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Beyond case studies: A city-level quantitative analysis of payments for ecosystem services system and atmospheric environmental quality

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ABSTRACT

China's economic growth model has posed challenges to quantifying ecosystem services, which are often overlooked in development planning. Payments for ecosystem services system (PESS) convert ecosystem value into economic value through various methods. A key question is whether PESS significantly enhances atmospheric environmental quality (AEQ), thereby improving air quality and reducing carbon emissions—critical steps toward mitigating climate change and promoting sustainable economic development. This study uses panel data from 280 Chinese prefecture-level cities (2004–2020) to assess the progress of PESS implementation. The econometric model evaluates the impact of PESS on AEQ and explores the underlying causal mechanisms. Empirical results show that PESS contributes to lower air pollution levels and enhanced atmospheric quality, particularly in regions with stronger fiscal decentralization and market-oriented institutions. Improvements in PESS implementation significantly reduce air pollution in China's eastern and central regions relative to the western region. Further investigation reveals that PESS enhances AEQ by promoting green innovation, facilitating industrial transformation, and influencing enterprise market entry behaviors. This study quantifies PESS implementation by incorporating all payment methods and examines its role in environmental governance.

1. Introduction

The dual threats of global climate change and air pollution have become pressing challenges for human society, driving governments worldwide to strengthen environmental governance. As the largest developing country, China has achieved rapid growth, yet it faces growing domestic and international pressure to curb emissions driven by severe environmental pollution (Liu et al., 2022). The Chinese government emphasizes atmospheric governance by prioritizing air pollution control as a foundation for sustainable development and implementing policies to reduce emissions and improve air quality³ (Geng et al., 2021). The Chinese government's environmental governance initiatives have produced measurable improvements in air quality and emissions reduction (Zhang et al., 2012). Fig. 1 highlights the following trends in China's AEQ improvement: Sulfur dioxide emissions have fluctuated

downward, with moderate increases in 2005 and 2011, followed by a more pronounced decline after 2015. Urban PM_{2.5} concentrations have demonstrated a downward trend, particularly from 2014 onward. While carbon dioxide emissions are still rising, the rate of increase has slowed in recent years.

China is confronted with serious environmental issues, including widespread air pollution in many cities, which negatively impacts public health and intensifies the vulnerability of ecosystems (Li et al., 2019a, 2019b; Lovett et al., 2009). Secondly, the rise in carbon emissions has exacerbated several problems, such as higher temperatures, more frequent and severe weather events, and growing threats to China's ecological balance and food security (Kellogg, 2019; Yang et al., 2021a, 2021b, 2021c). In order to meet its international obligations, China must actively pursue its 'dual carbon goals' through the reduction of greenhouse gas emissions and efforts to mitigate the global impacts of

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³ For instance, policies such as low-carbon pilot programs, the establishment of carbon emission trading markets, dual control zones policies, the trading policies of sulfur dioxide emissions, and the ten measures for air policy have played significant roles in this regard.

climate change (Liu et al., 2013). The Chinese government has developed a series of PESS models (Fang and Li, 2021; Zang et al., 2021). PESS promotes regional economic development and improves ecological quality by converting ecosystem value into economic value (FAO, 2011; Lansing, 2011). Studying the atmospheric governance effects of improving PESS is significant for China's "dual carbon goals" and air quality enhancement.

Extensive research has examined theories and case studies on the value of ecological products and ecosystem service payments (Johnston and Russell, 2011; Khademi, 2020; Xu et al., 2016). By encouraging public participation in environmental protection, promoting green transformation in development, and enhancing national governance, PESS contributes to ecological modernization (Li and Zhang, 2021). PESS can promote the industrialization of ecological products, incentivize regions to improve their supply capacity, and foster green production and lifestyles (Ouyang et al., 2016). The literature has also explored the impacts of carbon emissions trading, low-carbon pilot policies, environmental protection taxes, and central environmental inspections on atmospheric environmental governance (Hu et al., 2020; Li et al., 2021, 2022; Yuan et al., 2022a, 2022b). However, past research has not sufficiently quantified PESS development, assessed its impact on air contamination, or clarified the underlying mechanisms. This paper quantifies PESS progress and examines its influence on AEQ, expanding PESS research.

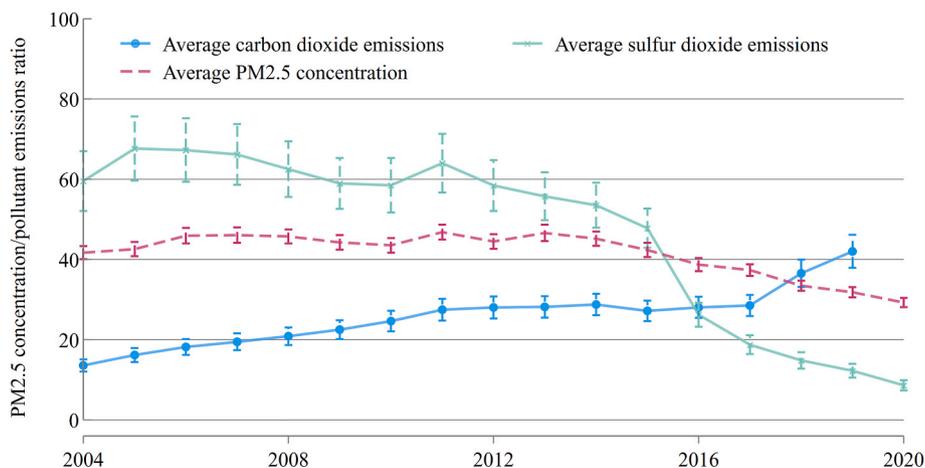
Enhancing AEQ through PESS involves establishing an incentive mechanism where beneficiaries are rewarded, users are charged, and polluters are held accountable. The enhancement of PESS drives regional green technology innovation, reduces local air pollutant emissions, and enhances AEQ (Borghesi et al., 2015; Cui et al., 2022; Sun et al., 2022a, 2022b). Enhancing PESS can transform industries and facilitate the integration of primary sectors, such as agriculture and forestry, into the service sector. This integration mitigates industrial concentration in specific regions, removes environmentally harmful enterprises, reduces carbon dioxide emissions, and enhances air quality (Hu et al., 2020; Li et al., 2019a, 2019b, 2021; Mason, 2013; Wan et al., 2022). Increasing PESS coverage can raise barriers to environmental degradation, attract environmentally conscious businesses, discourage polluting companies, and improve air quality (Sitruk et al., 2020; Subramaniam and Masron, 2022; Verde, 2020; Yang et al., 2021a, 2021b, 2021c).

China's unique context offers valuable insights into this issue. The Chinese government issued the PESS scheme, stressing the importance of ecosystem value for economic and social development. The PESS analysis in China focuses on macro-level dynamics and thoroughly assesses various initiatives, including programs that fund ecosystem

services, ecological premiums, and green finance. These mechanisms enable payments for ecosystem services through both tangible means—such as material and cultural products—and intangible means, including spiritual and cultural values (Yang et al., 2023). The Chinese government has developed a range of PESS approaches tailored to different ecological and regional contexts (Ouyang et al., 2016). As a key component of China's green development strategy, PESS is supported by a rich and expanding dataset.

This study explores the association between enhanced PESS performance, reduced atmospheric pollution, and improved air quality, with particular attention to the causal mechanisms that drive these outcomes. This study analyzes panel data from Chinese prefecture-level cities (2004–2020). The entropy method is employed to construct composite indicators capturing the development of comprehensive, profitable (tradable), quasi-public, and public PESS. The econometric model assesses how improvements in PESS influence air quality by uncovering the underlying causal pathways. The results indicate that improvements in PESS have enhanced AEQ, primarily driven by the rise of green technologies, changes in industrial structure, and the entry of new businesses. After conducting robust tests, the results remained consistent and valid. Further research suggests that PESS improvements have a more significant positive effect on AEQ in China's eastern and central regions than in the western regions. Additionally, profitable and quasi-public PESS effects are more pronounced. This effect is more notable in areas with higher fiscal decentralization and marketization. The study offers valuable insights for balancing economic development and atmospheric pollution.

This study makes three significant contributions. Firstly, it has developed a comprehensive measurement methodology for PESS, including profitable, quasi-public, and public PESS, summarizing feasible pathways and providing a valuable reference for future quantitative research. This macro-level approach enables a systematic assessment of PESS implementation across regions, overcoming the limitations of case-based or mechanism-specific studies and providing a foundation for extending PESS analysis from micro-level case studies to broader regional evaluations. Secondly, this study confirms the positive impact of PESS on air quality by analyzing green innovation, industrial restructuring, and firm dynamics. It highlights PESS's role in fostering green development, identifies effective firm behaviors, and offers industrial policy guidance for targeted emission reduction. This study assesses the effectiveness of PESS on AEQ across different attributes and regional heterogeneity, with a particular focus on the weaker effects observed in western China. It investigates the underlying causes and explores potential solutions, such as enhancing fiscal transfer payments to western regions, providing an empirical basis for identifying weak



Note: 95% confidence intervals are shown in the figure.

Fig. 1. Trends in the average emissions of air pollutants in Chinese prefecture cities.

PESS effects and informing effective policy responses. Furthermore, this study analyzes the moderating impact of PESS on AEQ regarding marketization and fiscal decentralization. The results highlight the importance of the institutional environment in the PESS process, clarifying how and under what conditions PESS achieves greater emission-reduction benefits and helping governments formulate effective environmental policies to address challenges such as air pollution and climate change.

The paper is structured as follows: Section 2 provides a theoretical analysis and outlines the research hypotheses. Section 3 covers the research design, introducing data sources and variable selection while constructing econometric models. Section 4 involves model estimation and results analysis. Section 5 summarizes the main conclusions and offers policy implications.

2. Theoretical analysis and hypotheses development

PESS plays a crucial role in China's efforts to reduce pollution and emissions by integrating government-led initiatives with market-based strategies. These mechanisms—including pricing strategies, supply-demand dynamics, competitive frameworks, risk management, and incentive structures—help advance green technologies, transform industrial structures, and shape corporate market behavior. The goal is to promote eco-friendly industries, reduce air pollutants and carbon emissions, and ultimately enhance atmospheric quality. A more in-depth analysis is presented below.

2.1. The PESS and AEQ

Higher PESS degrees enhance atmospheric quality by boosting incentive effectiveness. First and foremost, The methods within PESS promote green innovation among market entities, reducing the adverse externalities of traditional economic development and mitigating atmospheric pollutant emissions (Borghesi et al., 2015; Shi and Wang, 2022; Sun et al., 2022a, 2022b; Wang et al., 2023a, 2023b, 2023c). Secondly, PESS accelerates industrial transformation, encouraging market players to enhance their ability to supply green resources and products. This approach boosts positive externalities from green industries and simultaneously curtails the growth of polluting sectors (Hu et al., 2020; Li et al., 2019a, 2019b, 2021; Mason, 2013; Wan et al., 2022). Thirdly, PESS influences market entry, encouraging environmentally responsible enterprises while restricting polluting companies (Sitruk et al., 2020; Subramaniam and Masron, 2022; Verde, 2020; Yang et al., 2021a, 2021b, 2021c). PESS serves a dual purpose: converting ecosystem value to economic value, and mitigating air pollution to improve AEQ.

Hypothesis 1. Developing PESS enhances AEQ.

2.2. The PESS, green innovation, and AEQ

The PESS improves atmospheric quality by fostering sustainable green innovation. The development of PESS acts as a catalyst for industrial revitalization, improvement of production chains, and the implementation of innovative green solutions. As the value of ecosystems becomes more widely recognized and the costs of environmental pollution continue to rise, there is a growing impetus to internalize social and environmental externalities (Chan et al., 2017). By incentivizing investment in cleaner production technologies, this process fosters systemic advancements in pollution abatement, renewable energy deployment, and low-emission energy efficiency. Consequently, enterprises pursue green technological innovation while promoting sustainable and responsible production practices (Sun et al., 2023). Furthermore, the PESS promotes collaboration and knowledge exchange among stakeholders, generating spatial spillover effects that facilitate the diffusion of green technological innovation (Liu et al., 2022). PESS

contributes to raising environmental awareness among residents and encourages the adoption of sustainable consumption choices. In response to changing consumer demands, producers innovate efficient, cleaner, and energy-saving technologies, essential for maintaining competitiveness and enhancing AEQ (Chen et al., 2022; Hafezi and Zolfagharinia, 2018).

Hypothesis 2. PESS advancement enhances AEQ through green innovation.

2.3. The PESS, industrial structural transformation, and AEQ

By reshaping the industrial structure, PESS facilitates improvements in AEQ. The enhancement of PESS fosters the growth of green industries while curbing pollution-intensive firms. In the first instance, profitable PESS fosters growth in green industries by converting ecological assets into production factors, integrating ecological landscape and cultural heritage with economic development. This process facilitates industrial upgrades, increases the absorption of air pollutants, and contributes to the improvement of AEQ (Bleda and Valente, 2009; Yang et al., 2021a, 2021b, 2021c). Secondly, enhancing the quasi-public PESS through market price mechanisms stimulates efficient resource management and allocation, reducing waste and overconsumption, encouraging industrial upgrading, and lowering air pollutant emissions (Hu et al., 2020). Thirdly, enhancing public PESS incentivizes local governments to reassign environmental governance responsibilities to all industrial entities. This encourages polluters to leave the market or embrace green practices, driving industrial transformation and enhancing air quality (Marin et al., 2018; Wan et al., 2022; Wang et al., 2023a, 2023b, 2023c). As outlined above, PESS can serve as a mechanism for achieving atmospheric environmental governance through the promotion of industrial structural transformation.

Hypothesis 3. PESS enhancement promotes AEQ through industrial transformation.

2.4. The PESS, enterprise market entry, and AEQ

Enterprise market entry enhances AEQ, influenced by PESS implementation. PESS drives environmental governance through the restriction of polluting enterprises and the encouragement of environmentally responsible ones. Firstly, PESS relies on a well-preserved ecological environment. As PESS is implemented, local governments increase environmental admission standards, substantially curbing the number of polluting enterprises in the market (Dean and Brown, 1995). Secondly, PESS implementation is often accompanied by stronger environmental monitoring, thereby intensifying both moral and regulatory pressures on polluting enterprises contemplating market entry (Holland, 2012). Thirdly, PESS facilitates the entry of new and environmentally conscious businesses by improving resource efficiency, enhancing ecosystem services, and reducing air pollutants (Ball and Kittler, 2019; Cojoianu et al., 2020). Additionally, PESS stimulates the expansion of environmental protection industries, encouraging environmental platform companies to enter the market. These companies have the opportunity to benefit from pollution control and certification programs, which help reduce air pollutant emissions (Dean and McMullen, 2007).

Hypothesis 4. Improving PESS enhances AEQ by influencing business market entry decisions.

3. Research design

3.1. Variable selection

3.1.1. Dependent variable: atmospheric environmental quality

Based on Miao et al. (2019), this study evaluates air quality, emphasizing pollutant emissions and quality indicators. Carbon dioxide

(CO₂) and industrial sulfur dioxide (SO₂) emissions are used as key metrics in this analysis to evaluate atmospheric pollutant levels. Air quality is evaluated using PM_{2.5} concentration, a significant and readily accessible indicator defined by national air quality standards. Robustness tests in this study include the Air Quality Index and the count of good air quality days to assess air pollution control outcomes.

3.1.2. Main independent variable

The main independent variable is the comprehensive PESS progress for a city in year t , measured using the entropy method. This method provides objective weighting to accurately reflect the significance of each indicator in the composite index (Cunha-Zeri et al., 2022). Ecosystem products are classified as tradable and non-tradable goods, with non-tradable goods including quasi-public and public goods. Tradable goods follow the Coasean approach, which aligns with profitable PESS, while non-tradable goods correspond to the Pigouvian approach, encompassing quasi-public and public PESS. Sub-indicators for profitable, quasi-public, and public PESS are evaluated alongside overall PESS progress (Fan et al., 2003). The PESS indicator system is constructed, and progress is quantified based on existing literature classifications.⁴ Figs. 2–5 illustrate the PESS development across various attributes and tiers in Chinese prefecture-level cities in 2020. PESS categories are classified as high ($p75 < \text{high} < p100$), medium ($p25 < \text{medium} < p75$), and low ($p0 < \text{low} < p25$).⁵

The profitable (tradable) PESS originates from two main sources: direct tourism benefits (Groot, 2011) and resource premiums tied to ecological labels and green certifications (Seidl, 2014). Profitable PESS measurement includes cultural tourism, ecological resource tourism, and eco-product certifications. The assessment of traditional cultural tourism payment considers tangible and intangible aspects. Tangible cultural tourism includes activities at national cultural relics, traditional villages, and revolutionary sites (Li et al., 2010). Intangible cultural tourism includes activities related to national intangible cultural heritage (Dippon and Moskaliuk, 2020). The payment assessment for ecological resource tourism covers tourism activities in national scenic areas, ecological towns, ski resorts, forest parks, homestays, leisure streets, culturally distinctive towns, and key villages for rural tourism. Measuring payments for ecological certifications includes national geographical indication certifications (Moschini et al., 2008). These indicators reflect the development stage of profitable PESS.

The profitable PESS aims to transform ecosystem products into economic value by employing the following methodologies: By showcasing the distinctiveness of ecological resources, the tourism sector helps realize their value through shared management mechanisms and profit-oriented operations. Ecosystem value is realized through tradable commodities—such as agricultural, forestry, and fishery products, industrial goods, and services—by commercializing ecological resources. Geographical indications and green labels are crucial for converting regional ecosystem values into economic benefits. A healthy ecological environment contributes to high-quality certifications, which increase the premium value of ecosystem products.

The quasi-public PESS is derived from two critical sources. Firstly, the resource and environmental rights trading market helps internalize environmental impacts for market entities (Pirard, 2012). Meanwhile, primary and secondary green financial market transactions indirectly influence resource and environmental rights trading. The quasi-public

PESS focuses on trading pollution rights, carbon emissions rights, water resources rights, energy use rights, and green finance. A city's participation in the quasi-public pilot program improves the trading platform. The market's transparency and activity are disclosed in transaction data from the platform, which assesses the quasi-public market's maturity for ecosystem products. The following indicators reflect the development stage of the quasi-public PESS. The first dimension pertains to the trading of pollutant discharge rights, including participation in pilot initiatives. The second dimension includes carbon emissions trading, covering pilot program participation, participating enterprises, transaction volumes, and transaction values. The third dimension addresses water rights trading, covering pilots, trading volume, and project quantity. The fourth dimension emphasizes green financial transactions, highlighting pilot policy.

The quasi-public PESS approaches aim to convert ecosystem value to economic value through the following methods. Emission trading for sulfur and carbon dioxide internalizes external pollution costs through trading revenue. Water rights trading is a market mechanism that allows participants with higher efficiency to conserve water and gain economic benefits by transferring water rights. Green financial products, such as green credit, funds, bonds, and banks, play a crucial role in the green finance market. Market participants benefit from these products by supporting resource conservation and environmentally friendly practices (Garces-Voisinat and Mukherjee, 2016).

The success of public PESS arises from several key factors. The initial method comes from government-funded ecological transfer payments (Cheng et al., 2023a, 2023b). The second approach is derived from the ecological governance and conservation practices of central and local authorities (Cheng et al., 2023a, 2023b). The third approach is based on environmental penalties and compensations enforced through governmental administrative strategies (Heyes, 1996). The public PESS assessment focuses on three dimensions: vertical ecological compensation, horizontal ecological compensation, and environmental damage compensation. The first aspect involves vertical ecological compensation, including converting farmland to forests and establishing reserves (Liu, 2020). The second aspect includes horizontal ecological compensation for losses between upstream and downstream river basins (Zhang et al., 2023a, 2023b, 2023c; Zhou et al., 2022). The third aspect concerns environmental damage compensation, including pollution penalties and protection taxes (Li et al., 2021). These indicators reflect the progress made in realizing public value from ecosystem products.

The development of the public PESS occurs through the following processes. Vertical ecological compensation includes financial assistance from the central government to local authorities. China has successfully compensated for farmland converted to forests, helping combat soil erosion and desertification. National nature reserves consist of core, buffer, and peripheral zones, with ecotourism and limited revenue generation permitted only in the peripheral zone. The main support for the reserve comes from government transfer payments. Horizontal ecological compensation involves financial transfers from beneficiary areas to protected regions. For environmental damage compensation, those responsible for the damage face penalties through litigation, while those protecting the environment can pursue compensation through similar channels. Environmental protection taxes are crucial for fairly redistributing economic gains from ecological resources. Table 1 outlines the data for calculating PESS, including profitable, quasi-public, and public information.

3.1.3. Control variables

This paper builds on Miao et al.'s (2019) study and conducts city-year regression analysis, controlling for various factors such as economic development, openness, technology, finance, urbanization, capital intensity, infrastructure, and human capital. The model includes time and city fixed effects. The regional fixed effects account for constant, region-specific characteristics, such as historical and cultural factors related to prefecture-level cities, including Confucianism, religious

⁴ Measuring PESS through economic value is possible, but complex definitions hinder data collection on ecological product premiums and ecosystem benefits. Despite the significant economic value of ecological products, refining PESS rules enhances government management. Economic value suggests management success but doesn't guarantee returns, highlighting the need for method-based indicators for effective management of the economy and environment.

⁵ P0, P25, P50, P75, and P100 represent the quartiles of PESS.

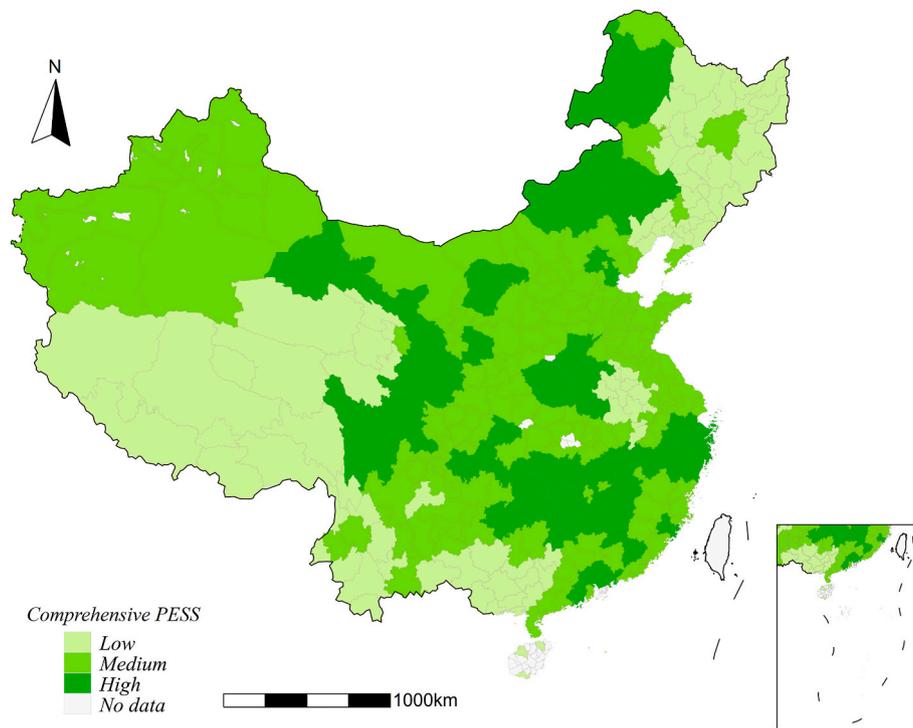


Fig. 2. The classification of comprehensive PESS categories in 2020.
Note: Map of China, with map review number (GS (2019) 1822).

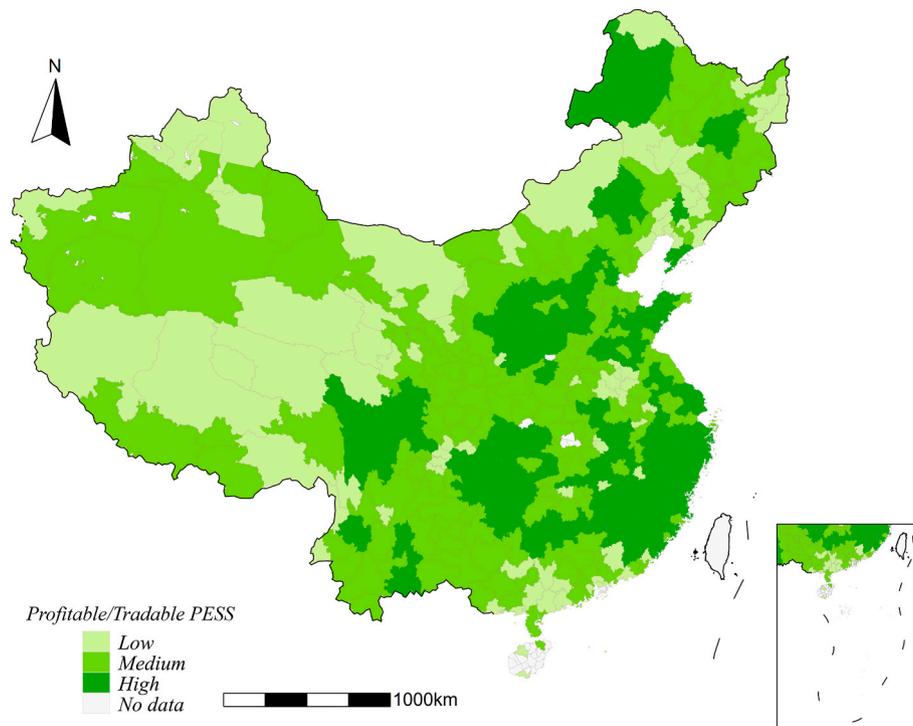


Fig. 3. The classification of profitable (tradable) PESS categories in 2020.
Note: Map of China, with map review number (GS (2019) 1822).

influences, and language cultures. The time-fixed effects capture time-specific shocks that are consistent across regions. Table 2 details the model's variables.

3.2. Data and sample

This study uses a multi-source dataset to examine how PESS impacts AEQ and its mechanisms. The final panel data covers 280 Chinese prefecture-level cities, excluding Hong Kong, Macao, and Taiwan, from

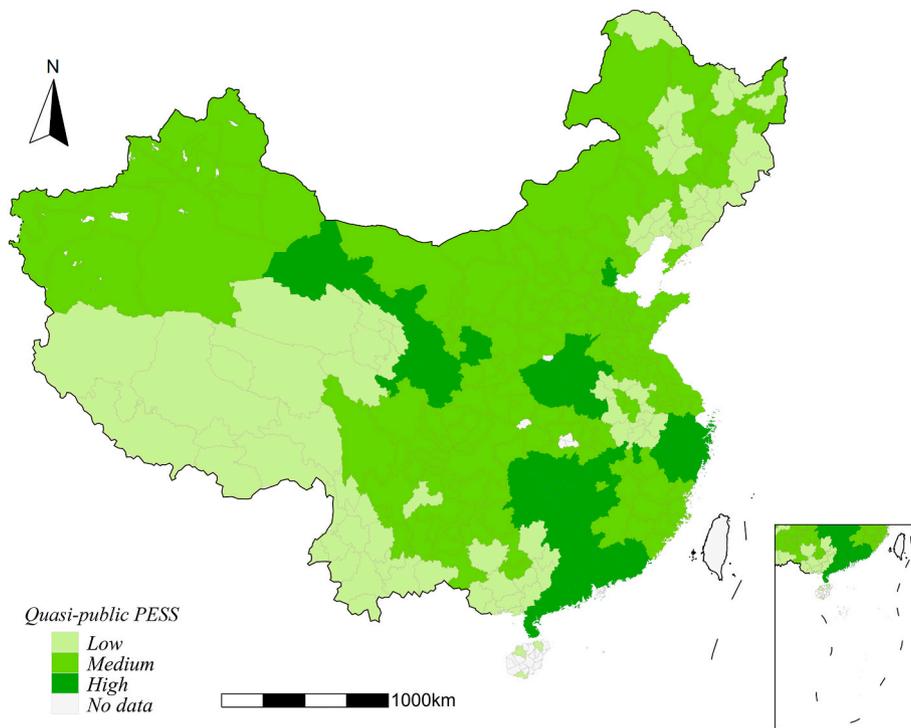


Fig. 4. The classification of quasi-public PESS categories in 2020.
Note: Map of China, with map review number (GS (2019) 1822).

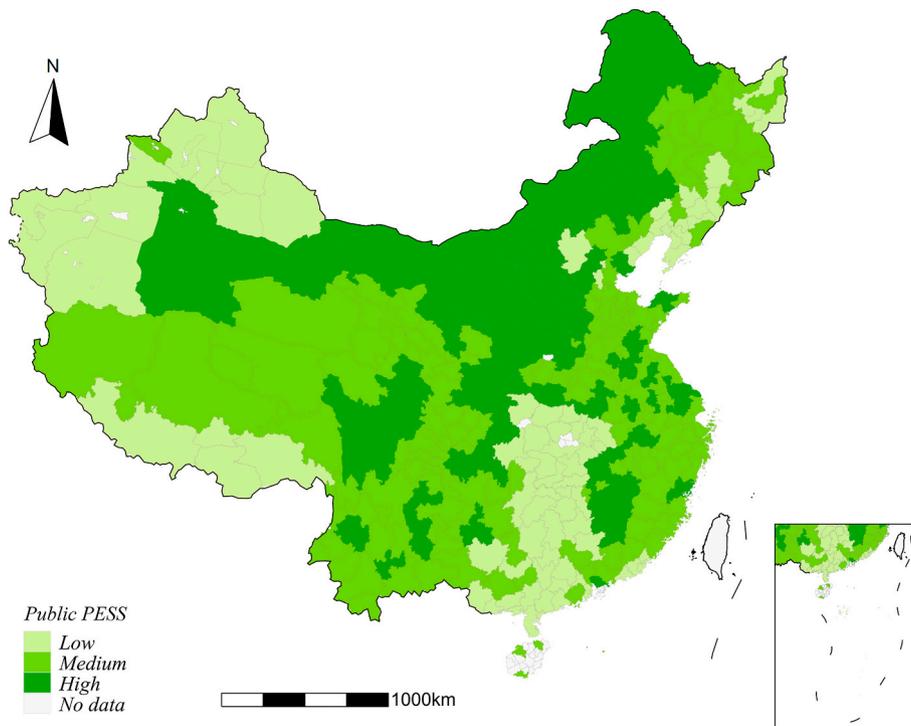


Fig. 5. The classification of public PESS categories in 2020.
Note: Map of China, with map review number (GS (2019) 1822).

2004 to 2020. [Table 3](#) provides descriptive statistics for all variables.

3.3. Econometric model

This study aims to empirically test the theoretical hypotheses at the

macro level across China's prefecture-level cities. An econometric model is developed to analyze the impact of integrated PESS progress on AEQ. The econometric model is as follows:

$$EP_{it} = \beta_0 + \beta_1 PESS_{it} + \beta_2 \sum Z_{it} + \mu_i + \tau_t + \varepsilon_{it}$$

Table 1
Variables for measuring the PESS.

Primary indicator	Secondary indicator	Variable definition	Data sources	
Profitable (Tradable) PESS				
<i>Traditional cultural tourism</i>	<i>Traditional tangible cultural tourism</i>	It is denoted by the count of national critical cultural heritage units within city <i>i</i> during year <i>t</i> .	<i>National Cultural Heritage Administration.</i>	
	<i>National traditional village tourism</i>	It is represented by the number of national traditional villages within city <i>i</i> in year <i>t</i> .	<i>Ministry of Housing and Urban-Rural Development and the National Cultural Heritage Administration.</i>	
	<i>Red revolutionary cultural heritage tourism</i>	It is denoted by the number of counties in the city during the year that engage in conserving and utilizing revolutionary cultural relics.	<i>National Cultural Heritage Administration.</i>	
	<i>Tourism related to traditional intangible cultural heritage</i>	It is represented by the number of intangible cultural heritage items possessed by city <i>i</i> in year <i>t</i> .	<i>China Intangible Cultural Heritage Digital Museum.</i>	
	<i>Ecological resources tourism</i>	<i>Tourism in natural scenic areas</i>	It is represented by the cumulative count of scenic spots at all levels established in city <i>i</i> during year <i>t</i> .	<i>Chinese Ministry of Culture and Tourism.</i>
		<i>Eco-town tourism</i>	The quantity of national ecological townships possessed by city <i>i</i> in year <i>t</i> is selected.	<i>Ministry of Ecology and Environment.</i>
	<i>National skiing tourism</i>	The total number of national ski resorts in the possession of city <i>i</i> in year <i>t</i> is calculated.	<i>Chinese Ministry of Culture and Tourism.</i>	
	<i>National forest park tourism</i>	Determine the count of national forest parks owned by city <i>i</i> in the year <i>t</i> .	<i>National Forestry and Grassland Administration.</i>	
<i>National homestay tourism</i>	It is denoted by the number of homestay tourism spots owned in city <i>i</i> in year <i>t</i> .	<i>Chinese Ministry of Culture and Tourism.</i>		
<i>National leisure district tourism</i>	It is the number of leisure blocks owned by city <i>i</i> in year <i>t</i> .	<i>Chinese Ministry of Culture and Tourism and the National Development and Reform Commission.</i>		
<i>National distinctive town tourism</i>	Small towns with national characteristics in city <i>i</i> during year <i>t</i> serve as a representation of this variable.	<i>Ministry of Housing and Urban-Rural Development.</i>		
<i>Eco-product certification</i>	<i>National geographical indication product certification</i>	The number of national geographical indication products owned in city <i>i</i> in year <i>t</i> is used.	<i>National Agricultural Geographic Indication System.</i>	
Quasi-public PESS				
<i>Emission trading</i>	<i>Emission trading scheme</i>	Use the emissions trading pilot for city <i>i</i> in year <i>t</i> .	<i>National Development and Reform Commission.</i>	

Table 1 (continued)

Primary indicator	Secondary indicator	Variable definition	Data sources
<i>Carbon emissions trading</i>	<i>Carbon emissions trading scheme</i>	Whether the city <i>i</i> belongs to a carbon emissions trading pilot is indicated by a dummy variable, where 1 signifies participation in the pilot program, and 0 denotes non-participation. It is quantified by the involvement of carbon emissions trading companies in city <i>i</i> during year <i>t</i> .	<i>National Development and Reform Commission.</i>
	<i>Number of carbon trading companies</i>	It is gauged by the annual average carbon emissions trading volume in city <i>i</i> during year <i>t</i> .	CSMAR database
	<i>Carbon emissions trading volume</i>	It is assessed through the annual average carbon emissions trading turnover in city <i>i</i> during year <i>t</i> .	CSMAR database
	<i>Carbon emission trading volume</i>	It is assessed through the annual average carbon emissions trading turnover in city <i>i</i> during year <i>t</i> .	CSMAR database
<i>Energy use right trading</i>	<i>Pilot trading of energy rights</i>	It is represented by whether city <i>i</i> is situated in a province with an energy use rights market in year <i>t</i> .	<i>National Development and Reform Commission.</i>
<i>Water rights trading</i>	<i>Water rights trading pilot</i>	It is indicated by whether city <i>i</i> is in a province with a pilot program for water rights trading in year <i>t</i> .	<i>National Development and Reform Commission.</i>
	<i>Water resources transaction volume</i>	The annual average traded water resources of irrigation water rights in city <i>i</i> during year <i>t</i> are employed to measure this variable.	<i>China Water Rights Trading Center</i>
	<i>Water resources trading project</i>	It is represented by the annual average number of projects of irrigation water rights trading in city <i>i</i> during year <i>t</i> .	<i>China Water Rights Trading Center</i>
<i>Green finance trading</i>	<i>Green finance reform</i>	It is indicated by whether city <i>i</i> is in a province with a pilot program for green finance trading in year <i>t</i> .	<i>The State Council.</i>
Public PESS			
<i>Vertical ecological compensation</i>	<i>Compensation for returning farmland to forest</i>	This variable is quantified using the average compensation amount for land conversion from farmland to forest per unit area in city <i>i</i> during year <i>t</i> .	<i>National Forestry Bureau and the National Bureau of Statistics.</i>
	<i>Area of nature reserve</i>	It is measured by the area of nature reserves owned in each city in a year. It is denoted by the number of nature	<i>National Forestry Bureau.</i>
	<i>Number of nature reserves</i>	It is denoted by the number of nature	<i>National Forestry Bureau.</i>

(continued on next page)

Table 1 (continued)

Primary indicator	Secondary indicator	Variable definition	Data sources
Horizontal ecological compensation	Basin ecological compensation	reserves in each city in a year. A binary dummy variable signifies whether the city is in a province implementing horizontal basin ecological compensation.	This data is sourced from the official websites of provincial governments.
	Penalties for environmental pollution	The count of environmental enforcement cases in city <i>i</i> during year <i>t</i> is computed.	Peking University Law Database.
Compensation for environmental damage	Environmental protection tax	The proportion of environmental protection taxes collected in the city during year <i>t</i> is estimated.	China Environmental Statistics Yearbook and China Taxation Yearbook.

$\sum Z_{it}$ represents control variables that vary over time and across cities. μ_i represent city-fixed effects. τ_t represent time-fixed effects. ε_{it} represent the error term. EP_{it} denotes the AEQ variable for city *i* in year *t*, including emissions, emission intensity, per capita emissions, and air quality. PES_{it} represents PESS development for the city *i* in year *t*. The coefficient β_1 measures the impact of PESS progress on atmospheric pollution. A negative estimated value of β_1 suggests that enhancing PESS is associated with reductions in air pollutant emissions and concentrations, thereby facilitating more effective atmospheric governance and improvements in air quality. If the coefficient is greater than 0, it suggests that developing the PESS failed to mitigate atmospheric pollution.

4. Empirical analysis

4.1. Benchmark regression

Table 4 reports the main results of the econometric analysis assessing the impact of comprehensive PESS on AEQ. The regression results show a significant positive coefficient for the PESS at a 5% confidence level or higher, indicating that advancing PESS contributes to lower pollutant emissions and improved air quality in cities after controlling for other variables. Columns (1)–(3) show that PESS expansion significantly lowers total carbon emissions, emission intensity, and per capita emissions, with a one-unit increase in PESS associated with a 60% reduction in carbon emissions ($p < 0.01$). Columns (4)–(6) demonstrate similar effects on industrial sulfur dioxide, where a one-unit increase in PESS corresponds to a 2.657-fold reduction in emissions ($p < 0.01$). Finally, Columns (7) and (8) show that PESS expansion significantly reduces urban PM2.5 concentrations, with a one-unit increase in PESS leading to a 40% decrease in PM2.5 concentration ($p < 0.01$), further confirming its role in improving air quality. Overall, these findings provide strong support for Hypothesis 1.

The coefficients of the control variables in Table 4 are economically significant. Technological advancement enhances AEQ, suggesting that regions with superior technology are more effective at reducing air pollution, which aligns with previous research findings (Popp, 2006). Urbanization significantly contributes to increased pollutant emissions, underscoring its role as a key factor in the deterioration of AEQ in Chinese cities. Financial development contributes to increased pollutant emissions, as urban loans predominantly finance profitable yet environmentally harmful businesses, thereby exacerbating the degradation of AEQ (Khezri et al., 2023; Zhang et al., 2021). The expansion of transportation infrastructure has led to increased pollutant emissions

Table 2

Variable definition.

Variable name	Symbol	Variable definition	Data sources
Dependent variables			
Total carbon emissions	$\ln CO_2$	The natural logarithm of carbon emissions data in the city in a year published by the IPCC in China's carbon emission database is used.	China Emissions Accounts and Datasets (CEADs, www.ceads.net)
Per capita carbon emissions	PCO_2	It is expressed as the logarithm of the total urban carbon emissions ratio to the city's population during year <i>t</i> .	
Carbon dioxide emission intensity	DCO_2	It is expressed as the logarithm of per unit area CO ₂ emissions in city <i>i</i> during year <i>t</i> .	
Sulfur dioxide emissions	$\ln SO_2$	It is expressed as the logarithm of industrial sulfur dioxide emissions in city <i>i</i> in year <i>t</i> .	China City Statistical Yearbook
Per capita emissions of sulfur dioxide	PSO_2	The logarithm of the city's per-capita industrial sulfur dioxide emissions during year <i>t</i> serves as the indicator for this variable.	
Sulfur dioxide emission intensity	DSO_2	The logarithm of sulfur dioxide emissions per unit area in city <i>i</i> in year <i>t</i> indicates this variable.	
Fine particle concentration	$\ln PM$	The logarithmic PM2.5 concentration is calculated in the city in a year.	Atmospheric Composition Analysis Group at Dalhousie University
Air quality	$Airquality$	It is represented by the air quality index (AQI) and the number of days with good air quality (AirGood) in the city in a year.	Online air quality monitoring and analysis platform.
Independent variable			
PESS development	PES	The score of the comprehensive PESS in the city in year <i>t</i> is calculated.	Calculated data.
Control variables			
Economic development	$\ln GDP$	It is expressed using the logarithm of the gross regional product in city <i>i</i> in year <i>t</i> .	China City Statistical Yearbook
Technology	$Tech$	The proportion of regional fiscal scientific expenditure to local fiscal general budget expenditure in the city in a year expresses it.	
Openness	$Open$	The proportion of FDI to regional GDP in the city in a year is used to test the "pollution paradise" hypothesis.	
Finance	$Finance$	The ratio of loans from financial institutions to GDP in the city in year <i>t</i> measures it.	
Urbanization	$\ln Urban$	It is expressed by the proportion of the city's population to the resident population in year <i>t</i> .	
Capital intensity	KL	It is measured by the logarithm of the city's fixed capital stock ratio	

(continued on next page)

Table 2 (continued)

Variable name	Symbol	Variable definition	Data sources
<i>Infrastructure</i>	<i>lnRoad</i>	to employment during year <i>t</i> . It is expressed by the logarithm of the city's road mileage in the year.	
<i>Human capital</i>	<i>lnHC</i>	The logarithm of the proportion of individuals with a standard professional or higher education level to the city's permanent population is used.	
<i>The central environmental inspection</i>	<i>CEI</i>	A policy dummy variable indicating whether a city was subject to the central environmental inspection in a given year.	Ministry of Ecology and Environment of the China
Instrumental variables			
<i>Lewbel method</i>	<i>IV</i>	The instrumental variable generated by heteroscedasticity and exogenous altitude is applied.	CNRDS database.
Mechanism variables			
<i>Green innovation</i>	<i>GI</i>	It is represented by the application number of green invention patents (<i>lnApply</i>), the number of green invention patents (<i>lnGrant</i>), the number of green utility model invention patents (<i>lnUapply</i>), and the number of green utility model invention patents (<i>lnUgrant</i>).	CNRDS database.
<i>Industrial structure</i>	<i>IND</i>	This variable comprises indicators of industrial structure rationalization and intensity, with the latter measured as the share of industrial enterprises above the designated size and their total output value in regional GDP.	China City Statistical Yearbook
<i>Firm entry</i>	<i>Entry</i>	The market entry of green firms is measured by the logarithm of entrants (<i>lnGER</i>) and the entry ratio (<i>GER</i>) of relevant service-industry firms in city <i>i</i> in year <i>t</i> . The market entry of polluting enterprises is measured by the logarithm of entries (<i>lnPER</i>) and the entry ratio (<i>PER</i>) of firms in the relevant polluting industry in the city in year <i>t</i> .	CNRDS database
<i>Firm entry scale</i>	<i>FS</i>	In city <i>i</i> and year <i>t</i> , the share of each type of entry scale in the city's total entry scale, measured by total industrial output value, total industrial sales value, total assets, number of employees, and paid-in capital.	China Industrial Enterprise Database

Table 2 (continued)

Variable name	Symbol	Variable definition	Data sources
<i>Existing firms</i>	<i>EF</i>	In city <i>i</i> and year <i>t</i> , measured as each industry's share of the total number of firms in the city.	CSMAR database
Other variables			
<i>PESS attributes</i>	<i>PES</i>	The calculated <i>profitable (tradable) PESS (PESP)</i> , <i>quasi-public PESS (PESQ)</i> , and <i>public PESS (PESC)</i> are indicators of it.	Calculated data.
<i>Marketization</i>	<i>MK</i>	The provincial marketization index in the city during the year is used (Fan et al., 2003).	China Marketization Index Report
<i>Fiscal decentralization</i>	<i>DE</i>	The ratio of the average fiscal expenditure in the prefecture city budget to the sum of average fiscal expenditures in the city's central, provincial, and prefecture budgets during the year is employed.	China City Statistical Yearbook
<i>Green dependence</i>	<i>NDVI</i>	The normalized difference vegetation index for city <i>i</i> in year <i>t</i> .	NASA MOD13A3
<i>Transfer payment</i>	<i>TS</i>	The general transfer payment amount for city <i>i</i> in year <i>t</i> .	Municipal government reports
<i>Time</i>	<i>Year</i>	Dummy variables	
<i>City</i>	<i>City</i>	Dummy variables	

and a decline in AEQ (Huang et al., 2020). This regression analysis does not provide conclusive evidence on the effects of economic development, foreign market openness, and capital intensity on atmospheric pollution.

4.2. Endogeneity and robustness checks

4.2.1. Endogeneity treatment

Notwithstanding the correspondence of the baseline regression results with the theoretical hypotheses articulated in this paper, it is plausible that these findings may be vulnerable to endogeneity bias. Firstly, the convergence of atmospheric environmental governance and PESS, as key components of regional development, may inherently demonstrate a certain degree of interdependence in practice. Guaranteeing the independence and exogeneity of these processes is challenging, as atmospheric conditions may influence the drivers of PESS. In regions with lower AEQ, local governments may have stronger incentives to improve the provision of ecological products, potentially leading to an increase in payments for ecosystem services. Such reverse causality may result in an overestimation of the impact of the PESS. Additionally, latent and unobservable factors may simultaneously affect AEQ and PESS, contributing to their correlation. Thirdly, the regression equation may omit relevant factors related to PESS, potentially leading to a correlation between the error term and the explanatory variables. Accordingly, this study employs an instrumental variable approach to mitigate potential endogeneity concerns.

In this study, the altitude of prefecture-level cities is used as an instrumental variable for PESS, primarily for the following reasons. The maturity of PESS depends on the natural resource endowments of cities. Cities at different altitudes experience distinct climatic conditions, such as variations in temperature, humidity, and sunlight duration. Moreover, regional differences in natural resource abundance influence the fundamental conditions for realizing the value of ecosystem products. Consequently, altitude serves as a valid instrumental variable for the development of PESS, satisfying the relevance condition. A city's altitude

Table 3
Descriptive statistics.

	Obs	Mean	Std.Dev.	Min	Median	Max
lnCO ₂	5169	2.85	0.93	-1.22	2.92	5.56
PCO ₂	4645	-2.90	0.73	-6.60	-2.90	-0.08
DCO ₂	4475	2.86	1.06	-0.98	2.89	5.90
lnSO ₂	5032	10.08	1.42	0.69	10.33	13.43
PSO ₂	4543	4.26	1.34	-3.38	4.41	7.98
DSO ₂	4760	10.05	1.44	2.34	10.17	13.59
lnPM	5695	3.62	0.52	0.62	3.68	4.69
PM	5695	41.51	16.77	1.87	39.52	108.53
PES	5729	0.03	0.04	0.00	0.02	0.41
PESP	5729	0.02	0.04	0.00	0.01	0.49
PESQ	5729	0.03	0.06	0.00	0.00	0.58
PESC	5729	0.06	0.08	0.00	0.03	0.57
lnGDP	5663	6.71	1.24	1.84	6.77	10.56
Tech	5049	0.01	0.01	0.00	0.01	0.21
Finance	5032	0.92	0.59	0.08	0.74	9.62
Urban	4862	51.12	16.44	15.28	49.06	100.00
Open	5048	0.02	0.02	0.00	0.01	0.21
KL	4777	0.92	0.67	0.03	0.73	4.39
lnROAD	4981	9.13	0.74	5.62	9.23	12.07
lnHC	4754	2.77	0.00	2.69	2.77	2.77
AQI	2469	0.81	0.32	0.18	0.76	2.55
lnAQI	2316	4.32	0.31	3.52	4.33	5.49
AirGood	3010	0.82	0.16	0.19	0.87	1.00
lnAirGood	3010	-0.22	0.23	-1.65	-0.14	0.00
Income	4092	0.25	0.46	0.00	0.10	5.87
Tourists	4421	0.18	0.23	0.00	0.10	2.76
lnPgrant	5335	2.11	1.77	0.00	1.79	9.21
lnApply	5413	3.31	1.96	0.00	3.09	10.09
lnUgrant	5335	3.61	1.84	0.00	3.47	9.60
lnUapply	5413	3.64	1.83	0.00	3.53	9.48
Ration	4275	0.28	0.22	0.00	0.23	1.72
Ind	4107	1.27	0.67	0.01	1.20	17.65
lndfirm	4873	0.77	0.59	0.02	0.63	10.89
PER	5695	0.08	0.05	0.00	0.07	0.58
GER	5695	0.14	0.06	0.00	0.13	0.48
lnPE	5690	7.14	1.21	0.00	7.11	10.83
lnGE	5691	7.75	1.25	0.00	7.67	11.81
MK	5729	7.30	1.95	-0.16	7.37	11.49
Fiscal	3432	0.26	0.15	0.00	0.23	0.88
Altitude	5270	104.95	193.55	0.60	25.45	2020.00

reflects climatic diversity and constitutes a geographic characteristic, thereby meeting the exogeneity assumption for a valid instrumental variable. Therefore, the altitude variable satisfies both the relevance and exclusion criteria, making it a valid instrument for addressing endogeneity concerns. As the altitude variable is cross-sectional and unsuitable for use as an instrumental variable in a fixed-effects model, this study constructs interaction terms between the cross-sectional altitude variable and a temporal variable to serve as instruments for PESS. In this study, the two-stage least squares method proposed by Lewbel (2012) is applied, combining heteroskedasticity-based internal instruments with external instrumental variables for regression analysis.

Table 5 presents the 2SLS estimation results for the impact of PESS on AEQ. Columns (1) to (16) report the second-stage regression results and associated statistical metrics. The presence of heteroskedasticity, confirmed by the Pagan-Hall test, supports the appropriateness of using this estimation method. The endogeneity test results show that the first-stage F-statistic exceeds the critical threshold of 10, indicating that the chosen instrumental variables are not weak instruments. The Hansen J-test and the endogeneity test jointly confirm the exogeneity of the instrumental and main explanatory variables. The regression results show that the positive relationship between PESS and AEQ improvements remains significant after addressing endogeneity concerns. Although the magnitude of the PESS regression coefficient has changed, its sign remains consistent with the baseline regression results. Accordingly, the expansion of the PESS contributes to reduced air pollution and improved AEQ.

4.2.2. Robustness checks

4.2.2.1. Replacing air quality data. According to He et al. (2016), to mitigate the impact of measurement errors, this study replaces the core dependent variable with alternative AEQ indicators, including the air quality index (AQI), its natural logarithm, the number of days with favorable air quality, and its natural logarithm. Table 6 displays the regression results. Columns (1) and (2) show that improvements in PESS lead to a significant decrease in AQI. Columns (3)–(4) indicate that improved PESS increases the number of days with good air quality (AirGood), thereby enhancing air quality. These results further confirm the conclusions drawn from the baseline regression.

4.2.2.2. Substituting PESS data. To address potential measurement errors of the main explanatory variables, this econometric model includes alternative indicators for assessing PESS growth. This section evaluates PESS from an economic perspective by focusing on city tourism revenue and tourist arrivals, assessing the financial benefits derived from the realization of ecosystem products. Panel A of Table 7 shows urban tourism income (PESS) on AEQ, while Panel B highlights urban tourist arrivals (PESS) on AEQ. The results consistently show that improved PESS, indicated by tourism metrics, significantly reduces atmospheric pollutant emissions and enhances urban air quality. This empirical test further reinforces the baseline findings.

4.2.2.3. Omitted variables at different hierarchical levels. Additional regressions, incorporating various fixed effects controls, were conducted to assess the potential impact of omitted variables on the model's estimation results. Table 8 presents results confirming that, even with potential omitted variables at the provincial and urban cluster levels, improvements in PESS significantly reduce atmospheric pollutant emissions. These findings highlight the PESS's effectiveness in reducing atmospheric pollutants and improving air quality.

4.2.2.4. The PESS and other air pollutants. Table 9 reports robustness checks of the PESS effect on additional air pollutants, including nitrogen dioxide (NO₂), carbon monoxide (CO), particulate matter (PM₁₀), and ozone (O₃). Columns (1), (3), (5), and (7) use pollutant concentrations as the dependent variables, while Columns (2), (4), (6), and (8) use their natural logarithms. The results indicate that PESS significantly reduces NO₂, CO, and PM₁₀, but has no significant effect on O₃. This is because PESS lowers primary pollutant emissions through industrial structure optimization and emission controls, whereas O₃, as a secondary pollutant, is formed through complex processes influenced by multiple environmental factors, so its concentration may remain unchanged even when precursor emissions decrease.

4.2.2.5. Excluding the 2020 pandemic. In 2020, the COVID-19 pandemic sharply reduced economic activity and temporarily lowered air pollution by restricting traffic and industrial operations. Although the model controls for time fixed effects—capturing shocks that vary over time but are common across regions—the pandemic may still have introduced heterogeneous impacts. To address this concern, data from 2020 were excluded. The results in Table 10 show that PESS continues to significantly reduce air pollutants, further confirming the robustness of the findings.

4.2.2.6. Excluding China's air pollution action plan: period-specific regression. Regressions were restricted to 2000–2013, before the plan's implementation, to address potential bias from China's air pollution action plan. By 2017, the plan had set differentiated regional targets: Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Pearl River Delta were required to reduce PM_{2.5} concentrations by 25%, 20%, and 15% relative to 2012 levels, while other cities were required to cut PM₁₀ by more than 10%. Restricting the sample to the pre-policy period removes

Table 4
The development of PESS and AEQ.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	<i>lnCO₂</i>	<i>PCO₂</i>	<i>DCO₂</i>	<i>lnSO₂</i>	<i>PSO₂</i>	<i>DSO₂</i>	<i>lnPM</i>	<i>PM</i>
<i>PES</i>	-0.599*** (0.229)	-1.563*** (0.263)	-0.524** (0.242)	-2.657*** (0.740)	-3.825*** (0.866)	-2.523*** (0.757)	-0.391*** (0.088)	-13.538*** (4.945)
<i>lnGDP</i>	0.258*** (0.036)	0.108*** (0.041)	0.200*** (0.042)	0.310*** (0.114)	0.191* (0.113)	0.256** (0.118)	-0.070*** (0.017)	-1.862** (0.890)
<i>Tech</i>	-1.086*** (0.349)	-2.063*** (0.566)	-2.209*** (0.654)	-4.513** (1.824)	-6.504*** (1.682)	-5.574*** (1.820)	-0.776*** (0.201)	-42.916*** (9.909)
<i>Finance</i>	0.068*** (0.024)	0.067** (0.027)	0.066*** (0.024)	0.116** (0.053)	0.084* (0.050)	0.107** (0.053)	-0.004 (0.006)	0.011 (0.367)
<i>Urban</i>	0.004*** (0.001)	0.008*** (0.002)	0.007*** (0.002)	0.003 (0.004)	0.007* (0.004)	0.006 (0.004)	-0.001 (0.001)	-0.062* (0.032)
<i>Open</i>	-0.583** (0.274)	-0.083 (0.359)	-0.805** (0.377)	-0.910 (1.478)	-0.708 (1.445)	-1.134 (1.496)	0.244* (0.141)	-8.968 (6.032)
<i>KL</i>	0.058*** (0.017)	0.030 (0.020)	0.042* (0.022)	-0.019 (0.062)	-0.057 (0.067)	-0.031 (0.063)	-0.001 (0.008)	-0.300 (0.444)
<i>lnROAD</i>	0.039** (0.016)	0.005 (0.036)	-0.044 (0.045)	-0.002 (0.082)	-0.050 (0.089)	-0.091 (0.090)	0.031* (0.018)	1.366* (0.739)
<i>lnHC</i>	1.772 (1.318)	2.975* (1.618)	2.549 (1.594)	11.012 (8.979)	12.509 (10.049)	11.226 (9.016)	-1.589** (0.702)	-19.552 (27.906)
Constant	-4.318 (3.684)	-12.328*** (4.432)	-5.560 (4.404)	-22.565 (25.019)	-31.421 (27.987)	-22.172 (25.124)	8.402*** (1.961)	104.113 (78.537)
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	4342	3949	4314	4621	4207	4592	4621	4621
<i>adj.R²</i>	0.98	0.94	0.98	0.84	0.84	0.87	0.95	0.94

Note: Unless noted otherwise, all following tables and figures include controls for economic development, technology, trade openness, finance, urbanization, capital intensity, infrastructure, and human capital. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

Table 5
Results of two-stage least squares method.

	<i>lnCO₂</i>		<i>PCO₂</i>		<i>DCO₂</i>		<i>lnSO₂</i>	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	<i>Lewbel internal IV</i>	<i>Lewbel internal & external IV</i>	<i>Lewbel internal IV</i>	<i>Lewbel internal & external IV</i>	<i>Lewbel internal IV</i>	<i>Lewbel internal & external IV</i>	<i>Lewbel internal IV</i>	<i>Lewbel internal & external IV</i>
<i>PES</i>	-0.551 (0.385)	-0.674* (0.379)	-1.189*** (0.410)	-1.278*** (0.409)	-0.262 (0.423)	-0.374 (0.419)	-2.246** (0.957)	-2.599*** (0.995)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>F-statistics</i>	99.57	72.68	76.67	57.14	95.95	71.08	176.82	132.65
<i>Hansen J test</i>	0.3400	0.0169	0.5696	0.0768	0.1742	0.0035	0.4768	0.0012
<i>Pagan Hall test</i>	402.3	395.9	404.2	400.2	423.5	419.5	1131.6	1106.8
<i>Bresuch Pagan test</i>	45154.3	47005.0	16875.7	16947.4	30747.2	31201.3	6427.4	6278.7
<i>Endogeneity test</i>	0.622	0.517	0.172	0.256	0.363	0.714	0.576	0.429
<i>N</i>	4342	4252	3953	3870	4314	4240	4621	4525
<i>adj.R²</i>	0.85	0.85	0.67	0.66	0.79	0.79	0.64	0.64
	<i>PSO₂</i>		<i>DSO₂</i>		<i>lnPM</i>		<i>PM</i>	
	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	<i>Lewbel internal IV</i>	<i>Lewbel internal & external IV</i>	<i>Lewbel internal IV</i>	<i>Lewbel internal & external IV</i>	<i>Lewbel internal IV</i>	<i>Lewbel internal & external IV</i>	<i>Lewbel internal IV</i>	<i>Lewbel internal & external IV</i>
<i>PES</i>	-3.529*** (1.019)	-3.835*** (1.060)	-1.933** (0.967)	-2.243** (0.991)	-0.280** (0.112)	-0.300*** (0.113)	-8.011 (6.502)	-11.124 (6.876)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>F-statistics</i>	157.51	119.93	171.99	129.76	176.82	132.65	176.82	132.65
<i>Hansen J test</i>	0.5010	0.0051	0.3726	0.0010	0.1225	0.0008	0.0256	0.0000
<i>Pagan Hall test</i>	1030.3	1005.4	1114.4	1093.6	845.0	812.0	1191.2	1170.5
<i>Bresuch Pagan test</i>	5762.9	5608.2	6320.8	6183.3	1963.9	1916.2	2481.8	2407.4
<i>Endogeneity test</i>	0.635	0.700	0.361	0.678	0.173	0.633	0.204	0.636
<i>N</i>	4207	4118	4592	4513	4621	4525	4621	4525
<i>adj.R²</i>	0.64	0.64	0.64	0.64	0.78	0.78	0.70	0.70

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

Table 6
PESS and AEQ: alternative air quality measurement methods.

	(1)	(2)	(3)	(4)
	<i>AQI</i>	<i>lnAQI</i>	<i>AirGood</i>	<i>lnAirGood</i>
<i>PES</i>	-0.125* (0.068)	-0.150* (0.085)	0.093 (0.057)	0.158* (0.084)
<i>Controls</i>	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes
<i>N</i>	1607	1607	1593	1593
<i>adj.R²</i>	0.91	0.94	0.91	0.88

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

potential policy effects. The results show that PESS significantly reduces CO₂ and SO₂ emissions as well as PM_{2.5} concentrations, further

Table 7
PESS and AEQ: changing the measurement for PESS.

Panel A: Regional tourism revenue								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	<i>lnCO₂</i>	<i>PCO₂</i>	<i>DCO₂</i>	<i>lnSO₂</i>	<i>PSO₂</i>	<i>DSO₂</i>	<i>lnPM</i>	<i>PM</i>
<i>Income</i>	-0.077*** (0.025)	-0.076*** (0.028)	-0.074*** (0.025)	-0.387*** (0.074)	-0.367*** (0.078)	-0.384*** (0.074)	-0.019** (0.009)	-0.994** (0.485)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	3763	3392	3743	3825	3441	3805	3825	3825
<i>adj.R²</i>	0.98	0.94	0.98	0.86	0.85	0.89	0.95	0.94
Panel B: Regional tourist numbers								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	<i>lnCO₂</i>	<i>PCO₂</i>	<i>DCO₂</i>	<i>lnSO₂</i>	<i>PSO₂</i>	<i>DSO₂</i>	<i>lnPM</i>	<i>PM</i>
<i>Tourists</i>	-0.050 (0.034)	-0.070* (0.038)	-0.058 (0.035)	-0.486*** (0.151)	-0.373** (0.152)	-0.486*** (0.154)	-0.040** (0.020)	-2.857** (1.135)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	3481	3156	3461	3611	3273	3591	3611	3611
<i>adj.R²</i>	0.98	0.94	0.99	0.86	0.85	0.89	0.96	0.95

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

Table 8
PESS and AEQ: different levels of omitted variables.

Panel A: Provincial level omission variables								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	<i>lnCO₂</i>	<i>PCO₂</i>	<i>DCO₂</i>	<i>lnSO₂</i>	<i>PSO₂</i>	<i>DSO₂</i>	<i>lnPM</i>	<i>PM</i>
<i>PES</i>	-0.341 (0.404)	-1.798* (0.998)	-0.228 (0.529)	-3.579 (2.443)	-4.848 (3.142)	-3.525 (2.587)	-0.317** (0.159)	-2.908 (7.719)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Prov-Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	4263	3870	4235	4538	4124	4509	4538	4538
<i>adj.R²</i>	0.99	0.97	0.99	0.87	0.88	0.89	0.98	0.98
Panel B: Urban cluster level missing variables								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	<i>lnCO₂</i>	<i>PCO₂</i>	<i>DCO₂</i>	<i>lnSO₂</i>	<i>PSO₂</i>	<i>DSO₂</i>	<i>lnPM</i>	<i>PM</i>
<i>PES</i>	-0.763** (0.344)	-1.626*** (0.427)	-0.539 (0.361)	-4.303*** (1.059)	-5.251*** (1.227)	-4.139*** (1.087)	-0.346*** (0.090)	-4.176 (5.919)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Metro-Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	2951	2764	2939	3142	2943	3130	3142	3142
<i>adj.R²</i>	0.99	0.95	0.98	0.84	0.85	0.86	0.98	0.97

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

confirming the robustness of the findings (see Table 11).

4.2.2.7. *Controlling for China's air pollution action plan.* Secondly, this policy was incorporated as a control variable in the regression model to address further the potential confounding effect of China's air pollution action plan. Since the policy ended in 2017, the sample period is limited to years before that date. A dummy variable for the policy implementation period and its interaction with policy intensity is included to isolate its impact on air quality. As shown in Table 12, controlling for this policy leaves the coefficient of PESS significantly negative, suggesting that its effectiveness in reducing air pollutant emissions holds after isolating the policy's effect.

4.2.2.8. *Combined policy and event effects.* To further ensure the robustness of the estimation, the model simultaneously incorporates several major policies and events that may affect air quality, namely the

Table 9
PESS and other air pollutants.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	NO_2	$\ln NO_2$	CO	$\ln CO$	PM_{10}	$\ln PM_{10}$	O_3	$\ln O_3$
<i>PES</i>	-15.848*** (2.982)	-0.544*** (0.110)	-0.338** (0.144)	-0.350*** (0.119)	-29.614*** (9.091)	-0.355*** (0.073)	2.457 (8.532)	0.025 (0.091)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	3547	3547	2168	2168	4621	4621	4621	4621
<i>adj.R²</i>	0.96	0.96	0.85	0.89	0.97	0.98	0.79	0.80

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

Table 10
PESS and AEQ: excluding 2020 pandemic.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	$\ln CO_2$	PCO_2	DCO_2	$\ln SO_2$	PSO_2	DSO_2	$\ln PM$	PM
<i>PES</i>	-0.599*** (0.229)	-1.563*** (0.263)	-0.524** (0.242)	-2.231** (0.893)	-3.659*** (1.027)	-2.182** (0.898)	-0.324*** (0.089)	-11.291** (4.979)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	4342	3949	4314	4347	3954	4319	4347	4347
<i>adj.R²</i>	0.98	0.94	0.98	0.83	0.83	0.87	0.95	0.94

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

Table 11
Excluding China's air pollution action plan: period-specific regression.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	$\ln CO_2$	PCO_2	DCO_2	$\ln SO_2$	PSO_2	DSO_2	$\ln PM$	PM
<i>PES</i>	-0.401 (0.292)	-2.627*** (0.628)	-0.949* (0.492)	-0.494 (1.863)	-1.848 (1.857)	-0.934 (1.819)	-0.851** (0.402)	-33.034** (14.865)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	2731	2505	2711	2731	2505	2711	2731	2731
<i>adj.R²</i>	0.99	0.95	0.99	0.85	0.84	0.90	0.96	0.96

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

Table 12
PESS and AEQ: Controlling for China's air pollution action plan.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	$\ln CO_2$	PCO_2	DCO_2	$\ln SO_2$	PSO_2	DSO_2	$\ln PM$	PM
<i>PES</i>	-0.415* (0.224)	-1.850*** (0.307)	-0.422* (0.241)	-1.986* (1.185)	-3.940*** (1.399)	-2.001* (1.184)	-0.350*** (0.120)	-17.283*** (5.554)
<i>Airplan</i>	-0.369** (0.159)	-0.388** (0.193)	-0.671*** (0.238)	-0.515 (0.632)	-0.352 (0.640)	-0.800 (0.643)	0.322*** (0.087)	16.545*** (3.928)
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	3823	3488	3797	3823	3488	3797	3823	3823
<i>adj.R²</i>	0.99	0.95	0.99	0.83	0.82	0.87	0.95	0.95

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

COVID-19 pandemic, China's air pollution action plan, and the central environmental protection inspection. In addition to the two shocks and policy effects mentioned above, the central environmental protection inspection enhanced local environmental enforcement through its supervision and accountability mechanisms. After controlling for these factors, the regression results show in Table 13 that the PESS coefficient remains significantly negative, suggesting that its effect on reducing air pollutant emissions persists even when potential confounding influences are removed.

4.2.2.9. Quantile regression results. Quantile regression is employed to examine whether the impact of PESS varies across cities with different pollution levels, thereby providing insight into its heterogeneous effects in low-, median-, and high-pollution contexts. Regressions were estimated at every 2.5th percentile of the dependent variable. As shown in Fig. A–H (Fig. 6), the PESS coefficient is significantly negative across all quantiles, indicating that PESS consistently reduces pollutant emissions. These results align with the baseline findings, further confirming the robustness of the main conclusions.

Table 13
Combined policy and event effects.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	$\ln\text{CO}_2$	PCO_2	DCO_2	$\ln\text{SO}_2$	PSO_2	DSO_2	$\ln\text{PM}$	PM
<i>PES</i>	-0.394* (0.229)	-1.902*** (0.306)	-0.401 (0.245)	-2.113* (1.190)	-4.147*** (1.387)	-2.127* (1.189)	-0.334*** (0.122)	-16.909*** (5.724)
<i>Airplan</i>	-0.383** (0.158)	-0.355* (0.193)	-0.685*** (0.236)	-0.432 (0.640)	-0.218 (0.648)	-0.717 (0.651)	0.312*** (0.088)	16.300*** (3.953)
<i>CEI</i>	0.020 (0.015)	-0.042** (0.018)	0.020 (0.017)	-0.116 (0.085)	-0.170* (0.089)	-0.116 (0.086)	0.015 (0.011)	0.345 (0.707)
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	3823	3488	3797	3823	3488	3797	3823	3823
<i>adj.R²</i>	0.99	0.95	0.99	0.83	0.82	0.87	0.95	0.95

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

4.3. Mechanism analysis

Previous empirical findings in this study have demonstrated that the PESS reduces atmospheric pollutant emissions and improves AEQ. To elucidate the causal mechanisms governing the impact of PESS on the city's air quality, this section delves into its influence from the perspectives of green innovation, industrial structure, and enterprise market entry.

4.3.1. Green innovation

PESS enhances air quality by promoting green innovation and a cleaner energy transition. PESS encourages industries to invest in R&D, adopt low-carbon technologies, reduce pollutant emissions, and improve air quality. This study employs the following econometric model to analyze the green innovation mechanism:

$$GP_{it} = \beta_0 + \beta_1 PES_{it} + \beta_2 \sum Z_{it} + \mu_i + \tau_t + \epsilon_{it}$$

This study demonstrates the green innovation effect of the PESS regarding green patent applications and authorizations, highlighting both potential and actual patent output (Howell, 2017). Table 14 presents the regression results for the causal mechanism of PESS on green innovation. The findings show that PESS growth significantly enhances the authorization and application of green invention and utility model patents, all at a significance level of at least 5%. The regression results support that PESS promotes green innovation, which in turn contributes to air pollution control. Therefore, PESS enhancement may reduce air pollutants, improve air quality, and preliminarily validate Hypothesis 2.

4.3.2. Industrial structure

The PESS can mitigate pollution emissions and improve air quality by promoting industrial restructuring. As the PESS expands, it constrains the growth of high-pollution industries in urban areas, encouraging a transition toward eco-friendly sectors, sustainable agriculture, and ecotourism. This facilitates the transformation of the urban economic structure. In this investigation, we formulate the subsequent econometric models for analysis:

$$IND_{it} = \beta_0 + \beta_1 PES_{it} + \beta_2 \sum Z_{it} + \mu_i + \tau_t + \epsilon_{it}$$

This research uses the industry structure rationalization index (*Ration*) and industrial intensity as indicators of industrial structure transformation (Zhao et al., 2020). Industrial intensity is quantified as two indicators: the ratio of the number of large-scale industrial enterprises (*Indfirm*) and the total industrial output value (*Ind*) to the regional gross domestic product (*GDP*). Table 15 reports the results of the industrial structure mechanism analysis. Column (1) shows PESS's effect on industrial rationalization, and Columns (2) and (3) detail its impact on industrial intensity. The results demonstrate that the expansion of PESS significantly reduces industrial intensity, promotes the rationalization of the industrial structure, mitigates air pollutant emissions,

and enhances regional air quality (Hypothesis 3).

4.3.3. Firm entry behavior

4.3.3.1. Firm entry: polluting and green firms. In theory, the development of PESS can reduce atmospheric pollutant emissions by influencing firms' market entry decisions. This reduction primarily results from an increased entry of environmentally friendly firms and a decline in the entry of polluting firms, thereby improving air quality. In areas where PESS is more effective, barriers to entry for polluting businesses increase, limiting their market access. Conversely, the entry threshold for eco-friendly enterprises is lower, fostering the rapid growth of the green economy and reducing atmospheric pollutant emissions (Hall et al., 2010). This study formulates the following econometric models:

$$Entry_{it} = \beta_0 + \beta_1 PES_{it} + \beta_2 \sum Z_{it} + \mu_i + \tau_t + \epsilon_{it}$$

This study uses the natural logarithm of newly registered mining and manufacturing enterprises, as well as their proportion relative to all new enterprises, as indicators of polluting enterprises entering the market. Similarly, the natural logarithm and proportion of enterprises entering relevant service industries serve as indicators of green enterprise market entry. Table 16 shows the results of the enterprise market entry mechanism. The regression results show that PESS significantly reduces both the number and proportion of polluting enterprises entering the market, while simultaneously increasing the number and proportion of green enterprises. The results highlight that PESS mitigates the emissions of atmospheric environmental pollutants by influencing enterprises' market entry behavior, thereby enhancing AEQ (Hypothesis 4).

4.3.3.2. Firm entry: industry heterogeneity. To better capture sector-specific dynamics in enterprise responses to PESS, Fig. 7 presents regression coefficients indicating that PESS has heterogeneous effects on firm entry across industries. Industries related to ecological protection, green technology, and environmental services, such as *information technology; health care and social work; culture, sports, and entertainment; wholesale and retail trade; and finance*, show significant positive effects, indicating that PESS preferentially supports sectors aligned with ecological sustainability and green development goals. In contrast, several high-pollution industries, including *transport, storage and postal services; manufacturing; agriculture; and utilities*, exhibit significant negative coefficients, indicating that PESS heightens entry barriers in these sectors, thereby discouraging new enterprise formation. For industries less directly connected to ecosystem services, such as *real estate; resident, repair, and other services; and education*, the estimated coefficients are close to zero and statistically insignificant, suggesting that PESS exerts little to no influence on enterprise entry in these sectors.

4.3.3.3. Existing firms: industry heterogeneity. Building on the firm entry analysis, this section examines whether the effects of PESS extend to

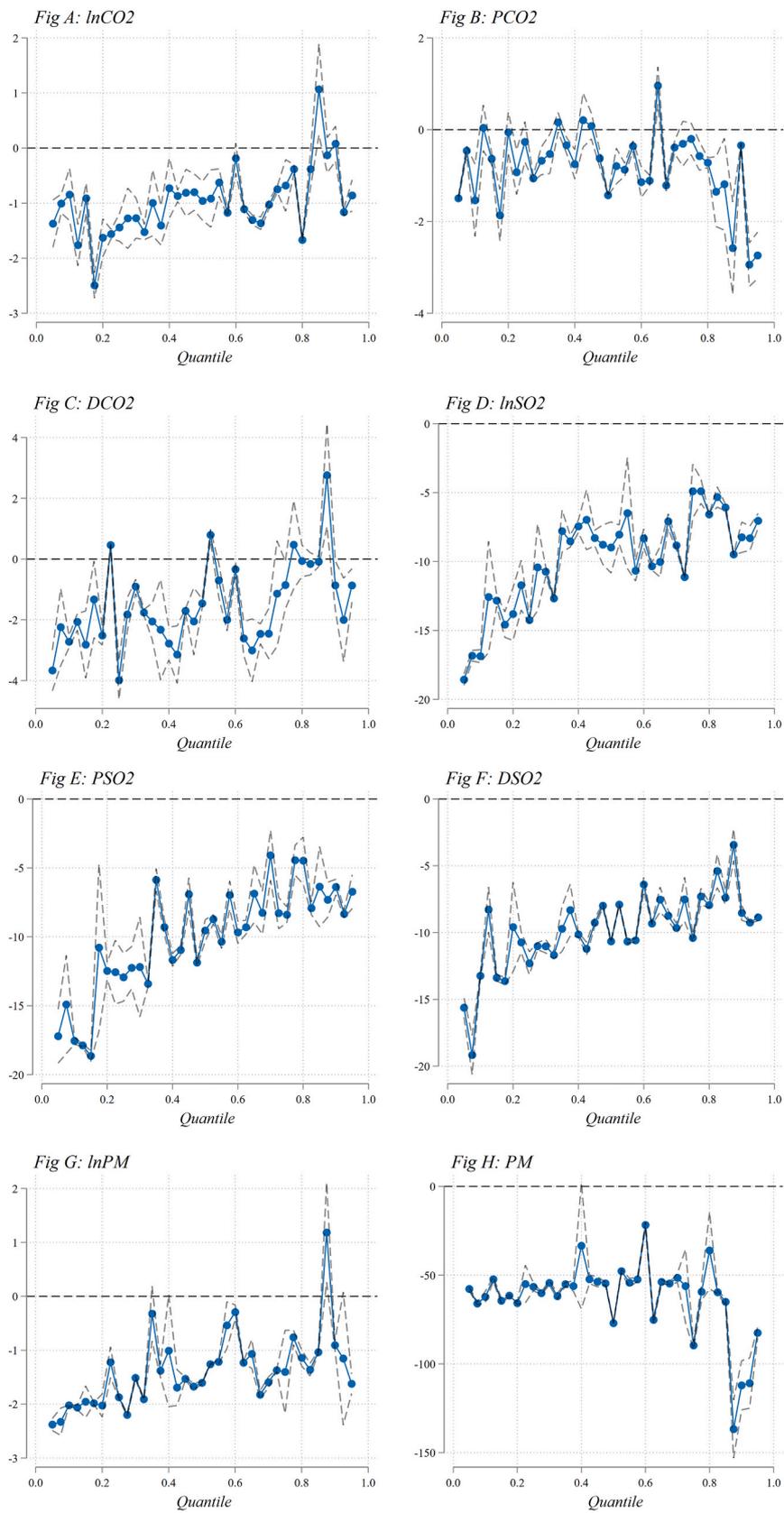


Fig. 6. Quantile regression results.

Note: 95% confidence intervals are shown in the figure. Unless noted otherwise, all following tables and figures include controls for economic development, technology, trade openness, finance, urbanization, capital intensity, infrastructure, human capital, and the central environmental inspection.

Table 14
PESS, green innovation, and AEQ.

	(1)	(2)	(3)	(4)
	<i>lnPgrant</i>	<i>lnApply</i>	<i>lnUgrant</i>	<i>lnUapply</i>
<i>PES</i>	1.505** (0.716)	1.127** (0.559)	2.286*** (0.461)	1.604*** (0.458)
Controls	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
<i>N</i>	4518	4574	4518	4574
<i>adj.R</i> ²	0.91	0.93	0.94	0.94

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

Table 15
PESS, industrial structural transformation, and AEQ.

	(1)	(2)	(3)
	<i>Ration</i>	<i>Ind</i>	<i>Indfirm</i>
<i>PES</i>	0.269** (0.129)	-1.052* (0.603)	-1.386*** (0.497)
Controls	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
<i>N</i>	4054	3820	4607
<i>adj.R</i> ²	0.82	0.71	0.80

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

Table 16
PESS, polluting and green firm entry, and AEQ.

	(1)	(2)	(3)	(4)
	<i>PER</i>	<i>GER</i>	<i>lnPE</i>	<i>lnGE</i>
<i>PES</i>	-0.146*** (0.039)	0.079** (0.032)	-0.585 (0.579)	1.035** (0.471)
Controls	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
<i>N</i>	4621	4621	4621	4621
<i>adj.R</i> ²	0.82	0.76	0.91	0.92

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

incumbent enterprises by assessing its impact on the number of existing firms across industries. Results presented in Fig. 8 indicate substantial heterogeneity that aligns closely with the entry patterns: PESS promotes the survival and growth of green enterprises, limits the presence of firms in high-pollution sectors, and has minimal influence on industries less connected to ecosystem services. The consistency of these outcomes provides additional evidence for the robustness of the firm dynamics mechanism.

4.3.3.4. Firm entry scale. Because firm dynamics analyses that focus solely on the number of entrants may neglect differences in environmental impact associated with firm size, potentially underestimating or overestimating the actual effect of PESS, this study also examines its influence on market entry scale. Matched data from the Enterprise Registration Data of mainland China and the China Industrial Enterprise Database are used, covering 2000–2014 firm entry scale indicators such as *industrial output value*, *industrial sales value*, *assets*, *number of employees*, and *paid-in capital*. Fig. 9 shows that PESS significantly reduces the entry number and scale of *manufacturing* and *utilities* (specifically, enterprises engaged in producing and supplying of electricity, heat, gas, and water), thereby reinforcing the robustness of the findings.

4.3.4. Contribution decomposition of mechanisms

The preceding empirical analysis provides an initial exploration of the mechanisms through which the PESS affects AEQ. The analysis quantitatively assesses the contributions of various mechanisms by constructing econometric models, effectively mitigating estimation bias arising from the interaction between different influencing mechanisms. The methodology proposed by Heckman et al. (2013) and Gelbach (2016) is employed to achieve this objective. In addition to the two-stage regressions, all variables related to the mechanisms are introduced as new explanatory variables, alongside the core variable, in the regression equation. The regression equations are structured as follows:

$$EP_{it} = \alpha + \beta PES_{it} + \phi X_{it} + \mu_i + \tau_t + \epsilon_{it}$$

$$M_{it} = \alpha + \delta PES_{it} + \phi X_{it} + \mu_i + \tau_t + \epsilon_{it}$$

$$EP_{it} = \alpha + \gamma PES_{it} + \sum \kappa M_{it} + \phi X_{it} + \mu_i + \tau_t + \epsilon_{it}$$

In the formula, M_{it} represents the value of mechanism variable j for city i in year t . It's important to note that the control variables are consistent with those used in the baseline regression. The results of the mechanism tests are presented in Table 17. The results show that the PES coefficients and significance levels have declined, providing evidence of the reliability of the selected mechanisms.

Gelbach (2016) demonstrated that $\beta = \gamma + \sum \kappa \delta$, where the portion explained by an individual mechanism j is $\kappa \delta$, and the unexplained portion after considering all mechanisms is γ . The weight of explanation by a single mechanism is given by $\kappa \delta / \beta$. The mechanism decomposition results are displayed in Table 18, and the mechanism decomposition graph is presented in Fig. 10. The findings highlight the substantial roles played by the mechanisms of green innovation, industrial structure, and corporate market entry behavior in quantifying improvements in AEQ. Notably, industrial structure exhibits the highest explanatory power, with an average contribution of 11.5%. Subsequently, green innovation follows with an average contribution of 4% and corporate market entry behavior with an average contribution of 9.9%. All mechanisms combined account for an average of 13.7%, highlighting the chosen mechanisms' reasonable reliability and explanatory capacity.

4.4. Further analysis

4.4.1. Differences in attributes of PESS

This study further explores the impact of heterogeneity in PESS attributes on air quality. Previous sections demonstrate that PESS decreases air pollutants and enhances air quality. However, it remained unclear which specific types of PESS—profitable, quasi-public, or public—exert the most significant influence. To this end, the study further investigates how different trading attributes of PESS contribute to improvements in air quality. The results presented in Table 19 columns (1)–(8), provide robust evidence that profitable PESS schemes significantly reduce air pollutant emissions and improve air quality. Moreover, the regression results in columns (9)–(15) highlight the significant role of quasi-public PESS enhancement in controlling atmospheric pollution. Finally, the regression results in columns (16)–(24) show that strengthening public PESS also contributes to reducing air pollutant emissions. These findings underscore the significant contributions of various PESS types to both generating economic value from natural resources and reducing atmospheric pollution.

4.4.2. Location heterogeneity

4.4.2.1. Eastern, central, and western heterogeneity. This study conducts a thorough examination of regional disparities in air quality improvements driven by the PESS across China's eastern, central, and western regions. Given the substantial variations in natural and socio-economic

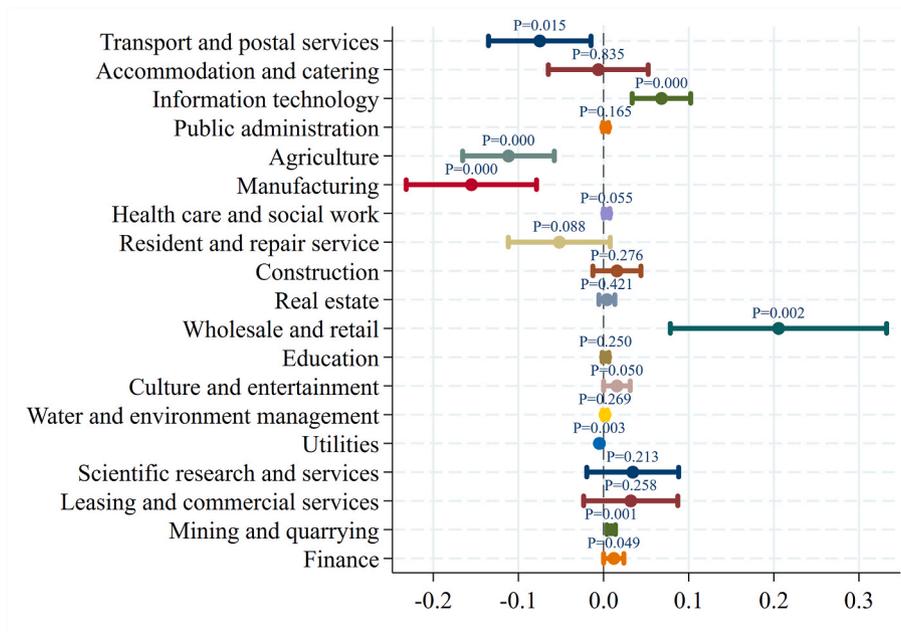


Fig. 7. PESS and firm entry: different industries.
Note: 95% confidence intervals are shown in the figure.

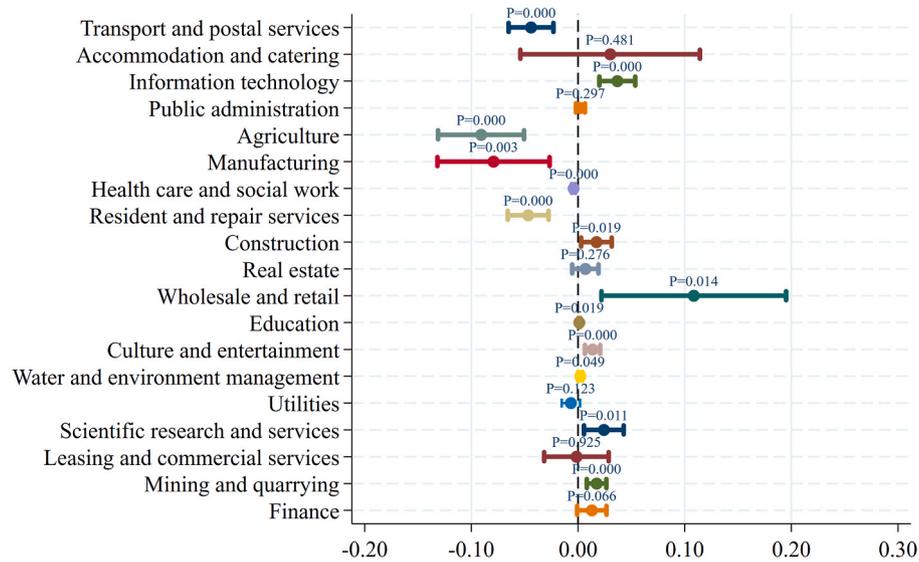


Fig. 8. PESS and existing enterprises: different industries.
Note: 95% confidence intervals are shown in the figure.

conditions across these regions, the impact of PESS on air quality improvement varies accordingly. Table 20 presents the results of segmented regressions on the impact of PESS on air quality in China's eastern, central, and western regions. The regression findings in Panels A and B highlight that PESS significantly diminishes air pollutant emissions in eastern and central China. Conversely, the results in Panel C suggest that the effect of PESS on air quality improvement in western China is comparatively less pronounced. The primary factor contributing to this contrast is the entrenched path dependence of economic development in western China, which relies either heavily on green resources or predominantly on energy extraction. Consequently, the enhancement of PESS remains relatively limited, leading to a less significant impact on emissions reduction and air quality improvement.

4.4.2.2. *Path-dependent constraints in western China.* The underlying reasons for the weaker effects of PESS in the western region are examined by dividing the area into high and low green resource-dependent zones, based on city-level Normalized Difference Vegetation Index (NDVI) split at the median. The regression coefficients shown in Fig. 11 indicate that PESS significantly reduces air pollutant emissions in high green resource-dependent areas. In contrast, the impact is less pronounced in low green resource-dependent regions. This heterogeneity reflects that high-dependence areas perform critical ecological functions and have higher ecosystem service values, allowing PESS investments to strengthen environmental governance more effectively. Moreover, local governments and regulatory agencies in green resource-dependent areas tend to prioritize ecological protection, ensuring more thorough implementation and supervision of PESS projects. In contrast, low-

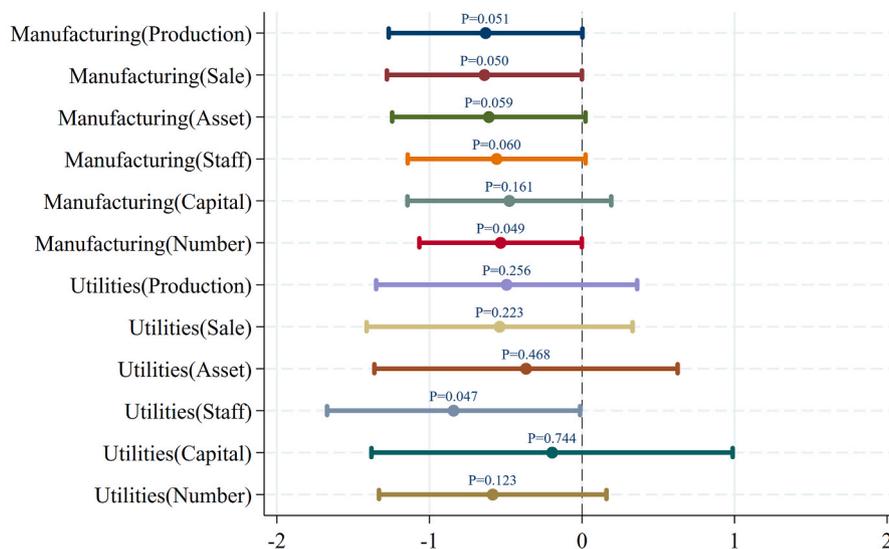


Fig. 9. PESS and enterprise entry scale: different industries.
Note: 95% confidence intervals are shown in the figure.

Table 17
 Regression of mechanism decomposition.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	<i>lnCO₂</i>	<i>PCO₂</i>	<i>DCO₂</i>	<i>lnSO₂</i>	<i>PSO₂</i>	<i>DSO₂</i>	<i>lnPM</i>	<i>PM</i>
<i>PES</i>	-1.022*** (0.335)	-1.819*** (0.390)	-1.104*** (0.339)	-4.071*** (1.319)	-5.015*** (1.415)	-4.227*** (1.316)	-0.306*** (0.112)	-14.762** (6.942)
<i>lnPgrant</i>	-0.005 (0.004)	-0.008 (0.007)	-0.009* (0.005)	-0.043** (0.019)	-0.041** (0.020)	-0.046** (0.019)	-0.009*** (0.003)	-0.362*** (0.113)
<i>lnUgrant</i>	0.007 (0.007)	-0.002 (0.008)	0.001 (0.008)	0.039 (0.028)	0.038 (0.029)	0.037 (0.028)	-0.014*** (0.003)	-0.393*** (0.145)
<i>Ind</i>	-0.009 (0.007)	0.001 (0.009)	-0.007 (0.008)	0.051 (0.042)	0.068 (0.050)	0.053 (0.043)	-0.007** (0.003)	-0.227* (0.137)
<i>Indfirm</i>	0.052*** (0.012)	0.039** (0.016)	0.053*** (0.015)	0.099 (0.061)	0.066 (0.066)	0.098 (0.061)	0.035*** (0.007)	1.496*** (0.287)
<i>GER</i>	0.390 (0.270)	-0.018 (0.307)	0.558** (0.274)	0.625 (0.473)	0.291 (0.484)	0.755 (0.472)	-0.026 (0.065)	-0.603 (3.049)
<i>PER</i>	-0.284 (0.334)	-0.389 (0.377)	-0.301 (0.338)	0.056 (0.610)	-0.070 (0.664)	0.071 (0.607)	-0.202*** (0.075)	-5.109 (3.362)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	3668	3385	3649	3720	3437	3701	3720	3720
<i>adj.R²</i>	0.98	0.95	0.99	0.84	0.84	0.88	0.95	0.95

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

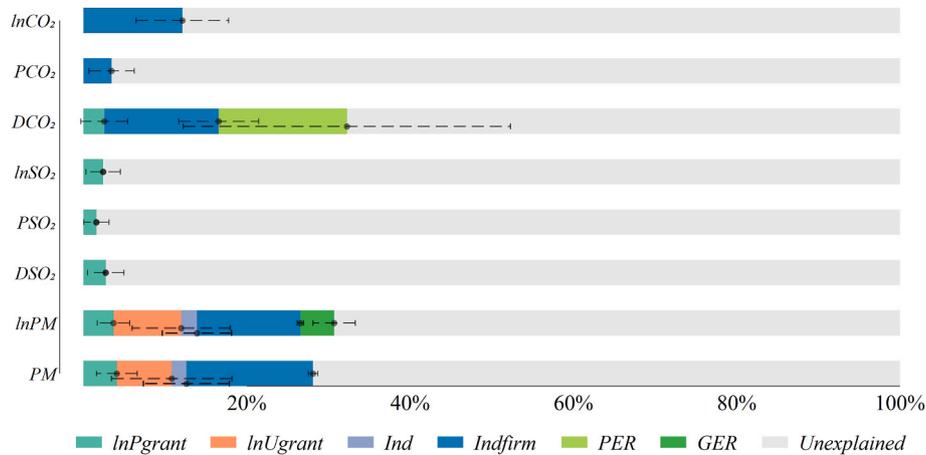
Table 18
 Quantification of explanatory proportions from various causal mechanisms.

Dependent variables	<i>Ind</i>	<i>Indfirm</i>	<i>GER</i>	<i>lnPgrant</i>	<i>lnUgrant</i>	<i>PER</i>	Total contribution (%)
<i>lnCO₂</i> (%)	-	12.11	-	-	-	-	12.11
<i>PCO₂</i> (%)	-	3.44	-	-	-	-	3.44
<i>DCO₂</i> (%)	-	14.01	-	2.54	-	15.71	32.26
<i>lnSO₂</i> (%)	-	-	-	2.41	-	-	2.41
<i>PSO₂</i> (%)	-	-	-	1.58	-	-	1.58
<i>DSO₂</i> (%)	-	-	-	2.72	-	-	2.72
<i>lnPM</i> (%)	-	12.68	4.13	3.68	8.28	-	28.76
<i>PM</i> (%)	-	15.52	-	4.08	6.73	-	26.33

dependence regions are dominated by other industries, demonstrating path dependence and industrial structure lock-in, which limits the effectiveness of PESS.

4.4.2.3. Quantile regression results in western China. This study employs quantile regression to examine emission-reduction differences across

pollution levels in western regions, confirming the weaker effects' robustness and elucidating their underlying sources. Grouping by pollution levels complements the earlier classification by vegetation dependence, and together the two approaches provide a more precise explanation of the weak effects observed in western regions. The results in Fig. A–H of Fig. 12 show that for some pollutants (CO₂ and SO₂), PESS



Note: The figure shows 95% confidence intervals for the contribution of each mechanism.

Fig. 10. Quantitative decomposition of different causal mechanisms.

Table 19
PES and AEQ: variations in PESS attributes.

Panel A: Profitable (tradable) PESS								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	<i>lnCO₂</i>	<i>PCO₂</i>	<i>DCO₂</i>	<i>lnSO₂</i>	<i>PSO₂</i>	<i>DSO₂</i>	<i>lnPM</i>	<i>PM</i>
<i>PES</i>	-0.509** (0.230)	-0.210 (0.265)	-0.419* (0.240)	-0.970 (0.763)	-0.699 (0.832)	-0.880 (0.771)	-0.195** (0.076)	-4.655 (5.026)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	4342	3949	4314	4621	4207	4592	4621	4621
<i>adj.R²</i>	0.98	0.94	0.98	0.84	0.83	0.87	0.95	0.94
Panel B: Quasi-public PESS								
	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	<i>lnCO₂</i>	<i>PCO₂</i>	<i>DCO₂</i>	<i>lnSO₂</i>	<i>PSO₂</i>	<i>DSO₂</i>	<i>lnPM</i>	<i>PM</i>
<i>PES</i>	-0.150 (0.151)	-0.966*** (0.167)	-0.013 (0.166)	-1.901*** (0.495)	-3.016*** (0.561)	-1.774*** (0.507)	-0.277*** (0.059)	-10.838*** (3.115)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	4342	3949	4314	4621	4207	4592	4621	4621
<i>adj.R²</i>	0.98	0.94	0.98	0.84	0.84	0.87	0.95	0.94
Panel C: Public PESS								
	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
	<i>lnCO₂</i>	<i>PCO₂</i>	<i>DCO₂</i>	<i>lnSO₂</i>	<i>PSO₂</i>	<i>DSO₂</i>	<i>lnPM</i>	<i>PM</i>
<i>PES</i>	-0.139*** (0.043)	-0.087 (0.063)	-0.268*** (0.067)	0.483** (0.211)	0.475** (0.209)	0.387* (0.218)	0.099*** (0.024)	4.450*** (1.166)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	4342	3949	4314	4621	4207	4592	4621	4621
<i>adj.R²</i>	0.98	0.94	0.98	0.84	0.83	0.87	0.95	0.94

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

reduces emissions in low-pollution areas but increases them in high-pollution areas, suggesting that the observed net increases predominantly originate from high-pollution regions. For other pollutants, such as $PM_{2.5}$, the effects show heterogeneity across pollution levels but are generally positive overall. Collectively, these analyses confirm the path dependence of development in western China. In high green-dependence areas, the established green industrial structure and ecological protection institutions enable PESS to reinforce environmental constraints, thereby narrowing the space for emissions. In high-pollution areas, entrenched heavy-industrial patterns and governance inertia lock in a high-emission trajectory. PESS is absorbed into the prevailing development model, rendering short-term emission

reductions difficult. From a broader perspective, the role of PESS in western China in promoting economic growth and industrial expansion outweighs its contribution to emission mitigation.

4.4.2.4. *The PESS, transfer payments, and AEQ in western China.* This study explores potential solutions to address the unexpected effects observed in western China. As a fiscal subsidy from the central government to local governments, transfer payments have long played a crucial role in regulating the region's development. Accordingly, the following model is constructed to examine how transfer payments influence the effect of PESS on AEQ in western China.

Table 20
The relationship between PESS and AEQ: regional differences.

Panel A: East								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	$\ln CO_2$	PCO_2	DCO_2	$\ln SO_2$	PSO_2	DSO_2	$\ln PM$	PM
PES	-1.137*** (0.289)	-1.492*** (0.355)	-1.116*** (0.293)	-2.795** (1.214)	-3.225** (1.296)	-2.771** (1.226)	-0.732*** (0.097)	-13.152* (7.675)
Controls	Yes							
City FE	Yes							
Year FE	Yes							
N	1591	1591	1591	1691	1691	1691	1691	1691
adj.R ²	0.97	0.94	0.97	0.85	0.82	0.84	0.97	0.95
Panel B: Central								
	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	$\ln CO_2$	PCO_2	DCO_2	$\ln SO_2$	PSO_2	DSO_2	$\ln PM$	PM
PES	0.396* (0.215)	-1.773*** (0.663)	0.505* (0.263)	-6.683*** (1.150)	-9.541*** (1.589)	-6.433*** (1.163)	-0.659*** (0.128)	-43.319*** (7.692)
Controls	Yes							
City FE	Yes							
Year FE	Yes							
N	1536	1275	1536	1634	1350	1634	1634	1634
adj.R ²	0.99	0.88	0.98	0.85	0.87	0.90	0.95	0.94
Panel C: West								
	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
	$\ln CO_2$	PCO_2	DCO_2	$\ln SO_2$	PSO_2	DSO_2	$\ln PM$	PM
PES	0.294 (0.406)	-0.361 (0.516)	0.402 (0.416)	1.953* (1.100)	1.168 (1.443)	2.236** (1.120)	0.551*** (0.165)	18.083*** (6.615)
Controls	Yes							
City FE	Yes							
Year FE	Yes							
N	1215	1083	1187	1296	1166	1267	1296	1296
adj.R ²	0.98	0.98	0.99	0.83	0.86	0.87	0.93	0.90

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

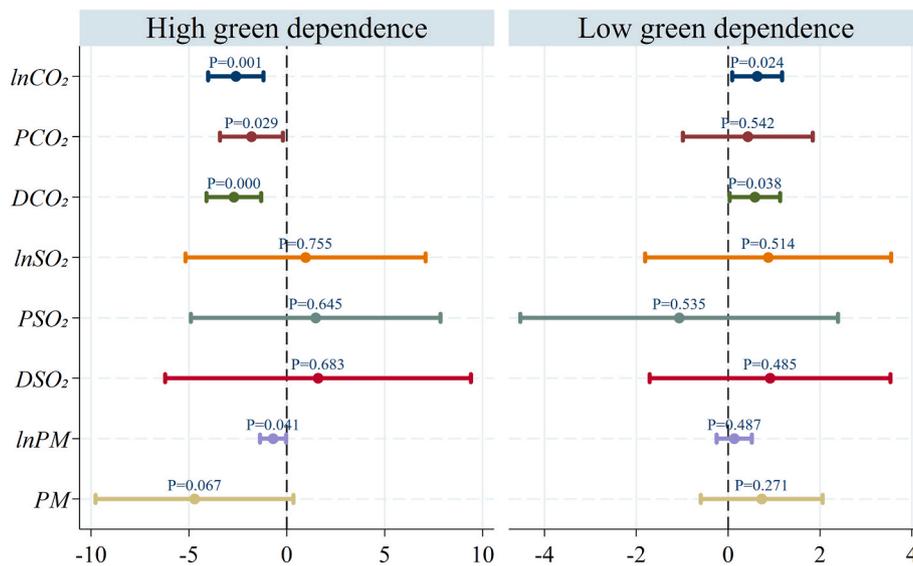


Fig. 11. PESS and AEQ in western regions: Green resource dependence.

Note: 95% confidence intervals are shown in the figure.

$$EP_{it} = \beta_0 + \beta_1 PES_{it} + \beta_2 W + \beta_3 \ln TS_{it} + \beta_4 PES_{it} \times W + \beta_5 PES_{it} \times \ln TS_{it} + \beta_6 \ln TS_{it} \times W + \beta_7 \ln TS_{it} \times W \times PES_{it} + \beta_8 \sum Z_{it} + \mu_i + \tau_t + \epsilon_{it}$$

In this specification, $\ln TS_{it}$ denotes the logarithm of the city-level transfer payments, W is a dummy variable indicating whether a city is located in the western region. The regression results in Table 21 show that most coefficients of the triple interaction term ($\ln TS \times W \times PES$) are significantly negative, indicating that in western regions, higher fiscal

transfer payments substantially enhance the emission-reduction effect of PESS. The results suggest that in western regions, higher fiscal transfer payments alleviate local fiscal constraints, enabling governments to allocate more resources to environmental protection through PESS rather than prioritizing economic expansion, and accelerating industrial upgrading toward greener sectors, further enhancing the emission-reduction effect of PESS. Consequently, increasing fiscal transfer payments to western regions, particularly when tied to environmental performance targets, could mitigate their weak-effect problem and

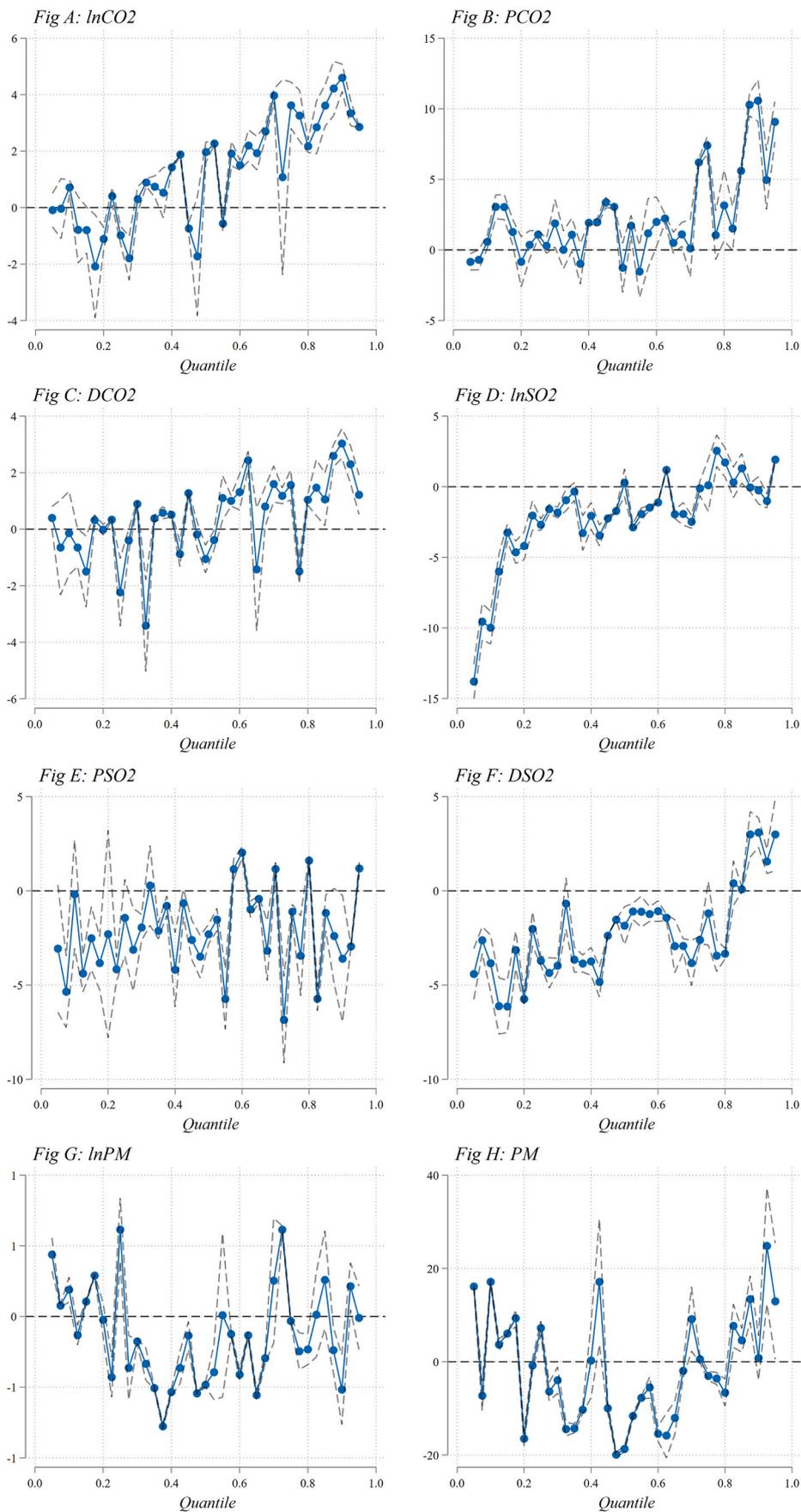


Fig. 12. Quantile regression results in western China.
Note: 95% confidence intervals are shown in the figure.

Table 21
PESS, transfer payments, and AEQ in western China.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	$\ln CO_2$	PCO_2	DCO_2	$\ln SO_2$	PSO_2	DSO_2	$\ln PM$	PM
<i>PES</i>	-1.906*** (0.489)	-2.010** (0.790)	-2.180*** (0.603)	-3.413 (2.800)	-4.304 (3.287)	-3.808 (2.767)	-0.574** (0.231)	3.966 (14.150)
<i>lnTS</i>	-0.019** (0.008)	-0.018 (0.012)	-0.027*** (0.009)	0.048 (0.050)	0.036 (0.052)	0.035 (0.051)	0.004 (0.005)	-0.075 (0.294)
<i>lnTS</i> × <i>PES</i>	0.259** (0.101)	0.122 (0.178)	0.309** (0.122)	0.170 (0.603)	0.110 (0.734)	0.229 (0.598)	0.079* (0.047)	-1.720 (3.063)
<i>W</i> × <i>lnTS</i>	0.054*** (0.014)	0.037** (0.015)	0.060*** (0.016)	-0.114 (0.082)	-0.203** (0.095)	-0.121 (0.085)	-0.015* (0.008)	0.149 (0.368)
<i>W</i> × <i>PES</i>	5.595*** (1.272)	6.371*** (1.794)	7.290*** (1.468)	12.380* (6.653)	17.858* (9.203)	15.195** (6.984)	1.976*** (0.694)	35.242 (42.453)
<i>lnTS</i> × <i>W</i> × <i>PES</i>	-1.041*** (0.274)	-1.107*** (0.372)	-1.382*** (0.320)	-2.009 (1.488)	-3.041 (1.962)	-2.596 (1.577)	-0.418*** (0.143)	-5.612 (9.028)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	2499	2203	2486	2504	2208	2491	2504	2504
<i>adj.R²</i>	0.98	0.94	0.99	0.85	0.84	0.88	0.95	0.94

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

support a transition to a more sustainable growth model.

4.4.3. Institutional environment

AEQ enhancement from PESS correlates positively with the marketization level. In regions with higher marketization, a well-established market environment promotes PESS's capacity to incentivize pollution reduction. In contrast, in areas with lower marketization, PESS's impact on AEQ is somewhat constrained by limited market incentives. To analyze the moderating effect of institutional contexts, the following econometric model incorporates the marketization index to represent the city's institutional environment (Fan et al., 2003).

$$EP_{it} = \beta_0 + \beta_1 PES_{it} + \beta_2 MK_{it} + \beta_3 PES_{it} \times MK_{it} + \beta_4 \sum Z_{it} + \mu_i + \tau_t + \epsilon_{it}$$

Table 22 reports the moderating effect of marketization on the impact of PESS on AEQ. The results indicate that the coefficient of the interaction term (*MK* × *PES*) is significantly negative, suggesting that higher levels of marketization enhance the effectiveness of PESS in reducing atmospheric pollutant emissions and improving AEQ. These findings suggest that a competitive market environment significantly enhances the emission reduction effects of payments for ecosystem services, and that China's transition toward a market-oriented economy has further strengthened this impact.

4.4.4. Fiscal decentralization

The regional fiscal decentralization significantly affects the PESS's influence on AEQ. Under China's decentralized governance model, varying levels of fiscal decentralization reflect differences in the

Table 22
PESS, the degree of marketization, and AEQ.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	$\ln CO_2$	PCO_2	DCO_2	$\ln SO_2$	PSO_2	DSO_2	$\ln PM$	PM
<i>PES</i>	4.347*** (0.987)	1.590 (1.176)	4.535*** (1.069)	3.952* (2.283)	1.277 (2.328)	4.189* (2.360)	1.566*** (0.345)	50.596*** (18.245)
<i>MK</i>	-0.003 (0.007)	-0.006 (0.008)	-0.000 (0.009)	-0.120*** (0.042)	-0.106** (0.043)	-0.116*** (0.043)	-0.004 (0.004)	-0.342 (0.218)
<i>MK</i> × <i>PES</i>	-0.524*** (0.103)	-0.326*** (0.117)	-0.535*** (0.111)	-0.705*** (0.244)	-0.533** (0.244)	-0.713*** (0.251)	-0.211*** (0.036)	-6.893*** (1.962)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	4342	3949	4314	4621	4207	4592	4621	4621
<i>adj.R²</i>	0.98	0.94	0.98	0.84	0.84	0.87	0.95	0.94

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

financial autonomy of cities in managing their fiscal expenditures. Such differences give rise to variations in local governments' capacity for environmental governance, ultimately affecting the efficacy of air pollution control in the implementation of payments for ecosystem services (Zhang and Zou, 1998). Following Guo et al. (2022), this study constructs a fiscal decentralization index for prefecture-level cities (*DE*) to evaluate regional fiscal autonomy. The following econometric model is designed to examine the moderating role of fiscal decentralization.

$$EP_{it} = \beta_0 + \beta_1 PES_{it} + \beta_2 DE_{it} + \beta_3 PES_{it} \times DE_{it} + \beta_4 \sum Z_{it} + \mu_i + \tau_t + \epsilon_{it}$$

Table 23 presents the regression results for the moderating role of fiscal decentralization in columns (1)–(8). The findings indicate that the interaction between fiscal decentralization and PESS is significantly positive, suggesting that greater fiscal decentralization enhances the effectiveness of PESS in reducing air pollution and improving air quality. This phenomenon can be attributed to the greater fiscal autonomy of local governments in regions with higher levels of fiscal decentralization. Local governments, leveraging their informational advantages in PESS development, are able to allocate fiscal resources more effectively. This facilitates industrial restructuring, promotes green technological innovation, and enhances atmospheric environmental governance outcomes.

5. Conclusions and policy implications

This study examines the influence of PESS on AEQ using panel data from 280 prefecture-level cities in China from 2004 to 2020. Econometric analysis provides robust evidence that PESS significantly

Table 23
PESS, fiscal decentralization, and AEQ.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	<i>lnCO₂</i>	<i>PCO₂</i>	<i>DCO₂</i>	<i>lnSO₂</i>	<i>PSO₂</i>	<i>DSO₂</i>	<i>lnPM</i>	<i>PM</i>
<i>PES</i>	0.009 (0.428)	-1.602*** (0.544)	0.108 (0.497)	2.886 (1.852)	-0.246 (2.204)	2.989 (1.883)	-0.101 (0.202)	-18.493* (10.372)
<i>Fiscal</i>	0.048 (0.057)	0.020 (0.073)	0.150* (0.087)	0.146 (0.292)	0.113 (0.309)	0.247 (0.297)	0.019 (0.034)	0.123 (1.816)
<i>DE×PES</i>	-1.484** (0.740)	-1.547* (0.805)	-1.805* (0.924)	-10.425*** (2.815)	-8.385*** (3.172)	-10.747*** (2.863)	-0.009 (0.419)	20.898 (19.341)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	3311	2995	3311	3313	2997	3313	3313	3313
<i>adj.R²</i>	0.99	0.95	0.99	0.85	0.85	0.89	0.95	0.94

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively; standard errors are clustered at the city level in parentheses.

contributes to the improvement of AEQ. The study reveals that the underlying mechanisms of this phenomenon involve increased PESS levels promoting green innovation, facilitating industrial restructuring, and restricting the entry of polluting enterprises while encouraging environmentally responsible firms, thereby improving AEQ. Moreover, the in-depth analysis indicates that the positive impact of PESS on AEQ is particularly pronounced in regions characterized by a high degree of marketization and greater fiscal decentralization. Additionally, the effectiveness of atmospheric governance facilitated by PESS is more pronounced in China's eastern and central regions than in the western region. The robustness of these findings is confirmed through a series of rigorous tests.

This study provides valuable policy insights for addressing the dilemma between economic sustainability and AEQ. It emphasizes the imperative of formulating scientifically and logically sound environmental policies and establishing effective mechanisms for atmospheric environmental governance. To begin with, this research clearly shows that increasing PESS leads to a significant decrease in atmospheric pollutant emissions and a corresponding improvement in AEQ. The conclusion highlights China's effective environmental governance framework, centered around PESS, and provides insights relevant to international environmental challenges. Additionally, research findings emphasize that the success of atmospheric environmental governance driven by PESS is especially notable in areas with higher marketization and increased fiscal decentralization, particularly in eastern and central China. When formulating policies, the central government could take institutional and regional disparities into account to maximize the positive effects of PESS on air quality enhancement.

The PESS process has a significant impact on China and has proven effective in enhancing AEQ in Chinese cities. Enhancing the PESS necessitates refining the mechanisms for realizing the differentiated value of ecosystem products. Firstly, in the lucrative PESS sector, it is essential to advocate for national sports, culinary, adventure, music, animation, and film tourism. Encouraging certifications for green buildings, organic agriculture, zero carbon emissions, carbon neutrality, low-carbon products, social responsibility, and eco-friendly packaging is crucial. Endorsement of certifications tied to geographical indications, regional cuisine, and local handicrafts holds significant importance. Secondly, in quasi-public PESS, enhancing market transaction efficiency for natural resources and establishing trading systems for biodiversity rights and watershed water quality is critical. Thirdly, for public PESS, authorities could strengthen environmental standards and establish ecological funds, while leveraging the complementarity and convertibility of different PESS types to design integrated schemes.

Based on the research conclusions, several policy recommendations are proposed to strengthen the effectiveness of PESS, particularly in western China. First, establishing a dedicated transfer payment mechanism for western PESS would provide stable financial support to key ecological function zones and high green resource-dependent areas. This

measure would mitigate the polarization arising from overreliance on either green resources or industrial development paths, thereby improving overall emission reduction outcomes and ensuring the sustainability of ecological governance. Second, PESS could be more closely integrated with the national policy on "the realization of ecological product values," with both incorporated into local government performance assessments to incentivize enhanced ecological protection. Third, differentiated compensation schemes could be designed, with funds allocated according to regional dependence on green resources and ecological importance to ensure more precise and equitable support. Moreover, local fiscal incentive and accountability mechanisms may be strengthened to direct PESS funds toward long-term ecological governance and green industrial development, avoiding short-term or symbolic implementation. Strengthening project supervision and performance evaluation is essential to guarantee that funds are allocated to high-value ecological initiatives.

China's payments for ecosystem services provide insights for balancing environmental preservation and economic growth. This experience significantly contributes to the advancement of sustainable development in both environmental and economic domains. Furthermore, this development-oriented concept provides valuable guidance for developing countries in achieving effective atmospheric governance. The success of PESS hinges on a well-established foundation of institutional frameworks and policies. Creating a multifaceted system for value realization requires the active involvement of various stakeholders, including government entities, corporations, cooperatives, individuals, financial institutions, and social organizations. The impacts of PESS vary according to regional environmental and economic factors. Governments could strengthen social institutions and improve economic conditions to support the development of PESS and enhance environmental governance outcomes.

CRedit authorship contribution statement

Jun Li: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Lan Fang:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Conceptualization.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cesys.2026.100417>.

Data availability

The STATA data and code that generate all results presented in the paper are available in the supplementary data.

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