordinated development of urbanization and ecological environmental efficiency. The insights gained from this study, in conjunction with the findings of past research, provide a robust foundation for policymakers and practitioners involved in urban planning, as well as environmental protection and conservation efforts [3,5]. By building upon the knowledge of coupling and coordination between urbanization and ecological environment efficiency, stakeholders could make informed decisions and develop strategies that promote sustainable urbanization and effectively preserve the environment. These findings have implications for policymakers, urban planners, and environmentalists seeking to promote sustainable urban development and preserve the ecological balance.

6. Conclusions

This study utilized panel data from 30 provinces in China spanning the years 2011 to 2020. This research employed the entropy right TOPSIS method, Malmquist–Luenberger productivity index, PCSE, FGLS, and kernel density to measure the coordinated development of urbanization and ecological environmental efficiency and to analyze the core drivers of their link. This study demonstrates that the average level of coupling and coordination between China's urbanization development and the ecological environment has remained consistently high from 2011 to 2020. However, notable differences are observed among the eastern, western, and northeast regions, indicating varying degrees of coupling and coordination in these areas. These findings highlight the importance of understanding and addressing regional disparities when considering the relationship between urbanization and ecological environmental efficiency. Future efforts should focus on promoting sustainable and balanced urban development strategies that prioritize ecological considerations, particularly in regions with lower levels of coupling. By integrating ecological factors into urban planning and implementation, policymakers and urban planners can strive for a harmonious coexistence between urbanization and environmental protection.

Several variables were also identified as significant factors influencing the coordinated development of urbanization and ecological environmental efficiency. The realization of new urbanization is a crucial long-term strategy for China, necessitating strengthened protection and efficiency of the ecological environment. To comprehensively promote new urbanization and enhance ecological environmental efficiency, the following recommendations are proposed:

1. Given the observed variations in coupling and coordination levels between urbanization and the ecological environment across different regions, policymakers should focus on regional planning and coordination strategies. This involves tailoring policies and approaches to the specific needs and challenges of each region, considering their unique characteristics and development priorities.
2. Urban planning should prioritize ecological and environmental protection, incorporating designs that emphasize small fragments, low density, and organic arrangement. The creation of green spaces and ecological parks should be emphasized to improve urban air and water quality. Energy conservation and environmental protection should be regarded as essential elements of urban planning, with comprehensive promotion of energy-saving and emission reduction technologies [80,83], facilitating the coordinated development of new urbanization and ecological/environmental protection. Thus, Curitiba (the capital city of the state of Paraná in Brazil) is often hailed as a model for sustainable urban planning. The city has implemented innovative

strategies to address urbanization and environmental challenges [84,85]. For instance, it has prioritized the development of an efficient public transportation system, including a well-integrated bus rapid transit (BRT) network. This emphasis on public transport has reduced congestion and air pollution, leading to improved ecological environmental efficiency in the city. Contrasting the Chinese model, Curitiba's approach highlights the importance of sustainable transportation solutions in achieving ecological balance in urban areas.

3. Urban green spaces are vital components of the urban ecological environment. It is recommended that new urbanization efforts prioritize strengthening urban greening coverage by increasing the area of urban green spaces, establishing new green spaces and ecological parks, developing water systems and wetlands, improving the urban ecological environment, and enhancing the overall image and appeal of cities. Portland (the United States of America) is renowned for its sustainable urban development policies [86,87]. The city has implemented land-use planning that encourages mixed-use neighborhoods, preserves green spaces, and promotes public transportation and cycling infrastructure. Portland's emphasis on compact urban growth and preservation of natural areas has contributed to improved ecological environmental efficiency.
4. Given the negative impact of the energy structure variable on the coordination between urbanization and ecological environmental efficiency, policymakers should prioritize energy transition and diversification efforts. This involves reducing the reliance on coal consumption and promoting the use of cleaner and renewable energy sources [88–90]. Implementing policies that incentivize the adoption of sustainable energy practices and technologies will contribute to a more coordinated and environmentally friendly urbanization process.
5. The positive correlation between digitalization level and the coordination of urbanization with the ecological environment emphasizes the significance of embracing digital technologies and fostering innovation. Policymakers should create an enabling environment for the digital transformation of urban areas, including enhancing internet infrastructure and promoting digital solutions for environmental monitoring, resource management, and sustainable urban development [91]. This includes encouraging the use of digital technologies in urban infrastructure planning, construction, and management to enhance efficiency and reduce environmental impacts. Additionally, implementing comprehensive data collection and analysis systems can effectively monitor urban environmental parameters and inform decision-making processes for urban planning, resource allocation, and environmental protection. Furthermore, ensuring widespread access to digital connectivity and utilizing digital platforms for public engagement, information sharing, and environmental education will raise awareness and empower individuals to actively contribute to the advancement of sustainable urbanization.

This research holds significance in the international context by offering insights, recommendations, and empirical evidence on the coordinated development of urbanization and ecological environmental efficiency and the core drivers of their link. Its findings have the potential to inform policy decisions, urban planning practices, and conservation efforts globally, ultimately contributing to a more sustainable and environmentally conscious approach to urban development.

Despite the valuable results, this study has a few limitations. The findings of this study are specific to the context of China and may not be directly applicable to other countries or regions. Different socioeconomic and environmental factors could influence the coordination between urbanization and ecological environmental efficiency in different contexts. This study primarily focuses on examining the relation between new urbanization and ecological environment efficiency. However, establishing a causal relationship requires further investigation using experimental or quasi-experimental research designs. Additionally, the possibility of reverse causality, where improvements in ecological environment efficiency may also influence new urbanization, should be considered.

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