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Research article

The role of the environmental subsystem in sustainable urban development: Evidence from megacities in China

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A R T I C L E I N F O

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A B S T R A C T

Conflicts in urban subsystems have severely hindered the realization of sustainable development, among which the most serious is the conflict between the environmental subsystem and urban development. Differing from studies considering individual environmental elements, this paper innovatively investigates the quantitative relationship between overall environmental performance and other development dimensions to understand the quantitative role of the environmental subsystem in sustainable urban development. Taking the nine megacities in China as an example, this paper first develops the performance variables of four urban subsystems, including the environment, by entropy method and analyzes the conflict or coordination level between the environment and other subsystems through the coupling coordination degree model (CCDM). Then, the interaction mechanism is further analyzed by the fully modified ordinary least square (FMOLS) and vector error correction model (VECM). This paper tries to provide a new reference for management and decision-making by focusing on the whole environmental subsystem rather than separate elements, which is of theoretical and practical significance. The main conclusions are as follows: (1) The coordination level between the environment and other urban subsystems is low; (2) 1 % rise in the economic and resource performance can respectively lead to 0.2014 % and 0.1388 % declines in the environmental performance; (3) 1 % increase in social performance can bring a 0.3738 % rise in environmental performance; (4) Improving environmental and resource subsystems' performance is the priority; (5) Coordinating urban subsystems is the key to long-run sustainable development. Despite the case studies on megacities in China, we hope to provide a new reference for cities worldwide with concentrated populations, rapid growth, and complex development contradictions.

1. Introduction

The environment, especially in rapidly developing areas, is critical to sustainable development due to its complex connections with other aspects. Urban sustainability, one of the Sustainable Development Goals [1], is a focal challenge recognized worldwide [2]. Among all urban development aspects, environmental sustainability is a crucial academic and practical topic since it directly or indirectly impacts and is impacted by other development factors [3,4]. However, the conflicts between urban development and the environment are increasingly challenging to be solved [5]. On the one hand, rapid urban expansion has a significantly negative impact

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on environmental sustainability [6], including pollution emissions [7], environmental degradation [8], and ecological problems [9]. On the other hand, environmental pollution adversely impacts other aspects of urban development, such as public health [10]. Compared with other countries, China is a developing country with an outstandingly rapid speed. There is a typical phenomenon of these conflicts in China's megacities, where the population is accumulated and development-centered [5]. Achieving coordinated development in such cities is an accelerating challenge [11].

For the critical challenges, scholars have conducted many studies on the urban scale, mainly including the following three aspects. The first is to evaluate environmental performance, capacity, and efficiency through indicator systems [4,11–13]. The second is to assess sustainability-beneficial management tools, such as environmental building certifications [14], environmental permits [15], green infrastructure [16], urban green space [17], government plans and actions [18], environmental regulation [19]. The third is to examine the relationships between urban development elements and environmental development, such as the relationship between urban development and pollution [7], the delinking of environmental performance and economic development [20], the relationship between economic growth and pollution emissions [21], the relationship between ecological footprint and urban development [5], the relationship between atmospheric environmental quality and urban industrial structure adjustment [22], and the relationship between population density and air pollution [23,24].

Those current studies, in general, mainly focus on evaluating overall environmental performance or the interactions of urban development with single factors such as CO_2 emission and PM2.5 concentration. A significant research gap exists on the overall environmental performance interaction mechanism with other urban aspects. More specifically, the questions are needed to explore further whether the performance of the environment and other dimensions improves synchronously and how changes in the performance of other development dimensions will affect that of the environment. Accordingly, this paper investigates the quantized role of the overall environmental subsystem in urban development, which is the first attempt to the best of our knowledge.

To that end, combining the econometric and coupling coordination degree models can provide a powerful tool for examining the interacting relationships and conflicts [25]. The fully modified ordinary least square (FMOLS) and vector error correction (VECM) models have been widely used in analyzing the interacting relationships [26–29]. The coupling coordination model provides evidence of the degree of conflicts or level of coordination [30–33].

Overall, this paper aims to examine the role of the environment subsystem in urban development. First, we evaluate the performance of environmental, economic, social, and resource subsystems in 9 Chinese megacities during 1995–2018. Then, we assess the degree of conflicts or coordination between the environment and the other three subsystems through CCDM. Finally, FMOLS and VECM are applied to analyze the interacting mechanism. This paper is of theoretical significance since it focuses on the role of the overall environmental subsystem but not on single elements. This paper is also of practice significance to provide a reference for policymakers in environmental management and promote sustainable development in cities worldwide with concentrated populations, rapid growth, and complex development contradictions.

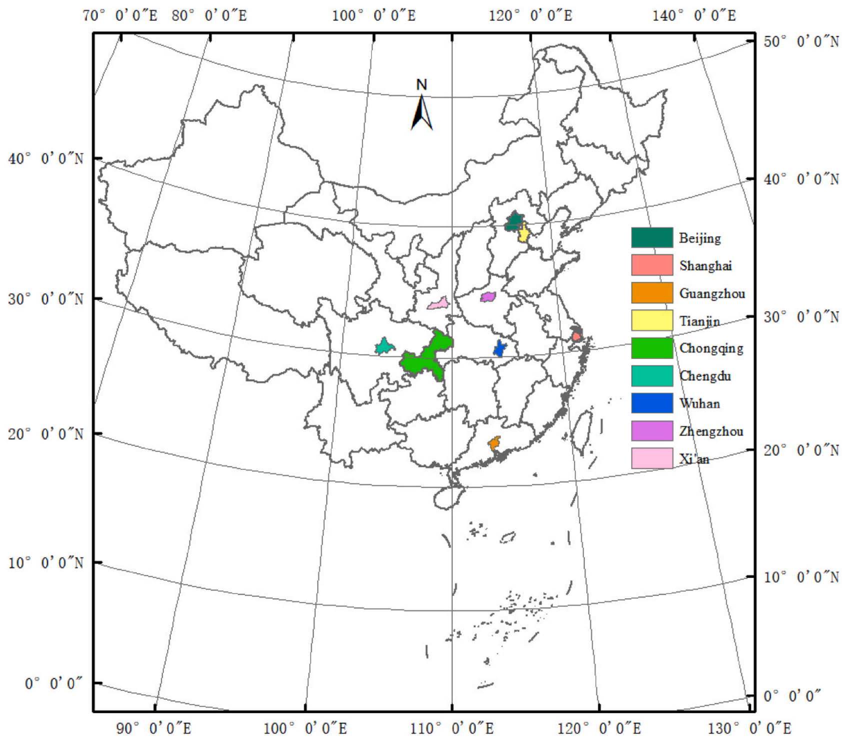

Fig. 1. Research cities and geographic locations.

2. Research materials

2.1. Study area

The State Council confirmed in 2014 that cities with more than 5 million populations are megacities. Considering data availability, we focus on nine megacities in China as the study area (Beijing, Shanghai, Guangzhou, Tianjin, Chongqing, Chengdu, Wuhan, Zhengzhou, and Xi'an), and the locations are as shown in Fig. 1. The urban population and GDP in 2019 are introduced in Table 1.

2.2. Data source

Comprehensively considering the data availability and previous studies [33–38], this paper develops an indicator system from the four subsystems of urban development (Table 2). To prevent the deviation from development scales, we apply the per capita, per unit of GDP, per unit area, or proportion level. To eliminate the impact of inflation, we convert all indicators related to RMB to 2000 as the base year. The weights are obtained through equations (1)–(5) in section 3.1. Data are collected from the China City Statistical Yearbook, City Statistical Yearbook of each city, China Environmental Statistical Yearbook, Statistical Yearbook of related provinces, China Statistical Yearbook of Urban and Rural Construction, China Statistical Yearbook of Urban Construction, China Statistical Yearbook, China Statistical Yearbook of Science and Technology, and Statistical Bulletin of each city. The data period is 1995–2018.

3. Methods

3.1. Entropy method

Before any analysis, data is standardized with the following two equations to eliminate the effects of different dimensions, magnitude, and directions on results [39,40]. Positive indicators can promote the subsystem's development, and negative indicators refer to those that hinder the development.

Positive indicator:

$$X_{ij}^{'} = \left(X_{ij} - min\{X_j\}\right) \Big/ \left(max\{X_j\} - min\{X_j\}\right) \tag{1}$$

Negative indicator:

$$X_{ij}^{'} = \left(max\{X_j\} - X_{ij}\right) \Big/ \left(max\{X_j\} - min\{X_j\}\right) \tag{2}$$

where X_{ij} and $X_{ij}^{'}$ are the original and standardized data of the j th indicator in i th year; $max\{X_j\}$ and $min\{X_j\}$ represent the maximum and minimum value of the j th indicator in all years.

Then, the entropy method is applied to confirm the subsystems' performance. It is a method to measure the disorder of a system, which has been widely used in evaluation [31,33,41,42]. The specific steps are as follows:

First, to calculate the weight Y_{ij} of the j th indicator in i th year among all years:

$$Y_{ij} = X_{ij}^{'} \Big/ \sum_{i=1}^{m} X_{ij}^{'} \tag{3}$$

Then, to calculate the information entropy e_j of the j th indicator:

$$e_j = -\frac{1}{ln\ m}\sum_{i=1}^{m} Y_{ij} \bullet ln\ Y_{ij} \tag{4}$$

Table 1
The urban population and GDP of the nine megacities (2019).

City	Population (10^4)	GDP (￥. 10^8)	GDP per capita (￥)	GDP growth rate (%)
Shanghai	2428	38155.3	157279	6
Beijing	1865	35371.3	164220	6.1
Chongqing	1541	23605.8	75828	6.3
Guangzhou	1352	23628.6	178403	6.8
Tianjin	1303	14104.3	90371	4.8
Wuhan	935	16223.21	145545	7.4
Chengdu	817	17013	103386	7.8
Zhengzhou	670	11590	113139	6.5
Xi'an	638	9321.19	92256	7.0

Source: (1) Statistical Yearbook of each city (2020). (2) Urban Statistical Yearbook of the Ministry of Housing and Urban-rural Development (2020).

Table 2
Indicator system of urban development in 9 Chinese megacities.

Subsystem	Indicator	Direction	Weight
Economy (EC,6)	X_{11}: GDP per capita (¥.10^4)	+	0.1671
	X_{12}: The proportion of tertiary industry in GDP (%)	+	0.1052
	X_{13}: Fixed asset investment per capita (¥.10^4)	+	0.1384
	X_{14}: Local government revenue per capita (¥.10^4)	+	0.2691
	X_{15}: R&D expenditure per capita (¥.10^4)	+	0.2141
	X_{16}: Urban registered unemployment rate (%)	–	0.1062
Society (S,6)	X_{21}: Birth rate (%)	+	0.1098
	X_{22}: Death rate (%)	–	0.0193
	X_{23}: Number of primary school students per capita	+	0.1915
	X_{24}: Number of health technicians per capita	+	0.1290
	X_{25}: Number of public books per capita	+	0.3105
	X_{26}: Road area per capita (m^2)	+	0.2399
Resource (R,5)	X_{31}: Land area per capita ($km^2/10^4$ people)	+	0.2759
	X_{32}: Cultivated land per capita ($km^2/10^4$ people)	+	0.2306
	X_{33}: Grain yield per unit of cultivated land (ton/km^2)	+	0.1932
	X_{34}: Grain yield per capita (ton/10^4people)	+	0.2415
	X_{35}: Energy intensity (tons of standard coal/¥.10^4)	–	0.0589
Environment (EN,5)	X_{41}: Domestic wastewater discharge per capita (ton)	–	0.0902
	X_{42}: Industrial wastewater discharge per secondary industrial output (ton/¥.10^4)	–	0.0410
	X_{43}: Domestic SO_2 emissions per capita (ton)	–	0.0091
	X_{44}: Industrial SO_2 emissions per secondary industrial output (ton/¥.10^4)	–	0.0488
	X_{45}: Proportion of environmental protection investment in GDP (%)	+	0.8109

Next, to calculate the weight w_j of the j th indicator among all n indicators:

$$w_j = (1 - e_j) \Big/ \sum_{j=1}^{n} (1 - e_j) \tag{5}$$

Finally, to calculate subsystem's development performance S_i in i th year:

$$S_i = \sum_{j=1}^{n} w_j \bullet X_{ij}^{'} \tag{6}$$

3.2. Coupling coordinated degree model

Based on the subsystems' performance, we assess the degree of conflicts or coordination between the environment and the other three subsystems through the coupling coordinated degree model. The specific steps are as follows:

First, to calculate the overall level of sustainable urban development T:

Table 3
Ranks of the coordinated level of the environment and other three subsystems.

Major ranks	*D*	Sub-ranks	Label
Superior CD (0.7, 1.0]	$0.9 < D \leq 1.0$	Quality CD	
	$0.8 < D \leq 0.9$	Favorable CD	
	$0.7 < D \leq 0.8$	Intermediate CD	
Barely CD (0.5, 0.7]	$0.6 < D \leq 0.7$	Slightly CD	
	$0.5 < D \leq 0.6$	Barely CD	
Slightly UCD (0.3, 0.5]	$0.4 < D \leq 0.5$	On the verge of CD	
	$0.3 < D \leq 0.4$	Slightly UCD	
Seriously UCD [0.0, 0.3]	$0.2 < D \leq 0.3$	Intermediate UCD	
	$0.1 < D \leq 0.2$	Seriously UCD	
	$0.0 \leq D \leq 0.1$	Extremely UCD	

Note: CD represents coordinated development, and UCD denotes uncoordinated development.

$$T = \beta_1 \bullet f(EC) + \beta_2 \bullet g(S) + \beta_3 \bullet p(R) + \beta_4 \bullet q(EN) \tag{7}$$

where $f(EC)$, $g(S)$, $p(R)$ and $q(EN)$ are performance levels of economic, social, resource, and environmental subsystems calculated through equations (1)–(6). $\beta_1, \beta_2, \beta_3$ and β_4 ($\beta_1 + \beta_2 + \beta_3 + \beta_4 = 1; \beta_1 > 0; \beta_2 > 0; \beta_3 > 0; \beta_4 > 0$) represents the contributions of the four subsystems. Since the four subsystems are equally important in this study and the coupling coordination degree is not significantly affected by the parameter β [42], they are equally set to be 0.25.

Then, to calculate the coupling degree C between subsystems:

$$C = 4 \bullet \left[\frac{f(EC) \bullet g(S) \bullet p(R) \bullet q(EN)}{(f(EC) + g(S) + p(R) + q(EN))^4}\right]^{\frac{1}{4}} \tag{8}$$

Finally, to calculate the coupling coordination degree D of the urban development:

$$D = \sqrt{C \bullet T} \tag{9}$$

The higher the value of D, the less the conflicting degree of the four subsystems and the higher the coordinated level. Drawing on the standards in the previous research [2,43], this paper divides the coordinated level into four ranks and ten sub-ranks, as shown in Table 3.

3.3. Methods to analyze the interacting mechanism

To test the interacting mechanism of the environmental subsystem with the other three subsystems, we construct the interaction model (F): $EN_t = f(EC_t, S_t, R_t)$. This paper converts the four performances into natural logarithms to prevent errors related to the distribution properties of variable sequences. Thus, each estimated coefficient in the model can be interpreted as an elastic effect. This paper applies the panel model since the data includes urban and time-series dimensions. The specific model is as follows:

$$\mathrm{F}: Ln\ EN_{it} = \alpha_0 + \beta_1 * LnEC_{it} + \beta_2 * LnS_{it} + \beta_3 * LnR_{it} + \mu_{it} \tag{10}$$

where α_0 represents fixed urban effect, μ refers to white noise, and β is the corresponding matrix of elastic coefficient.

Before any estimation, the stationary and cointegration tests should be carried out on each performance variable to prevent spurious regression [44]. First, this paper applies the most commonly used unit root test techniques, including the Im-Pesaran-Shin (IPS) panel test [45], Fisher-augmented Dickey-Fuller (ADF) panel test [46], and Fisher-Phillips-Perron (PP) panel test [47]. IPS assumes heterogeneity between sections, and ADF and PP allow heterogeneity between sections [29,48]. Then, the Fisher-type Johansen cointegration test is applied in this paper to test the existence of cointegration between performance variables [46]. It is a method that can provide more stable results than the traditional Engle-Granger two-step panel cointegration test [29,49].

After confirming the stationary and cointegration, this paper utilizes fully modified OLS (FMOLS) to estimate the long-run elastic coefficient [50]. It is a technique that considers heterogeneity [28,51] and can generate consistent estimates from inadequate samples [29,49]. It can also modify the possible long-run sequence correlation and explain the potential endogeneity of variables [27,28,51, 52]. The panel model of FMOLS is as follows:

$$\widehat{\beta}_{GFM} = N^{-1} \sum_{i=1}^{N} \widehat{\beta}_{FM,i} \tag{11}$$

where N is the number of cities, $\widehat{\beta}_{FM,i}$ is the parameter estimates of the i th city.

The corresponding T statistic is:

$$t_{\widehat{\beta}_{GFM}} = N^{-1/2} \sum_{i=1}^{N} \beta_{FM,i} \tag{12}$$

This paper then applies the panel Granger causality test based on the Vector Error Correction Model (VECM) to confirm the long-term and short-term causalities, which is helpful for decisions on sustainable urban development [29]. It is a vector autoregressive model based on cointegration to model nonstationary time series. For model F, the specific VECM estimation equation is as follows:

$$\begin{bmatrix} \triangle LnEN \\ \triangle LnEC \\ \triangle LnS \\ \triangle LnR \end{bmatrix} = \begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{bmatrix} + \sum_{j-1}^{k} \begin{bmatrix} \gamma_{11j} & \gamma_{12j} & \gamma_{13j} & \gamma_{14j} \\ \gamma_{21j} & \gamma_{22j} & \gamma_{23j} & \gamma_{24j} \\ \gamma_{31j} & \gamma_{32j} & \gamma_{33j} & \gamma_{34j} \\ \gamma_{41j} & \gamma_{42j} & \gamma_{43j} & \gamma_{44j} \end{bmatrix} \times \begin{bmatrix} \triangle LnEN_{it-j} \\ \triangle LnEC_{it-j} \\ \triangle LnS_{it-j} \\ \triangle LnR_{it-j} \end{bmatrix} + \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \end{bmatrix} ECT_{it-1} + \begin{bmatrix} \mu_{1it} \\ \mu_{2it} \\ \mu_{3it} \\ \mu_{4it} \end{bmatrix} \tag{13}$$

where $\triangle$, δ, γ, j, i, t, λ, ECT_{it-1} and μ respectively represent corresponding first-order difference, fixed urban effect, short-term causal effect coefficient of the explanatory variables, lag length, number of cities, years, long-term adjustment coefficient, lag error correction, and random error.

4. Results

4.1. Subsystems' performance from 1995 to 2018

The four subsystems' performance from 1995 to 2018 obtained by the Entropy method is shown in Fig. 2. In general, except for the resource subsystem, the performance showed an overall upward trend. Specifically, in terms of the economic subsystem, except for Guangzhou, the performance in other cities showed significant growth. Regarding the social subsystem, the performance in Tianjin, Beijing, and Chongqing fluctuated wildly and did not increase significantly, while that in other cities also fluctuated but showed significant growth. Regarding resource subsystem, the performance in Chongqing, Chengdu, and Guangzhou fluctuated wildly, while that in other cities declined slowly. Finally, as for the environmental subsystem, all cities except Chongqing and Chengdu saw an increase.

In addition to the different trends in different subsystems, there were significant differences among different cities. For example, Chongqing lagged other cities in the economic and social performance but had relatively high performance in the resource subsystem. Shanghai's economic, social, and environmental subsystems performed relatively well in most years, while the resource subsystem was relatively backward. The performance of Wuhan's economic, social, and resource subsystems was at the middle level among all nine megacities, but its environmental performance was relatively low. Guangzhou's economic and social performance was somewhat higher, while the resource and environmental performance were contrary.

4.2. Coordinated levels between the environment and other subsystems

Based on the four subsystem's performance variables, the coordinated level of the urban system is obtained through equations (7)–(9), and the results are shown in Fig. 3. In general, the coordination degree of the urban system in the nine megacities was not high; most of which was at the ranks of "on the verge of CD", "barely CD", and "slightly CD". Specifically, the coordination level in Shanghai was relatively the highest, and it entered the "slightly CD" in 1996, but there was no further improvement. On the contrary, the coordination level in Chengdu City and Wuhan City was relatively the lowest, "on the verge of CD" for a long time, and only entered the rank of "barely CD" in recent years. Other cities that remained "barely CD" include Guangzhou and Tianjin. Zhengzhou City and Xi'an City saw the most significant improvement, from "on the verge of CD" to "barely CD" and then to "slightly CD".

4.3. Interacting mechanism between the environment and other subsystems

4.3.1. Results of stationary and cointegration

Considering the time trend of macroeconomic data, we compare the panel unit root test that contains individual intercept with that includes both intercept and trend (Table 4). The results indicate that not all variables are stationary at all significance levels in both conditions. In contrast, the four variables are stationary in both states after the first difference. These tests confirm that all series are integrated on I (1), allowing us to examine the long-run equilibrium relationship among the interacting subsystems.

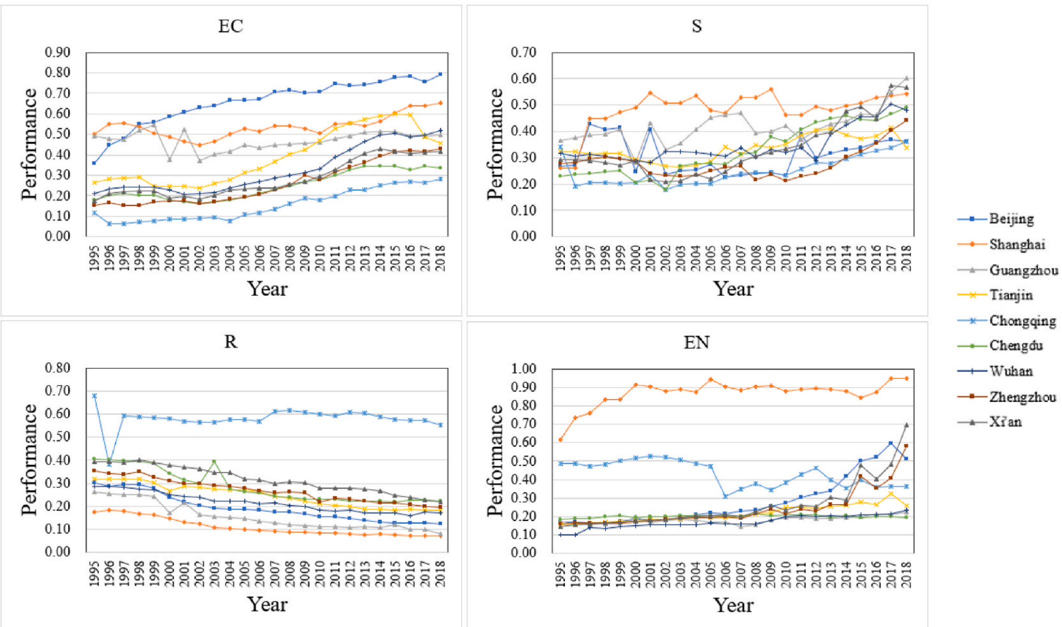

Fig. 2. Subsystems' performance from 1995 to 2018.

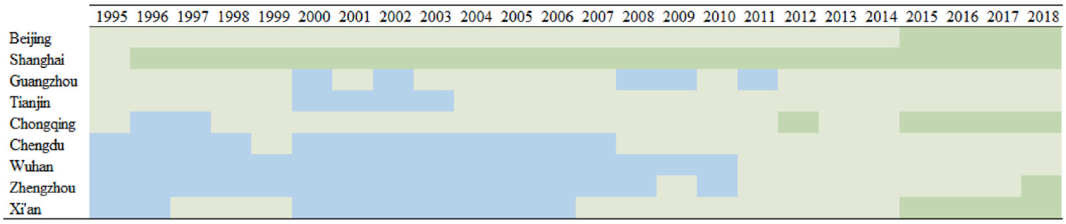

Fig. 3. Coordinated levels of the urban system (1995–2018).

Table 4
Results of panel unit root tests for the performance of the four subsystems.

Variables	Leve		First difference	
	Intercept	Intercept and trend	Intercept	Intercept and trend
IPS				
ln EC	2.32999 (0.9901)	−5.84123 (0.0000)*	−10.8378 (0.0000)*	−7.86594 (0.0000)*
ln S	2.32059 (0.9898)	−1.67901 (0.0466)**	−15.2123 (0.0000)*	−12.1361 (0.0000)*
ln R	0.19796 (0.5785)	−2.24275 (0.0125)**	−17.7846 (0.0000)*	−17.0439 (0.0000)*
ln EN	3.64529 (0.9999)	1.78922 (0.9632)	−15.3908 (0.0000)*	−13.7067 (0.0000)*
Fisher-ADP				
ln EC	6.86484 (0.9912)	69.2131 (0.0000)*	128.264 (0.0000)*	97.0992 (0.0000)*
ln S	13.4739 (0.7627)	37.4470 (0.0046)*	182.194 (0.0000)*	131.270 (0.0000)*
ln R	27.8576 (0.0643)***	43.1151 (0.0008)*	288.298 (0.0000)*	374.523 (0.0000)*
ln EN	18.1890 (0.4433)	16.8623 (0.5326)	183.826 (0.0000)*	153.865 (0.0000)*
Fisher-PP				
ln EC	40.6604 (0.0017)*	129.323 (0.0000)*	150.264 (0.0000)*	169.341 (0.0000)*
ln S	40.1602 (0.0020)*	44.8850 (0.0004)*	204.519 (0.0000)*	405.371 (0.0000)*
ln R	25.2488 (0.0082)*	70.3720 (0.0000)*	268.369 (0.0000)*	647.752 (0.0000)*
ln EN	44.7460 (0.0005)*	47.2814 (0.0002)*	201.500 (0.0000)*	414.354 (0.0000)*

Notes: (1) The values in parentheses are probabilities.
(2) *, ** and *** represent statistical significance at the 1 %, 5 % and 10 % levels, respectively.

Fisher-type Johansen cointegration test applies both max-eigen and trace tests to determine how much the cointegration exists. Table 5 shows the test results, indicating at least one cointegration equation among these four performance variables at a 1 % significance level. Therefore, there is a significant long-run equilibrium relationship among the four variables.

4.3.2. *Results of panel long-term parameter estimation*

The panel long-term parameter estimation results are obtained through the FMOLS technique, as shown in Table 6. The statistic values of R2 and adjusted R2 are very high, suggesting the sound-fitting effects of the models. From the results, a 1 % rise in the economic and resource performance can respectively lead to 0.2014 % and 0.1388 % declines in the environmental performance. By contrast, a 1 % increase in social performance can bring a 0.3738 % rise in environmental performance.

4.3.3. *Results of panel VECM Granger causality test*

Table 7 illustrates the results of the panel VECM Granger causality test in the short and long run among the four performance variables. The results show that there only exist unidirectional causalities from economic performance to social performance and from social performance to resource performance in the short run. However, in the long run, bidirectional causalities exist between each couple of the four variables. To present better, we summarize the Granger causalities in Fig. 4.

Table 5
Results of Johansen Fisher panel cointegration test.

Hypothesized No. of CE(s)	Trace Statistic	Max-Eigen Statistic
None	113.3896 (0.0000)*	80.68898 (0.0000)*
At most 1	32.70063 (0.0906)***	21.19784 (0.0707)***
At most 2	11.50279 (0.4944)	9.315010 (0.4008)

Notes: (1) The values in parentheses are probabilities.
(2) * and *** represents statistical significance at the 1 % and 10 % level.

Table 6
Results of the FMOLS estimation.

Explanatory variables	Coefficient	Prob.
ln EC	−0.201379*	0.0000
ln S	0.373800*	0.0000
ln R	−0.138786**	0.0172
R-squared: 0.972378		
Adjusted R-squared: 0.969408		

Table 7
Results of VECM panel Granger causality test.

Dependent variables	Short-run				Long-run
	△ln EN	△ln EC	△ln S	△ln R	ECT_{t-1}
	F-stat				t-stat
△ln EN	–	0.391733	1.626714	0.172868	−0.006496*
△ln EC	1.575424	–	0.770929	0.828498	−0.002795**
△ln S	0.490149	4.584461**	–	0.195371	−0.003321***
△ln R	0.036266	1.246598	6.221072**	–	0.005680*

Notes: (1) △ represents the first-difference operator.
(2) *, ** and *** represents statistical significance at the 1 %, 5 % and 10 % levels, respectively.

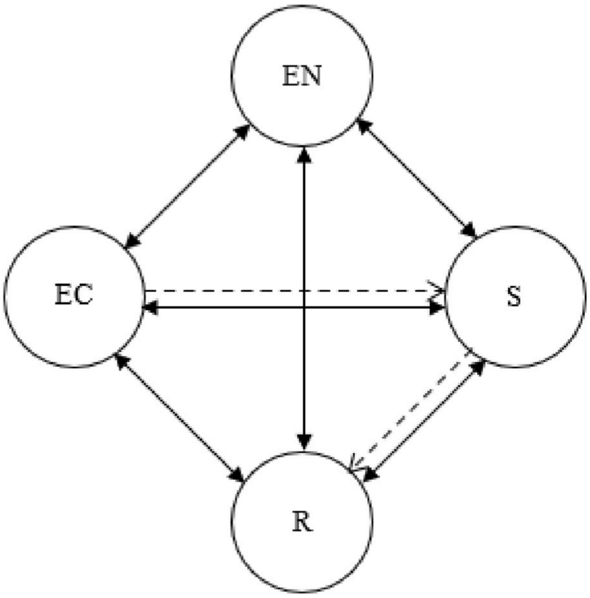

Fig. 4. Causality relationships for the four performance variables.Note: —→ represents short-run Granger causality; ——▶ represents long-run Granger causality.

5. Discussion

5.1. Low coordination level between environmental subsystem and other urban development aspects

The results reveal that the coordination level between the environmental subsystem and other urban development aspects (economic, social, and resource subsystems) was low in the nine megacities in China during 1995–2018, resulting in nonideal sustainable development. One possible reason is that improving these cities' economic performance and social welfare has always been resource-dependent, and not enough attention has been paid to pollution reduction and environmental protection. Previous studies have also proposed that developed cities are backward in the ecological environment [30]. In other words, the key to achieving sustainable development of these cities lies in decoupling from resources and improving environmental performance. This finding confirms that resource conservation and environmental protection are current development priorities [5,40].

The results of nonideal coordinated development are also consistent with previous studies that assessed the coordination degree between urban subsystems [25,53]. By contrast, the results contradict those focused on environmental elements rather than the overall subsystem's performance. For example, the research that only concentrated on air pollution suggested a high coordination degree between air quality and urban development [54]. The difference in these results indirectly proves that it is necessary to consider the performance of the overall subsystem, which can bring new references for environmental management and sustainable urban development.

Combined with the weights in the indicator system, it is indicated that increasing environmental protection investment and improving the support of land resources and grain yield capacity should be the priorities for sustainable urban development. Previous studies support increasing environmental investment [55]. Besides, the government should also adopt effective techniques to manage urban land and optimize urban land patterns [6].

5.2. *Negative effects of economic and resource subsystems on the environmental performance*

The results reveal that environmental performance is negatively affected by the improvement in economic performance. Economic development has two opposite effects on the environment. One is the negative impact of environmental pollution caused by economic growth. On the other hand, the positive impact of environmental improvement is driven by technological upgrading and increased protection investment, such as the positive effects of industrial structure upgrading and optimization [19]. Our results indicate that economic development's adverse impact in these cities is still more significant than the positive effects. In other words, these cities' economic development sacrificed the environment, supported by previous views [32]. Improving the positive role of the economy in the future is the focus—for example, increasing investment in environmental protection, which is consistent with the discussion in section 5.1 and previous studies [55]. As in section 5.1, the results will differ when only considering environmental elements. For example, economic growth can reduce rather than increase PM2.5 concentration [24,56] and industrial pollutants [7].

The results also reveal that environmental performance is negatively affected by the improvement in resource performance. It is mainly due to the pollution emissions in resource consumption and inefficient use of the resource inputs [57]. One possible way is to improve the proportion of renewable energy consumption, which has been proven to reduce pollution emissions [28].

Considering that the resource performance shows a downward trend, the low performance of the environmental subsystem is mainly caused by the adverse effects of economic development. This finding is consistent with previous studies, which suggested that the government should pay attention to the contradiction between the economy and the environment during urban development [38]. Enhancing environmental regulation is effective since it can reduce environmental pollutants directly discharged from economic production activities [24]. Besides, combining the weights in the indicator system and previous studies, increasing R & D investment is an excellent way to eliminate this adverse effect [7], since it can improve the technology level and enhance the treatment capacity of pollutants. In addition, optimizing economic structure is also necessary to increase the proportion of tertiary industries and reduce resource-based industries with high pollution [30,44,58].

5.3. *Positive effects of the social subsystem on the environmental performance*

The results reveal that environmental performance is positively affected by the improvement in social performance. It may be because improving people's livelihood and welfare has brought about a lifestyle change that has been proven to influence pollution reduction substantially [7]. The increase in road area per capita can reduce road density, the growth of which has been proven to increase the emission of air pollutants [44,58]. Implementing high-speed rail significantly improves urban environmental efficiency [59]. The positive role of education may be because the awareness of environmental protection has increased with the popularization of education, which positively affects environmental performance. Similarly, health awareness and demand enhanced people's desire to protect the environment.

5.4. *Bidirectional Granger causalities between environmental subsystem and other urban development aspects in the long run*

The long-run bidirectional Granger causalities indicate that it is unscientific to focus only on any single aspect of urban development. In other words, coordinated development among economic, social, resource, and environmental subsystems is essential to achieve sustainability. This finding is consistent with previous studies that suggest coordinated development as an inherent requirement for sustainability [37]. The empirical research in Wuhan City also proved that focusing only on the economy will result in an uncoordinated development [40]. How to promote positive interactions among these four subsystems is the key. For example, a sound environmental subsystem is necessary to achieve high economic development [21,32]. Without a healthy environment, urban development cannot be sustainable [55].

6. Countermeasures

Based on the above results and discussions, stakeholders can take measures to address the incoordination between the environment and other development subsystems:

The government should further establish and implement policies to reduce the dependence of urban development on resources, promote the use of clean energy, and thus reduce pollution emissions. At the same time, continue to increase the expenditure of fiscal revenue on environmental protection to improve environmental performance. Besides, enhancing the support of land resources and grain yield capacity is also essential for sustainable urban development, which can be achieved by technical management and optimization of land patterns. Reducing the negative impact of economic growth on the environment is also an issue that the government still needs to consider in the future, which requires continued optimization of the industrial structure layout and more serious environmental regulation. Last but not least, the government still needs to continuously improve social performance, such as public infrastructure and education.

Enterprises should continue to invest in technological research and development to improve resource utilization efficiency and reduce resource consumption emissions. Improving the technology level can also benefit the treatment capacity of pollutants. In addition, some profits can also be sacrificed to increase the proportion of green renewable energy consumption and thus reduce pollution emissions.

Scholars should enhance the systematic development concept and pay attention to the comprehensive urban system. In addition, scholars should also clarify the conflicts between subsystems more broadly and gain insight into the interaction relationships between specific elements simultaneously to provide references for policy formulation.

7. Conclusions and future perspectives

This paper creatively answers the question of whether the performance of the environment and other dimensions improves synchronously and how changes in the performance of other development dimensions will affect that of the environment. Taking China's megacities as an example, this paper analyzes the role of the whole environmental subsystem in sustainable urban development, which is of theoretical and practical significance. From 1995 to 2018, the coordination level of the environmental and other urban subsystems has no noticeable improvement, which means that the conflicts between the environment and urban development are still severe. Improving environmental and resource performance should be the priority in the future. Through further interaction analysis, we found that environmental performance is negatively affected by economic and resource subsystems, indicating an environment-sacrifice development model. On the other hand, it is positively affected by the social subsystem. Furthermore, coordinating urban subsystems is the key to long-run sustainable development.

However, there are limitations and further possibilities for future research. First, the selected subsystem indicators cannot perfectly represent the overall performance due to data availability, which should be continuously improved with the database update. Second, considering the critical role of megacities in their region, geospatial factors can be included in future analysis. Last but not least, based on our findings, future research can analyze the impact of each element of social livelihood on environmental performance, which is a significant research gap.

Data availability statement

The data that has been used is confidential.

CRediT authorship contribution statement

Fangli Ruan: Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Xuanying Li:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] UN, Transforming Our World: the 2030 Agenda for Sustainable Development, 2015.
[2] F.L. Ruan, The complexity of the urban system: Profiles based on current literature and gaps with Sustainable Development Goals, Sustain. Dev. 31 (4) (2023) 2137–2154.
[3] M. Ahmad, E. Satrovic, How do fiscal policy, technological innovation, and economic openness expedite environmental sustainability? Gondwana Res. 124 (2023) 143–164.
[4] H.S. Kilic, A.S. Yalcin, Comparison of municipalities considering environmental sustainability via neutrosophic DEMATEL based TOPSIS, Soc. Econ. Plann. Sci. 75 (2021) 20.
[5] Y. Yang, W.J. Li, The evolution of the ecological footprint and its relationship with the urban development of megacities in Western China: the case of Xi`an, J. Environ. Manag. 243 (2019) 463–471.
[6] Z.F. Liu, et al., The impairment of environmental sustainability due to rapid urbanization in the dryland region of northern China, Landsc. Urban Plann. 187 (2019) 165–180.
[7] F.J. Xu, et al., Reexamining the relationship between urbanization and pollutant emissions in China based on the STIRPAT model, J. Environ. Manag. (2020) 273.
[8] S.K. Abd-Elmabod, et al., Rapid urbanisation threatens fertile agricultural land and soil carbon in the Nile delta, J. Environ. Manag. 252 (2019) 12.

[9] K.Y. Soria, M.R. Palacios, C.A.M. Gomez, Governance and policy limitations for sustainable urban land planning. The case of Mexico, J. Environ. Manag. 259 (2020) 9.
[10] H. Fasihi, T. Parizadi, Analysis of spatial equity and access to urban parks in Ilam, Iran, J. Environ. Manag. 260 (2020) 6.
[11] M. Mapar, et al., A composite index for sustainability assessment of health, safety and environmental performance in municipalities of megacities, Sustain. Cities Soc. 60 (2020) 13.
[12] Z. Cui, et al., Assessing sustainability environmental performance of three urban agglomerations in China: an input-output modeling approach, Ecol. Indicat. 130 (2021) 15.
[13] J. da Silva, et al., Water sustainability assessment from the perspective of sustainable development capitals: conceptual model and index based on literature review, J. Environ. Manag. 254 (2020) 21.
[14] R. Lamy, et al., Potential contribution of environmental building certifications to urban sustainability-Curitiba case study, Sustain. Cities Soc. 73 (2021) 10.
[15] C.G. Mitincu, et al., Licensing sustainability related aspects in Strategic Environmental Assessment. Evidence from Romania's urban areas, Land Use Pol. 108 (2021) 13.
[16] S.H. Lin, et al., An evaluation framework for developing green infrastructure by using a new hybrid multiple attribute decision-making model for promoting environmental sustainability, Soc. Econ. Plann. Sci. 75 (2021) 16.
[17] H. Kruize, et al., Urban green space: creating a triple win for environmental sustainability, health, and health equity through behavior change, Int. J. Environ. Res. Publ. Health 16 (22) (2019) 22.
[18] C.A. Hossu, et al., An evaluation of environmental plans quality: addressing the rational and communicative perspectives, J. Environ. Manag. 256 (2020) 15.
[19] K. Chen, et al., The relationship between environmental regulation, industrial transformation change and urban low-carbon development: evidence from 282 cities in China, Environmental Research and Public Health 19 (19) (2022) 12837.
[20] K. Kourtit, P. Nijkamp, S. Suzuki, Are global cities sustainability champions? A double delinking analysis of environmental performance of urban agglomerations, Sci. Total Environ. 709 (2020) 11.
[21] J. Chen, et al., Economic growth, air pollution, and government environmental regulation: evidence from 287 prefecture-level cities in China, Technol. Econ. Dev. Econ. 27 (5) (2021) 1119–1141.
[22] X. Zhang, J. Zheng, L. Wang, Can the relationship between atmospheric environmental quality and urban industrial structure adjustment achieve green and sustainable development in China? A case of taiyuan city, Energies 15 (9) (2022) 3402.
[23] J.D. Chen, et al., The influence of increased population density in China on air pollution, Sci. Total Environ. 735 (2020) 13.
[24] D. Yan, et al., The heterogeneous effects of socioeconomic determinants on PM2.5 concentrations using a two-step panel quantile regression, Appl. Energy 272 (2020) 10.
[25] W.J. Li, et al., Coupling coordination analysis and spatiotemporal heterogeneity between urbanization and ecosystem health in Chongqing municipality, China, Sci. Total Environ. 791 (2021) 15.
[26] Y.L. Chen, et al., Exploring the effects of economic growth, and renewable and non-renewable energy consumption on China's CO_2 emissions: Evidence from a regional panel analysis, Renew. Energy 140 (2019) 341–353.
[27] M.M. Rahman, E. Velayutham, Renewable and non-renewable energy consumption-economic growth nexus: new evidence from South Asia, Renew. Energy 147 (2020) 399–408.
[28] K. Saidi, A. Omri, The impact of renewable energy on carbon emissions and economic growth in 15 major renewable energy-consuming countries, Environ. Res. 186 (2020) 11.
[29] H. Qiao, et al., The greenhouse effect of the agriculture-economic growth-renewable energy nexus: evidence from G20 countries, Sci. Total Environ. 671 (2019) 722–731.
[30] T. Shi, et al., Coupling coordination degree measurement and spatiotemporal heterogeneity between economic development and ecological environment –Empirical evidence from tropical and subtropical regions of China, J. Clean. Prod. (2020) 244.
[31] J.Y. Wang, et al., Coupling analysis of urbanization and energy-environment efficiency: evidence from Guangdong province, Appl. Energy 254 (2019) 12.
[32] Y.P. Fan, C.L. Fang, Q. Zhang, Coupling coordinated development between social economy and ecological environment in Chinese provincial capital cities-assessment and policy implications, J. Clean. Prod. 229 (2019) 289–298.
[33] X.G. Cui, et al., Assessing sustainability of urbanization by a coordinated development index for an Urbanization-Resources-Environment complex system: a case study of Jing-Jin-Ji region, China, Ecol. Indicat. 96 (2019) 383–391.
[34] Y.Q. Geng, L.W. Liu, L.Y. Chen, Rural revitalization of China: a new framework, measurement and forecast, Soc. Econ. Plann. Sci. 89 (2023) 16.
[35] A. Lewandowska, D. Szymanska, Ecologisation of Polish Cities in the Light of Selected Parameters of Sustainable Development, vol. 64, Sustainable Cities and Society, 2021.
[36] Z.R. Jing, J.M. Wang, Sustainable development evaluation of the society-economy-environment in a resource-based city of China:A complex network approach, J. Clean. Prod. (2020) 263.
[37] Q.S. Wang, et al., Evaluation and countermeasures of sustainable development for urban energy-economy-environmentsystem: a case study of Jinan in China, Sustain. Dev. 28 (6) (2020) 1663–1677.
[38] P.T. Yi, W.W. Li, D.N. Zhang, Sustainability assessment and key factors identification of first-tier cities in China, J. Clean. Prod. 281 (2021) 10.
[39] D. Cui, et al., An integrated approach to investigate the relationship of coupling coordination between social economy and water environment on urban scale - a case study of Kunming, J. Environ. Manag. 234 (2019) 189–199.
[40] L. Xing, M.G. Xue, M.S. Hu, Dynamic simulation and assessment of the coupling coordination degree of the economy-resource-environment system: case of Wuhan City in China, J. Environ. Manag. 230 (2019) 474–487.
[41] X.K. Wang, et al., Study on spatial and temporal distribution characteristics of coordinated development degree among regional water resources, social economy, and ecological environment systems, Int. J. Environ. Res. Publ. Health 16 (21) (2019) 20.
[42] J.Q. He, et al., Examining the relationship between urbanization and the eco-environment using a coupling analysis: case study of Shanghai, China, Ecol. Indicat. 77 (2017) 185–193.
[43] Y.Q. Geng, et al., Higher education and digital Economy: analysis of their coupling coordination with the Yangtze River economic Belt in China as the example, Ecol. Indicat. 154 (2023) 16.
[44] L.Y. Zhu, et al., Do economic activities cause air pollution? Evidence from China's major cities, Sustain. Cities Soc. 49 (2019) 10.
[45] K.S. Im, M.H. Pesaran, Y. Shin, Testing for unit roots in heterogeneous panels, J. Econom. 115 (1) (2003) 53–74.
[46] G.S. Maddala, S.W. Wu, A comparative study of unit root tests with panel data and a new simple test, Oxf. Bull. Econ. Stat. 61 (1999) 631–652.
[47] P. P C, P. P, Testing for a unit root in time series regression, Biometrika 75 (2) (1998) 335–346.
[48] X.Y. Liu, S. Zhang, J. Bae, The nexus of renewable energy-agriculture-environment in BRICS, Appl. Energy 204 (2017) 489–496.
[49] S.R. Paramati, M.S. Alam, C.F. Chen, The Effects of Tourism on economic Growth and CO_2 emissions: a Comparison between Developed and developing economies, J. Trav. Res. 56 (6) (2017) 712–724.
[50] P. Pedroni, Fully modified OLS for heterogeneous cointegrated panels, in: Nonstationary Panels, Panel Cointegration, and Dynamic Panels, Emerald Group Publishing Limited, 2001.
[51] P. Pedroni, Fully Modified OLS for Heterogeneous Cointegrated Panels and the Case of Purchasing Power Parity, 1996.
[52] A. Banerjee, Panel data unit roots and cointegration: an overview, Oxf. Bull. Econ. Stat. 61 (1999) 607–629.
[53] W.W. Li, P.T. Yi, Assessment of city sustainability-Coupling coordinated development among economy, society and environment, J. Clean. Prod. (2020) 256.
[54] W.P. Fan, et al., Spatio-temporal variation of the coupling relationship between urbanization and air quality: a case study of Shandong Province, J. Clean. Prod. (2020) 272.
[55] Y. Tao, et al., Measuring urban environmental sustainability performance in China: a multi-scale comparison among different cities, urban clusters, and geographic regions, Cities 94 (2019) 200–210.

[56] Q.C. Xie, X. Xu, X.Q. Liu, Is there an EKC between economic growth and smog pollution in China? New evidence from semiparametric spatial autoregressive models, J. Clean. Prod. 220 (2019) 873–883.
[57] Y. Zhang, J.J. Chen, An empirical study of the efficiency of haze pollution governance in Chinese cities based on streaming data, Sci. Total Environ. 739 (2020) 10.
[58] Q.Q. Liu, et al., The effect of natural and anthropogenic factors on PM2.5: empirical evidence from Chinese cities with different income levels, Sci. Total Environ. 653 (2019) 157–167.
[59] X. Sun, et al., High-speed rail development and urban environmental efficiency in China: a city-level examination, Transport. Res. Transport Environ. 86 (2020) 102456.