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The coupling dynamic effect of government environmental attention, green efficiency, and air quality

Yuequn Cao¹, Chaoyang Tu¹ [✉], Kexin Du¹ & Chenlin Cui¹

There exists a significant interactive coupling relationship between the government's environmental attention, green efficiency, and air quality. Studying the dynamic coupling effects among these variables is crucial for promoting the sustainable development of China's economy and society. This paper clarifies the coupling mechanism of government environmental attention, green efficiency, and air quality by analyzing 270 prefecture-level cities in China using the coupling coordination model and PVAR model. The results indicate that while government environmental attention, green efficiency, and air quality all show an upward trend, their temporal and spatial performances differ. The degree of coupling and coordination among these variables also exhibits significant fluctuations, indicating a dynamic relationship. Government environmental attention as a fundamental driving force in the dynamic coupling of these variables, promoting high-level development through factors like economic growth, technological progress, and socio-cultural influences. Finally, this paper proposes five key policy recommendations. The study provides valuable insights into promoting local governments' environmental initiatives, advancing China's ecological civilization, and addressing international environmental pollution in developing countries.

¹School of Economics, Minzu University of China, Beijing 100081, China. ✉email: t17637520019@163.com

Introduction

With the rapid development of globalization, environmental problems have emerged as significant factors limiting the sustainable development of various countries. Particularly, environmental pollution resulting from rapid economic growth has become a focal point of global attention. As a developing country, China's formulation and implementation of environmental policies is crucial not only for its sustainable development but also for addressing environmental issues in Asia and globally. In environmental improvement efforts, the government plays a critical role. The government's policy preferences, implementation efforts, and resulting impacts directly influence the optimization of environmental quality and the green sustainability of regional economic development (Zhang et al., 2021). In recent years, with the growing emphasis on environmental protection, the Chinese government has introduced a series of environmental policies and measures aimed at enhancing environmental management and regional green development while ensuring stable economic growth (Zhima, 2022). The implementation of these policies not only underscores the importance the government places on environmental issues but also has a profound impact on the green efficiency of cities (Lim et al., 2023). However, in practice, how to effectively implement these environmental policies and the specific dynamic coupling effects they produce require in-depth study.

Moreover, environmental protection and economic development have traditionally been seen as contradictory objectives. The conventional perspective holds that environmental protection often hampers economic growth, while rapid economic growth exacerbates environmental degradation (Anser et al., 2024). However, guided by the concept of green development, increasing evidence suggests that scientific and technological advancements and sound policy guidance can facilitate a positive interaction between the two, promoting mutual enhancement (Bi et al., 2023). Enhancing green efficiency not only fosters higher-quality economic development but also significantly improves air quality and advances ecological civilization, thereby achieving sustainable development goals (Deng et al., 2021). In light of this, this paper examines the interactive dynamic coupling effects among government environmental attention, green efficiency, and air quality as its research focus, aiming to address the following core questions that remain underexplored: What is the underlying interactive mechanism among government environmental attention, green efficiency, and air quality? How do their mutual dynamic coupling effects manifest?

The impact of government environmental policies on enhancing green efficiency has consistently been a central issue in environmental economics research. Currently, scholars generally believe that effective environmental policies can directly enhance regional environmental quality and also compel enterprises to adopt more environmentally friendly production and management methods, thereby improving overall green efficiency (Khattak & Ahmad, 2022). For example, Porter's "Porter Hypothesis" posits that appropriate environmental regulation can stimulate enterprise innovation, which not only compensates for environmental costs but also potentially provides additional competitive advantages (Porter & van der Linde, 1995). Subsequently, numerous empirical studies have supported this hypothesis (Lewis, 1954; Sjaastad, 1962). Increasingly, studies indicate that government environmental policies can indeed enhance enterprise efficiency and optimize industrial structures (Birdsall & Wheeler, 1993). However, some studies have highlighted that the impact of government environmental policies on improving green efficiency is not universally positive (Luo & Li, 2019). For instance, Tu Zhengge and Jindian found that in the

absence of adequate technical support and capital investment, solely relying on environmental regulation to enhance green efficiency may be insufficient and could even result in declining enterprise performance. Consequently, it has become a critical research direction in environmental economics to explore how top-level policy design and implementation can promote green economic growth while ensuring environmental quality (Cai et al., 2022).

Improvements in air quality are closely linked to government environmental policies. Empirical studies from various countries and regions have demonstrated that government environmental attention can significantly enhance air quality (Bardaka et al., 2019). Governments can effectively reduce air pollutant emissions by setting and enforcing strict emission standards, providing environmental subsidies, and supporting green technology innovation (Jalil & Mahmud, 2009; Tu et al., 2021). For example, China's "Ten Measures for Air" policy has significantly reduced PM2.5 levels in many cities, thereby improving public health. However, some studies have shown that the effectiveness of government environmental policies is influenced by several factors (Copeland, 1990), such as policy continuity and consistency, local government execution, and the adequacy of financial resources (Bardhan & Mookherjee, 2006; Tu et al., 2024). Therefore, it is crucial to study how governments can effectively implement environmental policies under various administrative systems and economic conditions to comprehensively improve air quality.

The study of the coupling dynamic effects of government environmental attention, green efficiency, and air quality is still in its early stages. Research in this area typically focuses on the impact of single policies on the environment or the economy, with less emphasis on the interaction and feedback mechanisms among multiple variables (Cao et al., 2023; Gray, 1987). Recently, some scholars have begun using machine learning models and coupling models to explore how government policies affect economic and environmental systems through various transmission paths (Jorgenson & Wilcoxon, 1990). For example, research shows that by building a dynamic feedback model between government policy intensity, enterprise technological innovation, and environmental quality, government environmental investment and policy support are key to promoting enterprise green innovation (Cui et al., 2018), while enterprise green technological innovation can significantly enhance regional environmental quality and economic efficiency. Additionally, an increasing number of studies have begun focusing on the relationship between government environmental policies and local governance capabilities (Zhang et al., 2019). Studies have found that the environmental governance capacity of local governments not only affects the formulation and implementation of policies but also plays a decisive role in their effectiveness and sustainability (Acemoglu & Restrepo, 2017). These studies suggest that to understand and address the coupling dynamic effects between government environmental attention, green efficiency, and air quality, comprehensive analysis of actual data is necessary.

In summary, although progress has been made in government environmental policies, green efficiency, and air quality, the coupling dynamic effects among these factors require further exploration. The potential marginal contributions of this paper are as follows: First, from a research perspective, this paper develops a comprehensive analytical framework to systematically investigate the dynamic coupling effects among government environmental attention, urban green efficiency, and air quality. Using the coupling coordination model and the PVAR model, this study analyzes both the static coupling relationships and the dynamic interactive effects among these three variables. This

approach offers a fresh perspective for understanding the intricate relationships among environmental policies, economic efficiency, and environmental quality. Second, regarding data and methodological innovation, this paper utilizes panel data from 270 prefecture-level cities in China covering the period from 2010 to 2020, ensuring extensive and representative coverage. Government environmental attention is quantified using word frequency statistics, while urban green efficiency is measured with the super efficiency SBM model and the Globe-Malmquist-Luenberger index. These methodological innovations enhance the scientific rigor and accuracy of the research. Finally, this study elucidates how government environmental attention impacts green efficiency and air quality through various mechanisms, considering the complexity and regional differences in policy implementation. It thereby provides a theoretical and practical foundation for designing more effective environmental policies.

The structure of this paper is organized as follows: Section “Analysis of connotation characteristics and action mechanism” elaborates on the connotations and characteristics and examines their mechanisms of action. Section “Model setting, index selection and data description” introduces the models and variable selection. Section “Result analysis” presents the results, while Section “Further GMM estimation of PVAR model” focuses on the GMM estimation of the PVAR model. Section “Further Analysis” discusses the empirical findings, and finally last section concludes the research with policy recommendations.

Analysis of connotation characteristics and action mechanism

Conceptual connotation and its interaction mechanism. Government environmental concerns, green efficiency, and air quality are critical areas of study in environmental economics. The government’s environmental focus encompasses efforts to enact environmental regulations, invest in environmental protection, and promote green technology, which protect the environment while fostering economic development (Du et al., 2024). Green efficiency reflects the efficiency and environmental friendliness of resource utilization (Chen & Wang, 2022). By introducing clean energy and environmental protection technologies, pollution emissions can be reduced, achieving both economic and environmental benefits. Air quality is a vital indicator of environmental health, and the government can significantly enhance it through strict emission standards and support for green technological innovation (Heal et al., 2012). The coupling of government environmental attention, green efficiency, and air quality refers to the complex interaction and mutual influence among government focus on environmental protection, regional green efficiency improvements, and air quality enhancements in a specific region (Chu et al., 2024). Government environmental attention encompasses not only the formulation and implementation of environmental policies but also their effectiveness and sustainability (Man et al., 2024). Green efficiency represents the efficiency and sustainability of regional natural resource use and economic activities, while air quality directly reflects the health of residents’ living environments.

The coupling mechanism of government environmental attention, green efficiency, and air quality reflects their interactive relationship and dynamic impact. This coupling effect operates through three main aspects: (1) improvement in government environmental attention leading to policy and regulatory measures, (2) enhancement of green efficiency, and (3) improvement of air quality. Specifically:

(1) enhancement in government environmental attention leads to policy and regulatory measures (Li et al., 2020). Government environmental attention is a fundamental driving force in the

coupling mechanism. With increased environmental awareness, the government guides improvements in green efficiency and air quality by formulating and implementing various environmental protection policies, promoting environmental legislation, strengthening environmental standards, and enhancing law enforcement measures (Khanna et al., 2014). For example, the government can implement strict emission standards and promote green technology, which not only facilitates the green upgrading of regional industries but also directly improves regional air quality. Such government measures often compel regional enterprises to change their business models and promote technological innovation, thereby creating a mandatory demand for the transition to green development (Yang et al., 2023).

(2) Improvement of green efficiency. As a direct result of government environmental attention, enhanced green efficiency often signifies higher resource utilization efficiency and more energy conservation and emission reduction measures (Xu & Cui, 2020). Improving green efficiency means that China can rely less on fossil fuels in economic production, adopt more renewable energy sources, and reduce carbon and waste emissions, thus directly enhancing air quality (Zheng & You, 2023). The improvement of green efficiency can not only promote the green transformation of enterprises and reduce environmental pressure while ensuring regional economic benefits but also provide a better path for sustainable development (Tian & Liu, 2021).

(3) Improvement of air quality. Enhanced air quality is a direct result of successfully implementing various policies under government environmental attention and is an inevitable outcome of improved green efficiency (Song et al., 2019). With the promotion of environmental protection policies and the application of green technologies, pollutant emissions have decreased, atmospheric conditions have improved, and air quality has enhanced (Callaway & Sant’Anna, 2021; Chen et al., 2018). The optimized air quality subsequently improves residents’ quality of life and reduces health risks caused by environmental problems, thus enhancing social support and recognition of government environmental protection policies and improving overall societal environmental awareness, better promoting the implementation of government environmental policies and the transformation of regional green production (Wu et al., 2022).

Overall, the coupling mechanism of government environmental attention, green efficiency, and air quality is a multi-level and multi-dimensional interactive process. Government environmental policies directly impact green efficiency and air quality through regulations and incentives, and indirectly promote the transformation of the economy and society towards sustainable development by fostering technological innovation and altering social behavior. Effective management and optimization of this coupling relationship are crucial to achieving a win-win situation between environmental protection and economic development.

The coupling evolution law of government environmental attention, green efficiency, and air quality. Government environmental attention, urban green efficiency, and air quality exhibit differentiated development trends. Regarding the evolution of green development efficiency, numerous scholars have presented varying perspectives. Zhao et al. (2021) suggested that China’s inclusive green efficiency exhibits a “V”-shaped evolution trend, initially decreasing and then increasing over time, based on the Super-EBM model with undesirable output, the modified gravity model, and social network analysis. Che et al. (2018) observed that China’s green development efficiency follows a phased trend of “initially stable, then rapid, and then stable.” Regarding the trend of air quality changes, Zhou et al. (2017) utilized PM2.5 data derived from NASA’s atmospheric remote sensing images,

along with geostatistics, geographical detectors, and GIS spatial analysis methods. They found that the average concentration of PM_{2.5} pollution in China initially increased rapidly before stabilizing. Similarly, Wang et al. (2019) noted that the PM_{2.5} concentration in urban agglomerations across China exhibits a fluctuating growth trend.

Building on prior studies on the evolution of green efficiency and air quality, this paper introduces the variable of government environmental attention and integrates the three variables into a unified framework for theoretical discussion. The objective is to analyze the coupling evolution patterns among government environmental attention, green efficiency, and air quality.

There are distinct periodic characteristics in the coupling effect of government environmental attention, green efficiency, and air quality. Specifically:

- (1) In the early stage of development, government environmental attention and urban green efficiency levels are relatively low, while air quality is relatively high. At this stage, the government's environmental focus and green efficiency gradually increase, while air quality declines. The coupling between the three variables is primarily at a low level, with changes driven more by their own inertia, and the interaction between government environmental attention, green efficiency, and air quality is not pronounced.
- (2) In the medium-term development stage, the government's environmental attention level increases rapidly, and while green efficiency and air quality may be affected, the coupling characteristics between the three are antagonistic. Furthermore, due to policy lags, the direct relationship among them is weak, but the supporting role of government environmental emphasis on green efficiency and air quality is growing. Additionally, a positive relationship exists between green efficiency and air quality.
- (3) In the later stage of development, the increase in government environmental attention slows, the indices of green efficiency and air quality gradually converge, and the coupling characteristics among the three elements become more aligned. At this stage, the role of government environmental attention has been fully realized, the negative effects among the three elements have weakened, and the driving effect of policy and environmental development needs has increased. The government's focus on meeting the demand for green efficiency and air quality has been strengthened.
- (4) In the final stage, the importance of government environmental attention reaches its peak, but is constrained by diminishing marginal benefits of development, leading to stable indices among the three systems, with high-level coupling characteristics.

In summary, there is a complex relationship between government environmental attention, green efficiency, and air quality.

Model setting, index selection and data description

Research method. The core objective of this study is to investigate the dynamic coupling effects among government environmental attention, green efficiency, and air quality, focusing on the changes in their interactions over time. On the one hand, it is crucial to examine the interactions among the three variables and assess their coordinated development. On the other hand, a dynamic analysis of their interactions is required. Traditional time series analysis methods often fail to adequately account for individual effects and heterogeneity. While structural equation modeling (SEM) effectively handles complex causal relationships,

it lacks the flexibility and intuitiveness required for analyzing dynamic coupling and coordinated development.

To address the complexity and multidimensionality of this research, this study employs the coupling coordination model, kernel density estimation method, and panel vector autoregression (PVAR) model as its analytical tools. The coupling coordination model assesses interactions and the degree of coordinated development among multiple systems, offering a robust quantitative framework for analyzing their dynamic coupling effects. The kernel density estimation method reveals the spatiotemporal characteristics of the coupling coordination degree. This method describes the phased and dynamic evolution patterns of statistical variables using continuous density functions, without relying on prior data distribution assumptions, offering deeper insights into the coupling dynamic effects. Finally, the panel vector autoregression (PVAR) model is employed to address variable endogeneity and analyze the mutual influence among government environmental attention, green efficiency, and air quality, offering a comprehensive perspective on dynamic effects.

Coupling coordination model. The coupling coordination model can directly express the synergy and degree of synergy among the three systems, and is typically used to study the interaction and coordination level between different systems and their elements. This paper constructs a coordination model for government environmental attention (GEA), urban green efficiency (GML), and air quality (PM) in China. The basic formula is as follows:

$$C = \left\{ \frac{GEA \times GML \times PM}{[(GEA + GML + PM)/3]^3} \right\}^{1/3} \quad (1)$$

In this model, the result of C represents the degree of coupling, with a value range of [0, 1]. When the value of C is closer to 1, it indicates a strong correlation among the three subsystems, signifying strong coupling. Conversely, the closer the C value is to 0, the weaker the correlation, indicating poor coupling among the subsystems.

$$D = (C * T)^{1/2} \quad (2)$$

$$T = \alpha GEA + \beta GML + \delta PM \quad (3)$$

In the formula, D represents the degree of coupled co-scheduling, with a value range of 0-1. When the value of D is close to 1, it indicates a strong relationship between China's government environmental attention, urban green efficiency, and air quality levels. Conversely, a lower D value suggests a weak relationship and minimal impact between the variables. In the above formula, T represents the comprehensive development index, and α , β , and δ represent the undetermined coefficients of the three subsystems, respectively. Referring to the research of Shen et al. (2020), we assume that $\alpha = \beta = \delta$, and $\alpha + \beta + \delta = 1$.

Kernel density estimation. The kernel density estimation method can describe the periodic and dynamic evolution of statistical variables using continuous multi-density functions without relying on prior knowledge of data distribution or setting basic parameter model assumptions. Therefore, this paper uses the kernel density estimation method to characterize the temporal and spatial characteristics of the coupling coordination among government environmental attention, urban green efficiency, and air quality. The specific formula of the kernel density estimation

method is as follows:

$$F(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x_i - x}{h}\right) \quad (4)$$

In this formula, n is the number of observed samples, h is the bandwidth, x_i is the sample observation value, x is the sample mean, K is the kernel function, and the Gaussian function is used in the estimation process. The geometric characteristics of the kernel density curve, such as the position of the center of gravity, the height of the wave crest, the number of wave crests, and the tail of the curve, can fully reflect the evolution trend of the coupling coordination among government environmental attention, urban green efficiency, and air quality.

Panel vector autoregressive (PVAR) model. This paper employs the PVAR (Panel Vector Autoregressive) model to simulate the dynamic relationship between government environmental attention, urban green efficiency, and air quality. The PVAR model effectively addresses the problem of endogenous variables, combining the VAR model in time series with panel data, and analyzes the interaction between variables using impulse response and variance decomposition. To systematically investigate China's government environmental attention, urban green efficiency, and air quality, this paper establishes the following model:

$$y_{it} = \alpha_0 + \sum_{j=1}^p A_j y_{t-j} + f_i + d_i + \varepsilon_{it} \quad (5)$$

Expand y_{it} to get the following formula:

$$y_{it} = \begin{cases} GEA_{it} \\ GML_{it} \\ PM_{it} \end{cases} \quad (6)$$

Among them, y_{it} represents the vector composed of endogenous variables in the i region in the t year, namely, China's government's environmental attention, urban green efficiency and air quality, $i = (1, 2, \dots, 270)$ represents 270 prefecture-level cities, t represents 2010-2020, j represents the lag order of variables, y_{it} represents all endogenous variables, α_0 represents the intercept, A_j is the regression coefficient matrix, f_i and d_i are fixed benefits and time effects respectively, and ε_{it} is the random disturbance term.

Construction of main indicators

Government environmental attention (GEA). To measure the government's environmental attention index, this study analyzes the textual information from government work reports of prefecture-level cities to identify their focus, using the total keyword frequencies from each city as a proxy for the level of government environmental attention. The specific construction steps are as follows: First, the government work reports of 270 prefecture-level cities from 2010 to 2020 are manually collected. Second, word segmentation is performed on the text of these reports. Finally, the frequency of environment-related words is counted and aggregated to derive the government's environmental attention index.

When determining keywords, most scholars categorize them into five dimensions: environmental protection, environmental pollution, energy consumption, collaborative development, and environmental co-governance (Shen et al., 2020; Shen et al., 2023; Yang et al., 2024). Zhang (2024) introduced an additional dimension, "promoting sustainable economic and social development," identifying a total of 140 environmental attention keywords. Additionally, given this paper's focus on green efficiency, it also references the work of Mao and Wang (2024), and incorporates five additional dimensions: development concept, green production, green life, green ecology, and system construction. These five dimensions capture both the local government's focus on economic growth targets and their commitment to sustainable social development.

In summary, this paper identifies 125 keywords across ten dimensions, including environmental protection, environmental pollution, and energy consumption, as shown in Table 1. Furthermore, since Jieba demonstrates superior performance in Chinese text segmentation (Sun & Ye, 2023), this paper uses Jieba to process the original text of government work reports from 270 prefecture-level cities spanning 2010 to 2020. After operations such as counting word frequencies and removing duplicates, the keyword frequencies for each prefecture-level city are aggregated to derive the government's environmental attention index.

Urban green efficiency (GML). The construction of urban green efficiency follows the method of Yang et al. (2023), utilizing the super efficiency SBM model and the global Malmquist-

Table 1 Keywords of environmental importance.

Environmental protection category: Environmental protection, Environmental protection, Environment, Pollution prevention and regulation, Pollution regulation, Pollution regulation, Greening, Green, Green development, Low carbon, Emission reduction, Ecology, Sewage treatment, Sewage treatment Environmental impact assessment, Environmental supervision, Household garbage harmless, Environmental quality, Air quality.
Environmental pollution category: Pollution, Pollutant discharge, Chemical oxygen demand, Sulfur dioxide, Carbon dioxide, Particulate matter, the PM2.5, Ammonia nitrogen, Nitrogen oxide, Air pollution, Pollutants, Dust, Dust fall, Waste, Garbage, Emissions, Air, Chemical oxygen demand, Sulfur dioxide, Carbon dioxide, the PM10, Haze, Greenhouse gases.
Energy consumption category: Water consumption, Energy consumption, Consumption, Resources, Conservation, Intensification, Energy, New energy, Clean energy, Coal to electricity, Coal to gas, Central heating, Recycling, Recycling, Renewable.
Coordinated development and environmental governance: Environmental protection coordination, Collaborative development, Collaborative governance, Departmental cooperation, Public participation, Border area, Sharing, Transfer, Joint prevention, Joint regulation, Joint governance, Regional coordinated development, Integrated watershed governance, Regional cooperation, Complementary advantages, Win-win cooperation, Joint promotion, Protection and cooperation, Collaborative pollution regulation, Sustainable.
Other classes: Blue sky, Clear water, Pure land, Green space, Forest, River length, River length system, Lake length, Lake length system, Green, White, Livable, Tree planting, Afforestation, Clear water and green mountains, Blue sky and white clouds, Ecological barrier, Water conservation, Water and soil conservation, Development, Soil, Returning farmland to forest, Natural forest.
Development concept: Low-carbon economy, Circular economy, Green economy, Ecological civilization demonstration zone, Ecological city.
Green production: High energy consumption, Energy saving and emission reduction, Water-saving irrigation, Industrial water-saving, Green manufacturing, Consumption reduction, Agricultural non-point source pollution.
Green Life: Household waste, Green consumption, Green travel, Toilet revolution.
Green ecology: Forest restoration, Afforestation, Water conservation, Green mountains.
System construction: Joint prevention and regulation, Local legislation, Public participation, Environmental supervision mechanism, Green governance.

Table 2 Green total factor input-output.		
index	variable	unit
Input index	Labor input	Ten thousand people
	Capital stock	Ten thousand yuan
	Energy input	Ten thousand KWH
Expected output	Real GDP	Ten thousand yuan
Undesirable output	Industrial SO2 emissions	Ten thousand tons
	Discharge of industrial wastewater	ton
	Industrial soot emission	ton

Luenberger index to calculate green total factor productivity. The specific model construction methods are outlined below:

This paper examines China’s urban green efficiency by referencing Tony’s (Jorgenson & Wilcoxon, 1990) super efficiency SBM-DEA model, fully accounting for the relaxation of expected and unexpected outputs in the region. Due to the investment-oriented method adopted in this paper, the model is as follows:

$$\min p_{SE} = 1 + \frac{1}{M} \sum_{i=1}^m s_i^- / x_{ik} \tag{7}$$

$$\text{s.t.} \sum_{j=1, j \neq k}^m x_{ij} \lambda_{ij} - s_i^- \leq x_{ik} \tag{8}$$

$$\sum_{j=1, j \neq k}^m y_{rj} \lambda_j \geq y_{rk} \tag{9}$$

Among them, $\lambda \geq 0$; $s \geq 0$; $i = 1, 2, \dots, m$; $r = 1, 2, \dots, q$; $j = 1, 2, \dots, n$ ($j \neq k$). Using the BCC model can obtain PTE (pure technical efficiency value) during the sample observation period, while using the CCR model can directly obtain TE (technical efficiency value) during the sample observation period, and SE (scale efficiency) during the sample observation period can be obtained through the scale efficiency calculation method “technical efficiency/pure technical efficiency”. As total factor productivity is used to calculate urban green efficiency in the actual calculation, this paper subsequently refers to Sten Malmquist’s productivity index Malmquist in 1953, cross period dynamic production efficiency analysis (Cui et al., 2018), and estimates total factor productivity. When the return to scale remains unchanged, the Malmquist productivity index formula from t period to $t + 1$ period is as follows:

$$M(y_{t+1}, x_{t+1}) = \frac{d_{t+1}(x_{t+1}, y_{t+1})}{d_t(x_t, y_t)} \left[\frac{d_t(x_{t+1}, y_{t+1})}{d_{t+1}(x_t, y_t)} \times \frac{d_t(x_t, y_t)}{d_{t+1}(x_t, y_t)} \right]^{\frac{1}{2}} \tag{10}$$

When $M > 1$, the level of productivity increases; when $M = 1$, the level of productivity remains unchanged; when $M < 1$, the level of productivity decreases. Furthermore, Eq. (10) can be decomposed as:

$$M(y_{t+1}, x_{t+1}, y_t, x_t) = \left[\frac{d_t(x_{t+1}, y_{t+1})}{d_t(x_t, y_t)} \times \frac{d_{t+1}(x_{t+1}, y_{t+1})}{d_{t+1}(x_t, y_t)} \right]^{\frac{1}{2}} \tag{11}$$

Using Eq. (2), the reasons for the change of productivity are divided into technological change and technological efficiency change, in which the change rate of technological efficiency is divided into pure technological efficiency change rate and scale efficiency change rate.

The specific input and output indicators are shown in Table 2.

Air quality (PM). PM2.5, a key indicator of air quality, directly reflects the concentration of fine particulate matter in the air,

Table 3 Descriptive statistics of panel data.				
Variable	Obs	Mean	Min	Max
GEA	2896	87.31285	25	161
GML	2912	1.003387	0.8810029	1.147856
PM	2912	42.51906	17.93062	86.34021

significantly affecting both human health and environmental quality. Therefore, using PM2.5 data as an air quality indicator enables a more accurate assessment of government environmental policy effectiveness and improvements in green efficiency. To ensure data reliability, accuracy, and availability, this study follows the approach of Professor Cao Guangzhong (Zheng & You, 2023) and uses the annual average concentration data of PM2.5 in prefecture-level cities in China, provided by the Center for Socioeconomic Data and Applications of Columbia University, as an indicator to measure urban air quality. The PM2.5 data covers all prefecture-level cities in China from 2010 to 2020, offering comprehensive and continuous data support for this study. Additionally, this dataset is widely used in scientific research and is well-recognized within the academic community. In summary, this study adopts the annual average PM2.5 concentration as an indicator of air quality for prefecture-level cities in China.

Descriptive Statistics of Variables. Since this study examines the interactive relationship of the coupling coordination degree among national government environmental attention, urban green efficiency, and air quality, panel data are utilized to meet the requirements of model construction and research methods. To ensure spatial continuity of the research area and analytical coherence, and considering data availability, this study selects panel data from 270 prefecture-level cities in China from 2010 to 2020 as the sample. The data from this period are relatively complete and reliable, encompassing key events significantly affecting environmental policies and air quality, such as the revision and implementation of the Clean Air Act. These events offer a unique perspective for analyzing the relationships among government environmental attention, green efficiency, and air quality.

Additionally, the data from this period capture both long-term trends and short-term fluctuations, offering a more comprehensive understanding of the dynamic relationships among these variables. The data sources primarily include the China City Statistical Yearbook, China Statistical Yearbook, and urban statistical bulletins, among others. The descriptive statistics of the primary variables are presented in Table 3.

Result analysis
Analysis on the level of government environmental attention, urban green efficiency and air quality. According to the measurement results and quantile classification of government environmental attention, urban green efficiency, and air quality, the three subsystems are divided into four categories: low level, moderate level, high level, and very high level. It should be noted that government environmental attention and urban green efficiency are positive indicators, where a higher level is better; while air quality is a negative indicator, where a lower PM2.5 concentration is better.

Government environmental attention. From 2010 to 2020, the level of government environmental attention (GEA) exhibited a significant upward trend, indicating a gradual increase in local governments’ concern for environmental issues. However,

significant fluctuations across regions and years highlighted variations in local governments' policy implementation. In terms of spatial distribution, GEA exhibited high randomness and lacked a consistent regional pattern. This randomness may be influenced by local officials' policy preferences, the implementation of environmental policies, and cities' future development plans. Overall, while local governments in China have increasingly prioritized environmental governance over time, the spatial distribution remains influenced by multiple factors, making it difficult to establish a clear pattern.

Urban green efficiency. From 2010 to 2020, the green efficiency of Chinese cities exhibited an initial rise followed by a decline, accompanied by a distinct spatial distribution pattern of "large agglomeration and small dispersion." Specifically, between 2010 and 2014, green efficiency increased significantly, with most cities achieving high levels, peaking in 2014. From 2014 to 2020, green efficiency experienced a moderate decline, potentially due to diminishing marginal returns commonly observed in the process of improving efficiency. In terms of spatial distribution, green efficiency in Chinese cities exhibited a pattern of "large agglomeration and small dispersion." High green efficiency was concentrated in provincial capitals, large cities, and core cities within provinces, forming a radiating effect centered on these urban hubs. Other cities within provinces displayed a degree of small-scale dispersion in green efficiency. Overall, significant potential remains for improving green efficiency in Chinese cities. Strengthening the leading and radiating roles of large cities could be an effective strategy for enhancing green efficiency in the future.

Air quality. From 2010 to 2020, urban air quality in China, measured primarily by PM_{2.5} concentration, exhibited a downward trend, indicating overall deterioration during the study period. While air quality improved in certain years due to climatic and meteorological factors, the overall downward trend reflects the long-term and complex nature of air pollution control. Spatially, cities with high air quality gradually shifted from northern to southern regions. Between 2010 and 2017, cities with high air quality were concentrated in northeastern, western, and northern-central regions. By 2020, air quality in central-western and northeastern regions had significantly declined, while southeastern regions experienced noticeable improvements, with more cities achieving high air quality. This trend suggests that the southeastern region has achieved notable progress in air governance, whereas other regions must intensify efforts to achieve balanced air quality improvement nationwide.

Temporal and spatial evolution of coupling coordination between government environmental attention, urban green efficiency and air quality

Timing characteristics of coupling coordination level. According to the calculation results of the coupling coordination degree of the Chinese government's environmental importance, urban green efficiency, and air quality, this paper uses the kernel density estimation method to analyze the temporal characteristics of the coupling coordination degree. From 2010 to 2020, the kernel density curve of government environmental attention and the coupling coordination of urban green efficiency and air quality first extends to the left and then to the right along the horizontal axis. This indicates that the overall level of coupling coordination initially declined, then rose, and recovered.

Specifically, the center of gravity of the curve continues to migrate to the left, roughly from 0.67 to around 0.62, indicating a significant decline in the degree of coupling coordination. The

height of the main peak of the curve has been declining, suggesting an expanding regional gap in the degree of coupling coordination. The curve has changed from "one main and one secondary peak" in 2010 to a "single peak" in 2014, indicating that the phenomenon of two-level differentiation of coupling coordination is narrowing. After 2014, the center of the curve began to migrate to the right, indicating an upward recovery in the degree of coupling coordination. However, the height of the main peak of the curve continued to decline, showing that the regional gap in coupling coordination in China was still widening. Additionally, the tailing on the left side of the curve has greatly shortened, and the tailing on the right side has slightly extended, indicating a significant trend of catching up in the low-value area of coupling coordination and a slow increase in the high-value area.

Timing characteristics of coupling coordination level. From 2010 to 2020, the coupling and coordination between the Chinese government's environmental attention and urban green efficiency and air quality showed an evolutionary trend, initially declining and then gradually recovering. Specifically, in 2010, China's overall coupling coordination was at its highest, with most cities achieving intermediate or good coordination levels, and only a few cities experiencing low-level coordination and imbalance. By 2014, there had been a nationwide decline, with most cities showing primary coordination levels and an increase in imbalances. This decline continued until 2017, with most cities showing reluctant coordination and imbalance, increasing the gap between cities in coupling coordination levels, leading to serious two-level differentiation. The overall decline improved between 2017 and 2020, with coupling coordination improving and polarization narrowing. Although the number of cities with good coupling coordination decreased significantly, the overall level greatly improved. However, the early decline in coupling coordination is not entirely due to declining marginal benefits, indicating significant potential for future development in coupling coordination levels. Overall, there are still relatively few areas where government attention to the environment and the coupling coordination of urban green efficiency and air quality are good or above, indicating the need for further improvement in the coordination of these three systems (Figs. 1–6).

Further GMM estimation of PVAR model

Empirical testing

Panel unit root inspection. Before conducting PVAR model analysis, it is essential to test for unit roots in each variable to determine their stationarity and avoid potential false regression problems caused by nonstationary data. Currently, panel unit root test methods are mainly divided into two categories: homogenous unit root tests based on LLC, Hadri, and Breitung tests; and heterogeneous unit root tests based on ADF Fisher and IPS. To ensure the robustness of the results, this paper selected three panel unit root tests: IPS, LLC, and ADF-Fisher. The specific results are shown in Table 4.

Optimal lag order selection. In the PVAR model, determining the lag order of variables is crucial for the model's setup and results. According to MAIC, MBIC, and MQIC criteria, the optimal lag order of variables in the PVAR model can be determined. Generally, the minimum value (indicated by the largest number of * signs) for each criterion represents the optimal lag order. If the * signs are the same, priority is given to the MAIC criterion. The selection results for the optimal lag order in this paper are shown in Table 5.

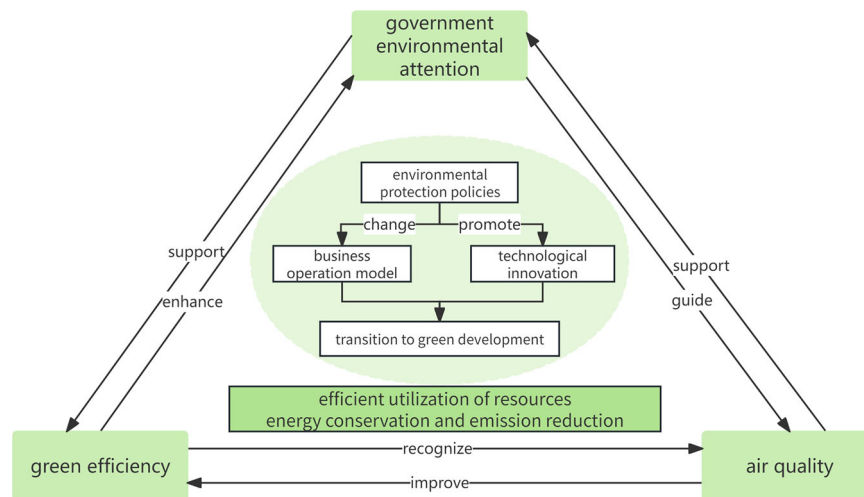


Fig. 1 Coupling mechanism of government environmental attention, green efficiency and air quality.

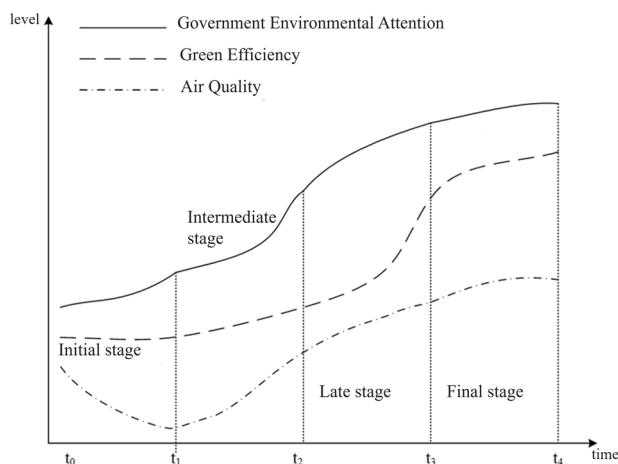


Fig. 2 Coupling evolution law of government environmental attention, green efficiency and air quality.

According to Table 5, in the national optimal lag order test, the lag orders suggested by MAIC, MBIC, and MQIC are not consistent; therefore, the optimal lag order suggested by MAIC is preferred, determining that the optimal lag order of variables in the model is 4.

Testing the stationarity of variables. This paper constructs a PVAR model to analyze the relationship between government environmental attention, urban green efficiency, and air quality. Previous tests indicated that the best results were obtained when the data lagged by 4 periods. The causality tests conducted in this paper found a causal relationship between the three variables. Since the three variables in this paper are endogenous, it is necessary to test the stationarity of the model, with the results shown in Fig. 7. Observing the stability of the AR model shows that all points lie within the circle, confirming that the PVAR model is stable.

Granger causality test. To further clarify the short-term dynamic effects and causality among the three variables of government environmental attention, urban green efficiency, and air quality, this paper conducts a Granger causality test based on the constructed PVAR model and the optimal lag results mentioned above. The results are shown in Table 6.

According to the results in Table 6, the PVAR model shows a two-way Granger causality between urban green efficiency and air quality, indicating a significant two-way interaction between these variables. However, the one-way Granger causality between government environmental attention and the other two variables is not significant. This is consistent with the results of the coupling mechanism described above, indicating that there is a lag in the implementation of the government's environmental attention in China. It does not have a strong direct effect on urban green efficiency and air quality in the short term. However, urban green efficiency and air quality significantly impact government environmental attention, suggesting that these factors can adversely affect it.

Shock pulse response analysis. The impulse response function can be used to analyze and test the relationships and impacts among government environmental attention, urban green efficiency, and air quality. By observing the impulse response graph in Fig. 8, we can determine the response of variables in the PVAR model to each impact over time. The relative importance of various structural shocks is assessed by analyzing their contributions to the endogenous variables. In this paper, the reaction time is set at 10 years, and the impulse response function is obtained through 500 Monte Carlo simulations based on GMM estimation. The impulse response function is employed to analyze and test the relationships and impacts among government environmental attention, urban green efficiency, and air quality. By observing the impulse response graph presented in Fig. 9.

The GML estimation results in Table 7 reveal the following: Regarding the dynamic relationship of urban green efficiency, the lagged terms of GML itself (L1-L4) do not significantly affect current GML, suggesting that its dynamic evolution may be more strongly driven by other variables, such as environmental attention and air quality. However, certain lagged terms of PM (air quality) and GEA (government environmental attention) significantly affect GML, indicating that air quality improvements and heightened government attention may enhance green efficiency through technological innovation or policy incentives. Regarding the dynamic relationship of air quality, the early lagged terms of GML (L1, L2) have no significant impact on PM, while later lagged terms (L3) exhibit a positive impact, suggesting that improvements in green efficiency have a lagged effect on air quality enhancement. The lagged terms of GEA exhibit a significant positive impact, indicating that increased government

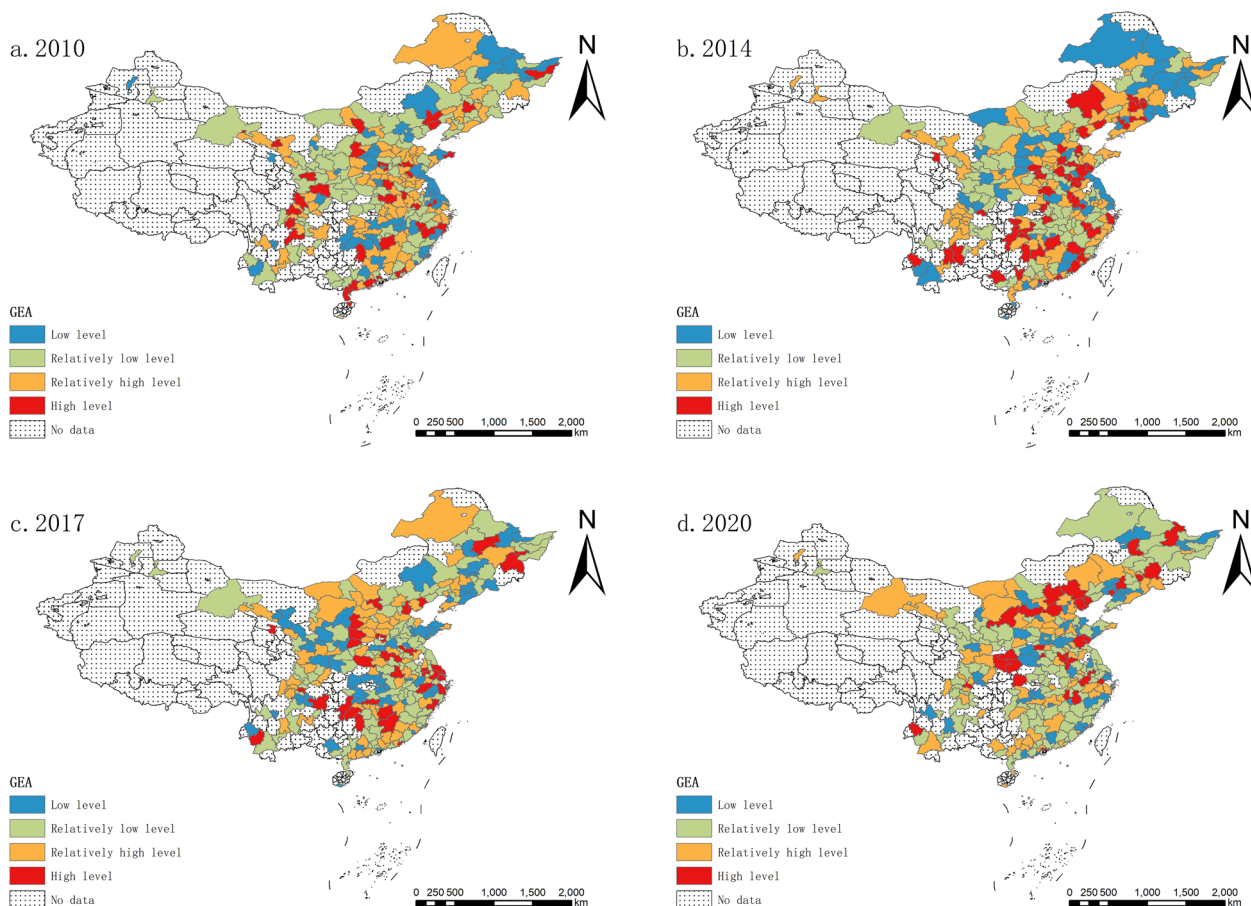


Fig. 3 Temporal and spatial evolution of government environmental attention level. a Government environmental attention level (2010). **b** Government environmental attention level (2014). **c** Government environmental attention level (2017). **d** Government environmental attention level (2020).

environmental attention directly improves air quality through stricter pollution control policies or environmental investments. For the dynamic relationship of government environmental attention, the early lagged terms of GML (L1, L2) have no significant impact on GEA, while later terms (L3) exhibit a negative impact, potentially reflecting reduced environmental pressure in cities with high green efficiency. Certain lagged terms of PM (L2, L3) exhibit a significant positive impact on GEA, indicating that air quality improvements further enhance government environmental attention, forming a feedback mechanism. From the above analysis, it is evident that government environmental attention is the core driver of green efficiency and air quality, a point that requires further exploration through the impulse response graph (Table 8).

Figure 8 illustrates the interrelationships and impulse response results among government environmental attention, urban green efficiency, and air quality. In the figure, the abscissa represents the lag length of the impact, the ordinate represents the response of endogenous variables to the impact, and the positive and negative standard deviations of the impulse response function on both sides of the red line represent the possible range of impulse response.

The first row of Fig. 9, from the perspective of urban green efficiency, depicts the impacts of GML on itself, PM, and GEA. Figure 9 illustrates the interaction between government environmental attention, urban green efficiency, and air quality, along with the impulse response results of their respective shocks. From the perspective of government environmental attention, there is an obvious positive impulse effect on itself. In particular, the government's environmental attention

demonstrates strong self-sufficiency but declines with its own marginal decrease. According to the chart, the government's environmental attention gradually weakens between the first and fourth periods, maintaining a long-term equilibrium level afterward. Meanwhile, it shows a negative impulse effect on green efficiency, which begins to decline in the base period, reaches a minimum around the third period, and then starts to improve. This indicates that the government's environmental attention has had some negative effects on the improvement of green efficiency, consistent with the previously discussed coupling results. Currently, China's government environmental attention still lags; while it provides important support, its immediate effect is not yet evident. A similar result is observed in the impact of government environmental attention on air quality, showing a negative impulse effect that reaches its lowest point after phase 1. However, this result differs from that of urban green efficiency. The air quality index, quantified by PM2.5, improves as its value decreases. Therefore, it can be considered that the government's environmental attention has improved air quality at this stage, with long-term improvements until marginal benefits decrease.

The second row of Fig. 9, from the perspective of urban air quality, depicts the impacts of PM on GML, itself, and GEA. From the perspective of urban green efficiency, the impulse effect on the government's environmental attention fluctuates. Initially, it has a positive impulse effect, which gradually spirals down to a negative effect, turning around the lowest point and stabilizing around the eighth period. This indicates that urban green efficiency improves the government's environmental attention level in the early stages. However, as green efficiency improves,

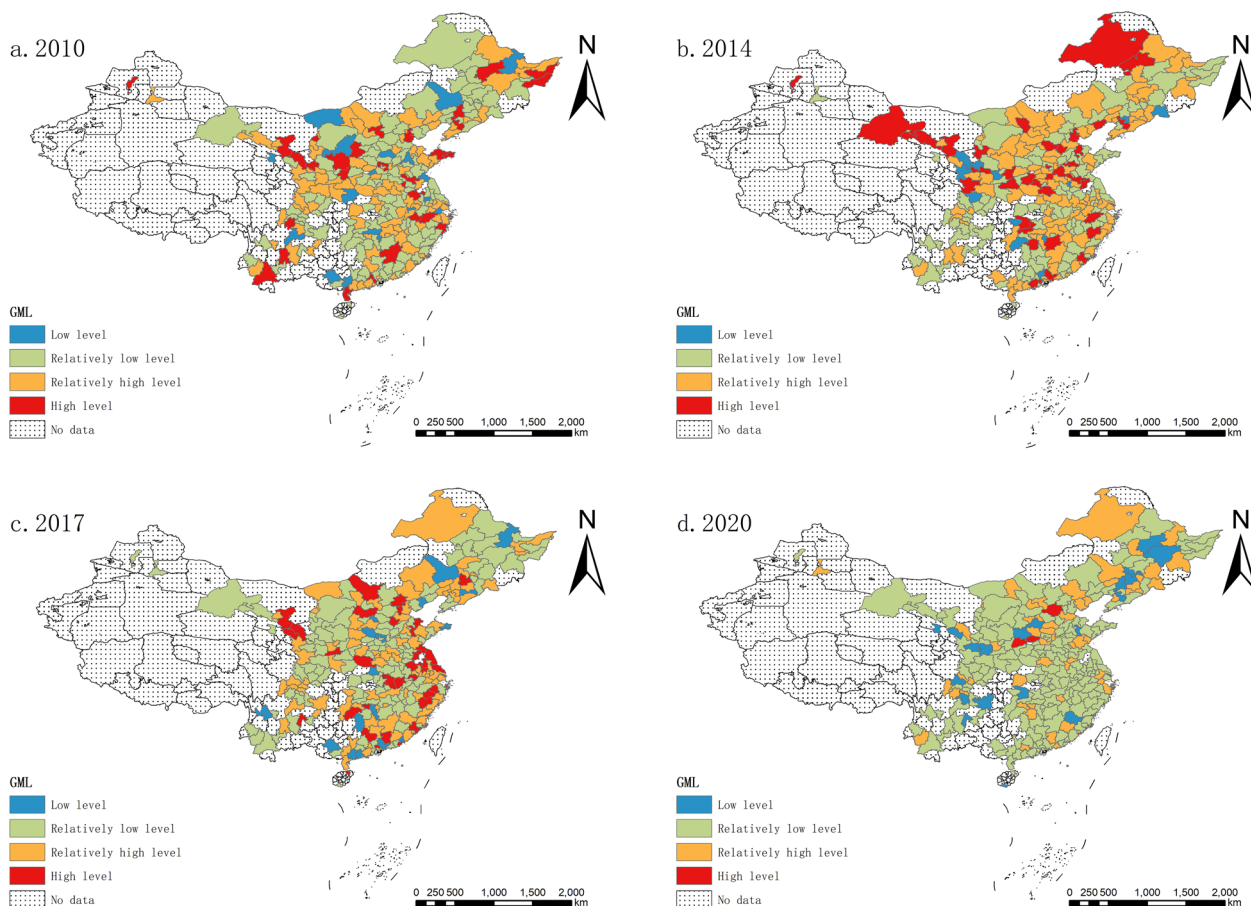


Fig. 4 Temporal and spatial evolution of urban green efficiency level. **a** Urban green efficiency level (2010). **b** Urban green efficiency level (2014). **c** Urban green efficiency level (2017). **d** Urban green efficiency level (2020).

the marginal benefit of government environmental attention decreases, leading to a reduction in the attention level until stabilization. Urban green efficiency shows a declining positive effect on itself, indicating that its spontaneous growth intensity is low and requires external promotion. Urban green efficiency on air quality shows a negative impulse effect initially, followed by a positive effect. This is consistent with the coupling coordination results in the medium-term stage in China, indicating that both will have a more pronounced positive effect and gradually stabilize.

The third row of Fig. 9, from the perspective of government environmental attention, depicts the impacts of GML on GEA, PM on GEA, and GEA on itself. From the perspective of urban air quality, as the PM_{2.5} index is used to quantify air quality in this paper, government environmental attention has exhibited a negative impulse effect on air quality. It can be considered that the improvement of air quality will drive the enhancement of government environmental attention over a long period. This is consistent with the impulse response of government environmental attention to air quality, suggesting a diminishing marginal benefit between the two. Urban air quality has a relatively weak and short-term negative effect on urban green efficiency, indicating that while air quality can improve urban green efficiency, the impact is relatively weak. This is because air quality is unlikely to have a direct impact on urban green efficiency improvement but may influence it indirectly by enhancing people's awareness of environmental protection. The impulse effect of air quality on itself is positive, indicating a downward inertia in the current air quality level in China. The

PM_{2.5} index level is naturally rising and lasting for a long time, necessitating other factors for control.

Variance decomposition. To further evaluate the impact of the disturbance term on endogenous variables and the contribution of different structural shocks during changes between variables, this paper decomposes the variance of the PVAR model. The analysis focuses on the first, tenth, and twentieth periods of the sample to assess the contributions of government environmental attention, urban green efficiency, and air quality.

From the data results, the variance decomposition of government environmental attention, urban green efficiency, and air quality show that each variable's contribution to its own growth is over 85%, indicating strong positive inertia characteristics. Over the 20 observation periods, the contribution rates of the three variables to have been declining, while the interaction contributions between the three variables have been rising.

In the long run, the contribution rates of government environmental attention to urban green efficiency and air quality in the 20th period are 9.3% and 2.1%, respectively, indicating a direct and significant impact on green efficiency. Under current conditions, the contribution rates of urban green efficiency to government environmental attention and air quality in the 20th period are 1.3% and 1%, respectively, which are relatively low, indicating significant room for improvement in promoting green efficiency in China. The contribution rates of air quality to government environmental attention and urban green efficiency in the 20th period are 8.8% and 2.2%, respectively, showing that

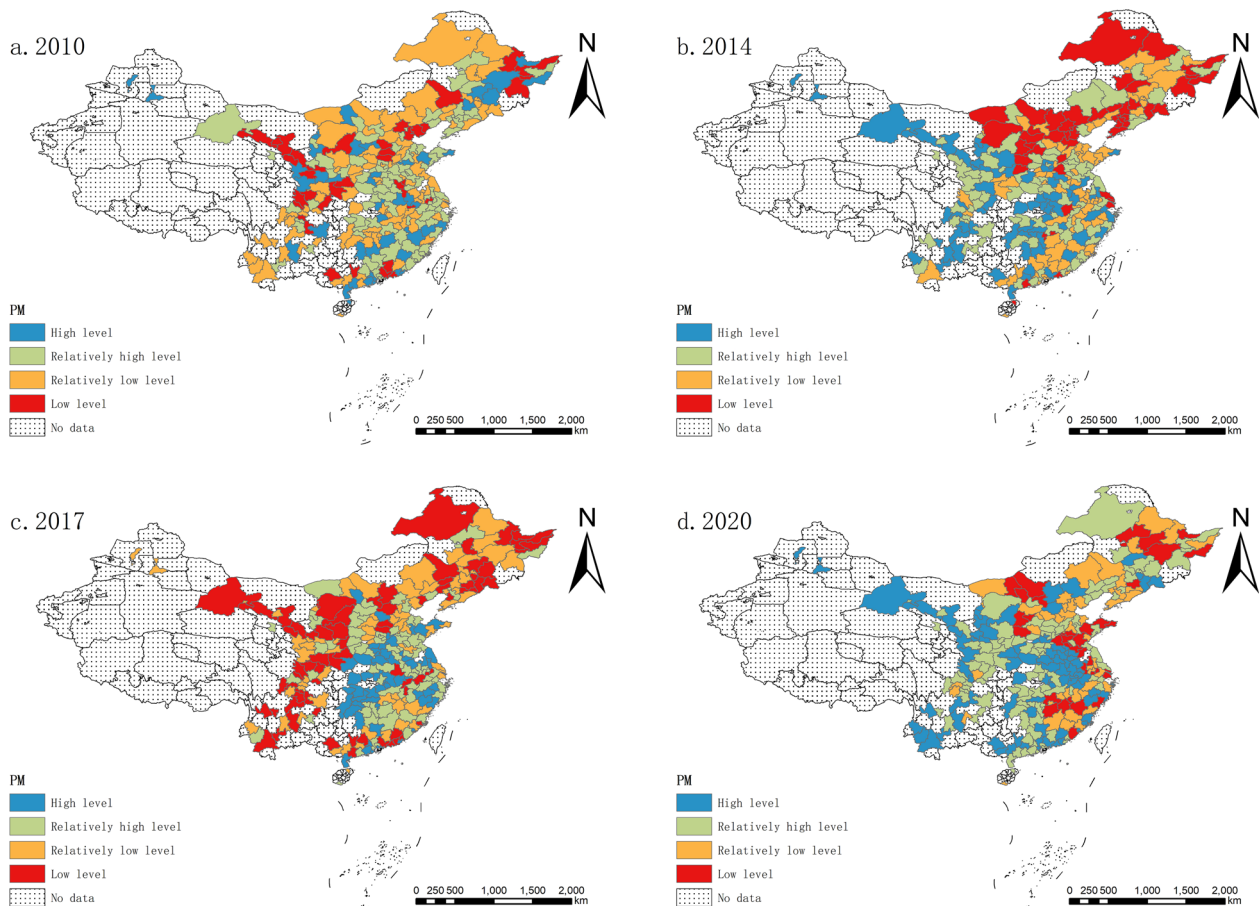


Fig. 5 Temporal and spatial evolution of air quality. a Air quality level (2010). **b** Air quality level (2014). **c** Air quality level (2017). **d** Air quality level (2020).

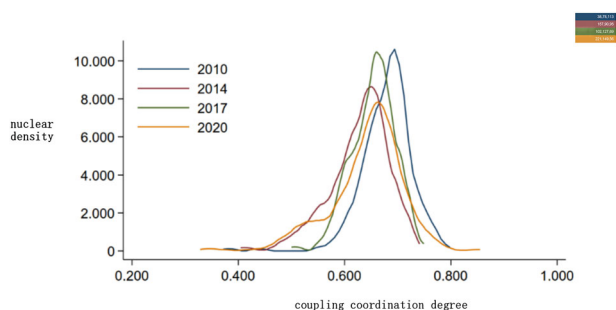


Fig. 6 Nuclear density diagram of coupling coordination between government environmental attention, green efficiency and air quality.

the improvement of government environmental attention is highly sensitive to declines in air quality.

Further analysis

To achieve a more comprehensive and in-depth understanding of the earlier analysis results, further exploration within the theoretical framework of environmental economics is essential. On one hand, this study uncovers the complex dynamic feedback mechanisms among government environmental attention, green efficiency, and air quality, offering significant theoretical insights into the relationship between environmental governance and economic development. On the other hand, the findings of this study support and extend the “Porter Hypothesis,” which posits that moderate environmental regulation can foster a win-win

outcome for the economy and the environment. However, the results highlight significant regional and spatiotemporal variations in policy effects. The detailed analysis is as follows:

Regional differences in policy effects. From the perspective of regional differences, this study further confirms the imbalance in the effects of environmental policies. The findings reveal that the eastern region, characterized by high economic development, strong policy implementation capacity, and robust technological R&D capabilities, has established a virtuous cycle between government environmental attention and the improvement of green efficiency. In economically advanced city clusters such as the Yangtze River Delta and the Pearl River Delta, policy implementation has been highly effective, with a notable impact of green efficiency on air quality improvement.

In contrast, the central and western regions, constrained by resource-based economic structures, depend heavily on external policy support for environmental governance. Policy implementation in these regions is further limited by inadequate local finances and technological reserves. Moreover, the concentration of high-pollution industries in some cities, coupled with insufficient policy implementation capacity, results in limited air quality improvements.

This finding aligns with the classic theory of resource allocation and regional policy effect differences in economics. It underscores the need for “adapting measures to local conditions” in regional policy design and highlights the importance of cross-regional policy coordination. Moving forward, it is essential to strengthen regional cooperation, optimize resource allocation, and reduce disparities in policy effects across regions. These efforts will

Table 4 Unit root test.				
Sample	Variable	Government environmental attention	Green efficiency	Air quality
Whole country	IPS	−2.8849***	−3.2951***	−3.1555***
	LLC	−16.1350***	−31.4322***	−16.9917***
	ADF-Fisher	22.0140***	27.1286***	21.9215***
Stability	Smoothness	Smooth	Smooth	Smooth

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 5 Selection of lag order.				
Sample	LAGS	MAIC	MBIC	MQIC
Whole country	1	12.5062	14.477*	13.2231
	2	12.382	14, 5846	13.1882*
	3	12.5152	15.0062	13.4333
	4	12.2945*	15.1569	13.3579
	5	12.6986	16.0635	13.9603

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

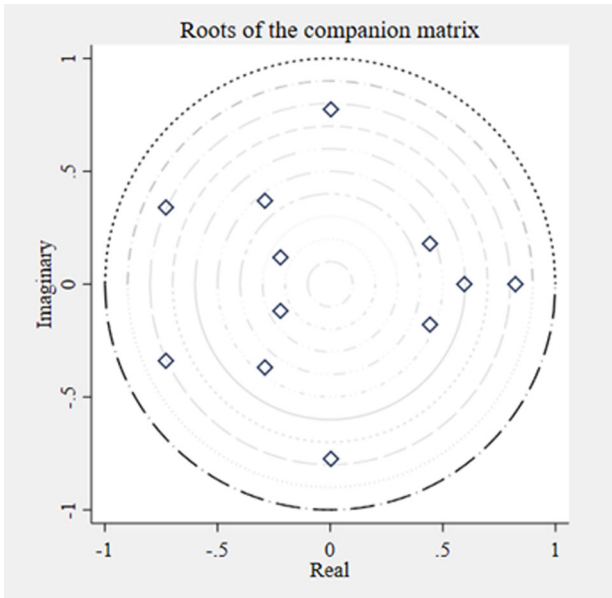


Fig. 7 Stability test results.

provide a theoretical foundation for designing differentiated regional environmental policies.

Spatiotemporal differences in policy effects. Using the PVAR model, this study uncovers the dynamic coupling relationships among government environmental attention, green efficiency, and air quality, revealing that the transmission pathways of environmental policies are non-linear and exhibit complex spatiotemporal characteristics with multi-stage dynamic effects.

On one hand, the lag effect of environmental policies is a critical factor that cannot be overlooked. In the short term, during the initial stages of policy implementation, insufficient implementation strength and the adjustment cycles of enterprises may result in limited or even negative effects on green efficiency and air quality. In the long term, as policy implementation intensifies, technological innovation and industrial upgrading drive continuous improvements in green efficiency and air quality. The impact of government

environmental attention on green efficiency and air quality also exhibits a significant lag effect. This lag arises from the “adaptation period” during the initial implementation of China’s environmental policies, encompassing the refinement of policy formulation, promotion of implementation, and response cycles of enterprises and the public. This suggests that environmental policy implementation should prioritize “stability” and “continuity.” Furthermore, frequent changes in environmental policies and fluctuations in implementation strength may undermine their long-term effectiveness and contribute to “policy fatigue” among implementing entities.

On the other hand, the spatial spillover effect of green efficiency plays a crucial role. The environmental technological advancements and management expertise of developed regions can diffuse to surrounding areas through technology transfer and policy demonstration effects, driving improvements in green efficiency in neighboring regions. This “center-radiation” model holds significant importance for small and medium-sized cities as well as resource-based cities. However, the strength of the spillover effect is limited by the intensity of economic linkages between regions and the effectiveness of policy coordination mechanisms. In some areas, “policy island” phenomena persist, weakening the overall impact of policies.

Moving forward, it is essential to strengthen regional policy integration and cross-regional coordination mechanisms to enhance green development cooperation across regions. This study provides a theoretical foundation for formulating differentiated regional environmental policies while exploring the regional and spatiotemporal variations in their effects. Strengthening regional environmental policy cooperation can effectively promote the coordination and sustainability of environmental governance and economic development, thereby reducing regional disparities in policy outcomes.

Research conclusions and inspirations

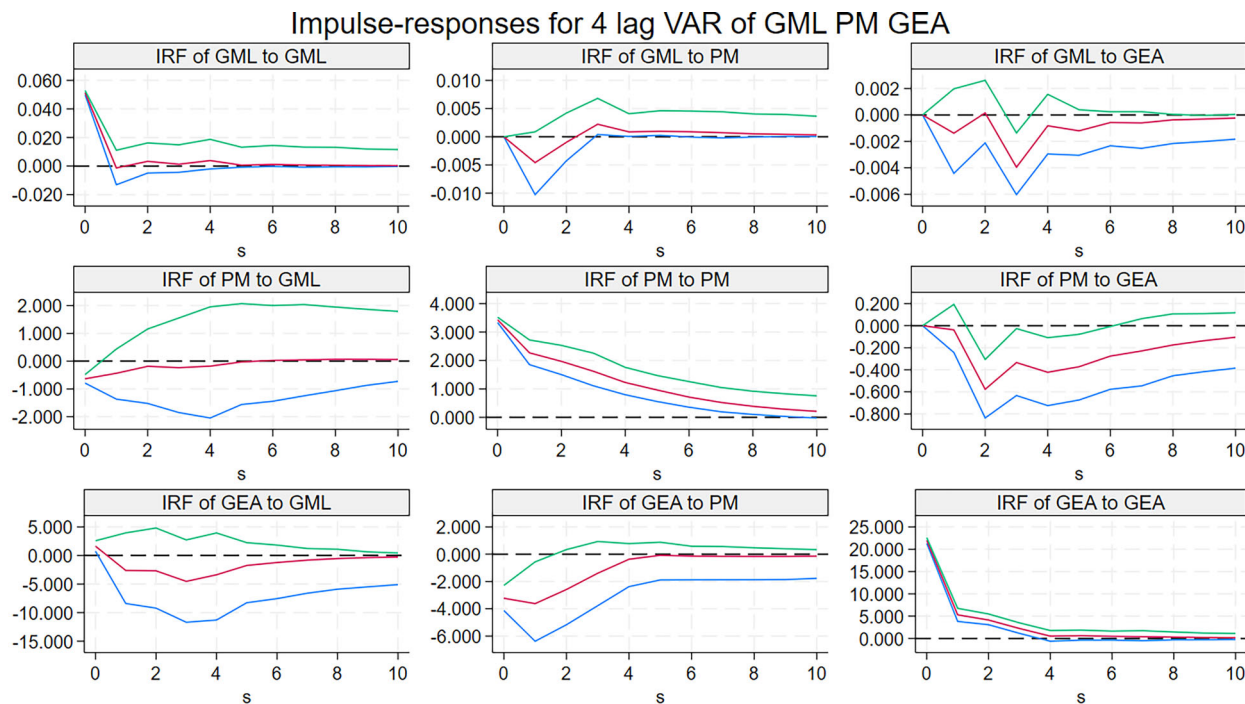
Research conclusion. By clarifying the coupling effect of government environmental attention, urban green efficiency, and air quality, this paper uses the coupling coordination model, PVAR model, and other research methods to analyze the coupling and dynamic effects of these variables from 2010 to 2020. The main conclusions are summarized below:

- (1) The three variables of government environmental attention, urban green efficiency, and air quality exhibit temporal and spatial variations. Firstly, the government’s attention to environmental issues has shown an overall upward trend over time. However, significant spatial fluctuations exist across different regions, attributed to the uncertainty of regional administrators and development planning for that year, making it difficult to infer a consistent spatial distribution pattern. Secondly, China’s urban green efficiency has exhibited a development trend of initially rising and then declining over time. Spatially, it displays a pattern of “large agglomeration” and “small dispersion.” Most high-efficiency cities demonstrate a dispersion phenomenon, organized by provinces and centered around provincial capitals and major cities. Finally, China’s air quality levels

Table 6 Granger causality test results.

Sample	variable	Null hypothesis	Card side	conclusion
Whole country	Government environmental attention	Urban green efficiency is not the reason	7.711	Accept the null hypothesis
	Government environmental attention	Air quality is not the reason	6.7311	Accept the null hypothesis
	Government environmental attention	None of them are the reason	18.818**	Reject the null hypothesis
	Urban green efficiency	Government environmental attention is not the reason	14.888**	Reject the null hypothesis
	Urban green efficiency	Air quality is not the reason	24.359***	Reject the null hypothesis
	Urban green efficiency	None of them are the reason	46.575***	Reject the null hypothesis
	Air quality	Government environmental attention is not the reason	39.197***	Reject the null hypothesis
	Air quality	Urban green efficiency is not the reason	14.739**	Reject the null hypothesis
	Air quality	None of them are the reason	55.145***	Reject the null hypothesis

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.



Errors are 5% on each side generated by Monte-Carlo with 500 reps

Fig. 8 Impulse response results.

- have generally exhibited a downward spiral trend. Spatially, cities with high air quality levels are increasingly found in the south, demonstrating clear regional characteristics.
- (2) The coupling relationship between government environmental attention, urban green efficiency, and air quality varies significantly across time and space. Data analysis of 270 prefecture-level cities in China reveals that the coupling coordination degree of these variables fluctuates over time, initially showing a downward trend followed by an upward trend. This indicates that China's government may face significant resistance and policy adaptation challenges during the initial stages of policy implementation. However, with the in-depth promotion of policies, the overall improvement effect gradually emerges, and the level of coupling coordination eventually recovers.
 - (3) There is an evident dynamic relationship between government environmental attention, urban green efficiency, and air quality. Firstly, the government's

environmental attention has a positive impulse effect on itself, which gradually weakens in the initial stage and then tends to balance. It has a negative impact on green efficiency, initially declining and then rising again. The government's environmental attention has a long-term positive effect on air quality, though the marginal effect decreases over time. Secondly, urban green efficiency has a positive effect on government environmental attention in the early stages, turning negative and stabilizing later. The intrinsic growth capacity of urban green efficiency is low, requiring external factors for promotion. Urban green efficiency has a pulse effect on air quality, transitioning from negative to positive. Finally, the improvement of urban air quality drives the growth of government environmental attention, though the marginal benefit decreases. The improvement of urban green efficiency is small and short-term, with a positive impulse effect on itself, indicating inertia in the decline of air quality, requiring control by external factors.

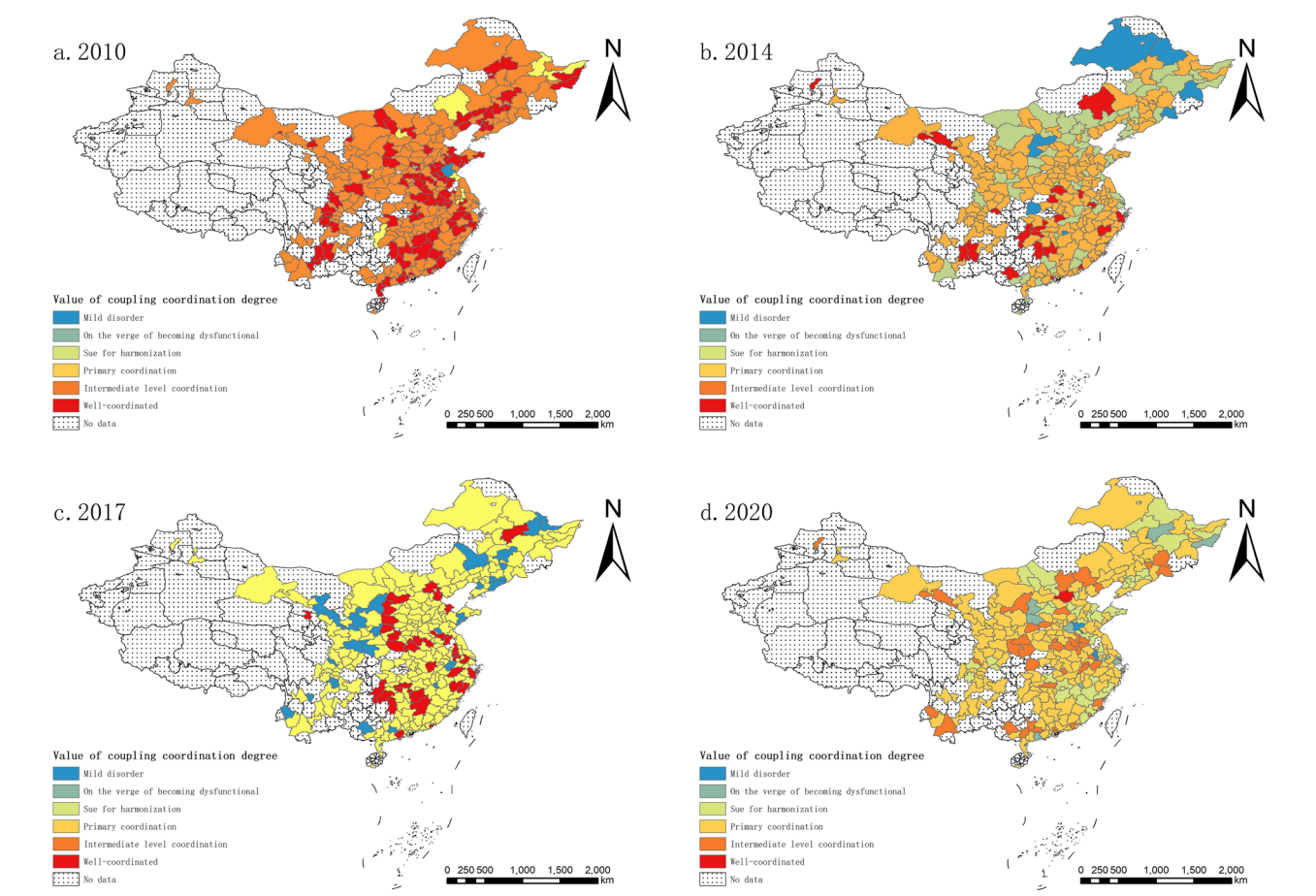


Fig. 9 Temporal and spatial distribution of coupling coordination between government environmentalattention, green efficiency and air quality.

Table 7 GMM estimation results.				
Variables	(1) L1	(2) L2	(3) L3	(4) L4
GML → GML	−0.040782 (−0.25)	0.055162 (0.39)	0.044421 (0.45)	0.060390 (0.66)
GML → PM	−0.001392 (−1.27)	0.000530 (1.28)	0.000937*** (2.69)	−0.000133 (−0.21)
GML → GEA	−0.000063 (−0.68)	0.000017 (0.28)	−0.000204*** (−3.62)	0.000005 (0.08)
PM → GML	−0.278051 (−0.02)	4.032011 (0.40)	−2.633410 (−0.37)	−1.716936 (−0.27)
PM → PM	0.659193*** (8.69)	0.112367*** (3.66)	0.006481 (0.31)	−0.038657 (−1.00)
PM → GEA	−0.001743 (−0.30)	−0.024663*** (−5.65)	0.008794** (2.32)	−0.003780 (−0.88)
GEA → GML	−68.576790 (−0.86)	−51.564360 (−0.71)	−65.363990 (−1.33)	−31.992660 (−0.73)
GEA → PM	−0.827855 (−1.51)	0.072708 (0.39)	0.247306* (1.66)	0.167375 (0.62)
GEA → GEA	0.240951*** (6.00)	0.124364*** (4.92)	0.002402 (0.11)	−0.050832 (−1.59)

Standard errors in parentheses. **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

Policy implications. Given the challenges of mutual restriction and interaction between government environmental attention, urban green efficiency, and air quality, this paper investigates the coupling and dynamic effects of these variables, which is crucial for achieving coordinated development. Based on the

above research conclusions, the policy implications of this paper are as follows:

- (1) Governments should strengthen the continuity of environmental policies and enhance their effectiveness across

Table 8 Variance decomposition results.

Region	Periods	Sample	Government environmental attention	Urban green efficiency	Air quality
Whole country	1	GEA	1.000	0.000	0.000
	1	GML	0.005	0.995	0.000
	1	PM	0.024	0.029	0.947
	10	GEA	0.886	0.093	0.021
	10	GML	0.013	0.977	0.010
	10	PM	0.087	0.021	0.892
	20	GEA	0.886	0.093	0.021
	20	GML	0.013	0.977	0.010
	20	PM	0.088	0.022	0.890

multiple dimensions. It is undeniable that overall, based on China’s experience the level of environmental attention by local governments in China has gradually increased, and the impact of this attention on green efficiency and air quality is generally positive. However, the analysis reveals significant regional differences in the environmental implementation capacity of local governments in China, as well as disparities in their ability and attitude towards executing environmental protection policies. Some local governments may exhibit “duplicious” behavior. To address this phenomenon, central governments of comparable countries should continuously refine performance appraisal systems and evaluation indicators for cities and officials. Additionally, they should allocate funds for ecological protection and supervision in the annual fiscal budget for ecological and environmental protection, ensuring an independent and unrestricted funding channel. This would alleviate the environmental development burden on local governments. Internationally, countries should diligently implement the United Nations Framework Convention on Climate Change and the Paris Agreement, while promoting the “Belt and Road” green and low-carbon development cooperation mechanism. Regular research and practical cooperation on environmental and green technological innovation should also be prioritized.

- (2) Governments should consistently encourage green technological innovation, foster technological progress, and enhance green efficiency. With the rapid advancement of the global economy, technological innovation has emerged as a critical factor for environmental optimization and enhanced green efficiency. On the one hand, governments should actively promote and disseminate advanced technologies that improve production efficiency and reduce pollutant emissions. On the other hand, they must prioritize cultivating innovative talents in environmental policy, stimulating their creativity and entrepreneurial enthusiasm to focus on innovation. Local governments must take proactive measures to optimize the talent environment. This approach is vital for effectively implementing government environmental attention and achieving sustainable green development at the regional level. Therefore, governments in developing countries should consistently refine fiscal budgets, tax incentive policies, and green financial systems while fostering innovation in low-carbon technology, clean energy, and energy-saving technology. Simultaneously, while actively adopting advanced green technologies from developed countries, they should implement supportive green technology policies and low-carbon industrial development strategies. Governments should encourage domestic enterprises to continuously adopt green technologies, develop

- low-carbon capabilities, and gain competitive advantages in differentiated market environments, fostering a win-win scenario for economic and environmental benefits.
- (3) Central governments should tailor the intensity of environmental regulations to local conditions and promote differentiated environmental policy mechanisms. Government environmental attention and regulation intensity complement each other, with appropriate levels effectively improving local air quality and environmental conditions. Therefore, governments must recognize that implementing environmental policies requires not only policy support but also effective and balanced government oversight. First, central and local governments should collaborate to leverage big data, cloud computing, artificial intelligence, and other technologies to develop a comprehensive, multi-level, and three-dimensional environmental monitoring system. This system should cover elements such as air, water, and soil, enabling end-to-end monitoring and coordinated oversight of pollution sources. Simultaneously, local governments must align with central policies, continuously advancing complementary local regulations. They should integrate vertical and local management systems, establish inter-departmental coordination mechanisms, and enhance collaboration between central and local governments as well as among local governments. These measures will improve governance capabilities for managing atmospheric pollution emissions and ensure that industries operate reasonably, legally, and compliantly under detailed environmental regulation policies.
- (4) Central governments should consider the environmental development of all regions within their countries and account for differences arising from varying levels of economic and social development. Local governments in less developed regions may tolerate high pollution and emissions to achieve short-term economic benefits and growth. Therefore, central governments should assist localities in adopting a long-term development perspective, abandoning the “pollute first, then govern” model. They should promote the principle that “green waters and green mountains are as valuable as gold and silver mountains,” fostering sustainable economic, social, and environmental development nationwide. Moreover, as indicated by the above results, green efficiency has a low intrinsic growth capacity and requires external drivers for improvement. Consequently, developed regions should assume responsibility for providing technological innovation support and financial assistance. This would reduce initial resistance to environmental policy implementation in less developed regions and promote the effective adoption of environmental protection policies and improvements in green efficiency.
- (5) Developing countries should effectively utilize domestic resources while efficiently leveraging international environmental resources. On the one hand, developing countries should efficiently utilize available international financial and technical support to enhance air quality and green efficiency. When utilizing various funds provided by the Climate Fund and Global Environment Facility offered by developed countries, transparency and openness should be ensured. On the other hand, developing countries must recognize that, in the context of economic globalization, achieving green development requires green competitiveness, which, in turn, necessitates a strong capacity for green development. The capacity for green development can only be achieved through independent learning, innovation, and management reform. Financial and technical assistance from developed countries can only indirectly contribute to the improvement of green efficiency in developing countries. Therefore, while receiving technical assistance

from developed countries and international organizations, developing country governments must prioritize building their own capacity for green development. They should avoid dependence on external technical and financial support without fostering independent green development capabilities.

Data availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Author contributions

Tu contributed to the manuscript framework, methodology, software, and writing. Cao contributed to manuscript research guidance and review. Du contributed to the literature review and writing. Cui contributed to the manuscript language revision and manuscript review.

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The authors declare no competing interests.

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The authors of this article have been aware of all the requirements for publication in the journal.

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Correspondence and requests for materials should be addressed to Chaoyang Tu.

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