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Original Research

Can Carbon Sequestration by Terrestrial Vegetation Improve Air Quality? Evidence from China

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Abstract

Carbon sequestration by terrestrial vegetation (Cstv) is a vital ecosystem service for regulating global climate change. This study utilizes satellite data and a two-way fixed effects model to comprehensively examine the relationship between Cstv and haze pollution. The findings indicate that Cstv significantly reduces haze pollution, a conclusion that remains robust under various checks. Mechanism analysis reveals that Cstv mitigates haze pollution through two pathways: enhancing environmental performance and improving economic performance. Additionally, the study identifies regional differences in the effectiveness of Cstv in reducing haze pollution. In non-key areas for air pollution prevention and control, Cstv significantly reduces haze pollution, whereas in key areas for air pollution prevention and control, Cstv has no effect. Furthermore, Cstv has a greater impact on non-key environmental protection cities than on key environmental protection cities. This study provides theoretical support and practical insights for the development of scientifically sound environmental protection policies and economic development strategies.

Keywords: carbon sequestration by terrestrial vegetation, haze pollution, satellite data, environmental performance, economic performance

Introduction

With the increasing severity of global climate change and environmental pollution, haze pollution has become a focal point of global attention [1, 2]. China, as one of the most populous countries in the world, faces particularly formidable environmental challenges [3, 4]. Haze pollution, a pervasive environmental issue, has exerted profound and undeniable impacts on human health and ecological systems [5-7]. With the rapid development of urbanization and industrialization, haze pollution in China has been on the rise, exhibiting characteristics of uneven spatial distribution and prolonged duration [8, 9]. Haze pollution not only negatively impacts human health but also inflicts severe damage to the natural environment and ecosystems. Numerous studies have indicated the association of haze pollution with the occurrence of various diseases, including cardiovascular diseases, respiratory diseases, and lung cancer [10, 11]. Furthermore, haze pollution can result in issues such as leaf damage in plants, hindered photosynthesis, and ecological system imbalances. Hence, haze pollution

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has become a pressing issue in the current field of environmental science. To better comprehend and address this problem, this study focuses on the impact of carbon sequestration by terrestrial vegetation (Cstv) on haze pollution, exploring the potential role of vegetation in improving air quality.

Terrestrial vegetation, as a primary component of the global carbon reservoir, plays a crucial role in the global carbon cycle. Through photosynthesis, vegetation converts atmospheric carbon dioxide into organic carbon, subsequently sequestering it in biomass [12, 13][1]. This ecological process is not only crucial for maintaining the balance of ecosystems but also plays a significant role in regulating greenhouse gas concentrations in the atmosphere [14, 15]. Vegetative carbon sequestration, where carbon dioxide is converted into organic matter within plant tissues, serves as a vital ecological regulation mechanism [16, 17]. This process maintains carbon equilibrium within ecosystems, helping to prevent the excessive accumulation of greenhouse gases in the atmosphere and thereby mitigating the pace of climate change. Through photosynthesis, plants accumulate organic carbon in trees, vegetation, and soil, forming vast carbon reservoirs. This biomass accumulation not only impacts soil fertility but also yields positive effects on the overall stability of ecosystems [18]. However, the rapid expansion of urbanization and industrialization has led to severe vegetation degradation in many regions. Extensive land development, deforestation, and urban sprawl have resulted in vegetation reduction and fragmentation, directly threatening the capacity of Cstv. This anthropogenic-induced reduction in vegetation not only slows down the rate of carbon dioxide absorption but also accelerates greenhouse gas emissions. Therefore, the protection and restoration of vegetation are critically important for maintaining the carbon sequestration capacity of land vegetation and the stability of global ecosystems [19, 20].

Land ecosystems, through the photosynthetic process of vegetation, absorb a substantial amount of carbon dioxide from the atmosphere. This is widely acknowledged as an economically feasible and environmentally friendly approach to mitigating the increase in carbon dioxide concentrations [21, 22]. Therefore, enhancing the carbon storage and sequestration capacity of terrestrial ecosystems has become a crucial area in global climate change research and a focal point of international attention [23]. In this study, we utilize satellite remote sensing technology to acquire urban-level Cstv data, conducting a detailed analysis of the relationship between land vegetation carbon sequestration and haze pollution. Satellite remote sensing data, with its high temporal and spatial resolution, provides us with a comprehensive and objective observation tool, facilitating a thorough understanding of the varying impact levels of Cstv on haze pollution in different regions. The primary objective of this research is to employ econometric regression methods to explore whether Cstv has a mitigating effect on haze and to delve into the underlying mechanisms influencing the impact of Cstv on haze pollution. Additionally, considering distinct urban characteristics, we aim to further investigate the variations in the effectiveness of Cstv across different cities. Through a comprehensive understanding of the role of vegetation in haze control, we aspire to offer more effective guidance for future environmental policy formulation, contributing to global sustainable development and ecological balance.

As shown in Table 1, we summarize national-level carbon sink policies in recent years. From 2010 to 2021, China has gradually improved its carbon sink policy framework to promote the key role of forestry carbon sinks in addressing climate change. Early policies focused on establishing technical standards and operational norms for carbon sink afforestation and ensuring effective implementation and monitoring of carbon sink projects. With the passage of time, the carbon sink policy has gradually transitioned from the technical level to a market-oriented mechanism to promote the trading and market development of forestry carbon sink products. At the same time, the state has continued to strengthen the combination of ecological protection and carbon-neutral policies, encouraging green and low-carbon development through diversified compensation mechanisms and incentives. After entering 2020, the carbon trading market began to land gradually, and forestry carbon sinks became an important part of the carbon emissions trading system. On the whole, the carbon sink policy has realized comprehensive coverage from technical requirements and market mechanisms to legal safeguards, providing a solid institutional foundation for realizing pollution reduction and carbon reduction and promoting a win-win situation between ecological protection and economic development.

Our econometric model yields the following findings: Firstly, Cstv significantly reduces haze pollution. In other words, Cstv notably improves air quality, a conclusion that remains robust after undergoing various robustness tests. Secondly, enhancing environmental performance and economic performance proves to be an effective mechanism for Cstv to alleviate haze pollution. Thirdly, in non-key areas for air pollution prevention and control,

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[1] Over the past few decades, China's terrestrial ecosystems have played a significant role as carbon sinks. For instance, during the period from 2001 to 2010, the average annual carbon sequestration in terrestrial ecosystems reached 201 million tons, equivalent to offsetting 14.1% of China's fossil fuel carbon emissions during the same period. Notably, forest ecosystems served as the primary carbon sink, contributing approximately 80% of the total carbon sequestration, while cropland and shrubland ecosystems contributed 12% and 8% of the carbon sequestration, respectively. The carbon balance in grassland ecosystems remained relatively stable. Information derived from: https://www.gov.cn/xinwen/2018-04/19/content_5283872.htm.

Table 1. Summary of carbon sink policies at the national level[2]

Release time	Publisher	Policy name	Policy nature
July 2010	State Forestry Administration	Technical regulations on carbon sink afforestation (trial)	Normative
July 2010	State Forestry Administration	Measures for Inspection and Acceptance of Carbon Sink Afforestation (Trial)	Normative
October 2010	State Forestry Administration	Guidelines for measuring and monitoring carbon sink in afforestation projects	Normative
August 2011	National Development and Reform Commission and other departments	Measures for the operation and management of clean development mechanism projects (revised)	Normative
June 2012	National Development and Reform Commission and other departments	Interim Measures for the Management of Greenhouse Gas Voluntary Emission Reduction Trading	Normative
June 2014	State Forestry Administration	Guidance on Promoting Carbon Sinks Trading in Forestry	Supportive
September 2015	State Council, etc.	General Program for the Reform of the Ecological Civilization System	Supportive
November 2016	State Council Office of the People's Republic of China	Opinions of the General Office of the State Council on Improving the Collective Forest Rights System	Supportive
May 2018	Forestry and Grassland Administration	Opinions of the State Forestry and Grassland Administration on Further Liberalization of Collective Forest Management Rights	Supportive
December 2018	National Development and Reform Commission and other departments	Action plan for the establishment of a market-oriented and diversified ecological protection compensation mechanism	Supportive
October 2020	Ministry of Ecology and the Environment	Guidance on Promoting Investment and Financing to Address Climate Change	Supportive
December 2020	Ministry of Ecology and the Environment	Administrative Measures for Carbon Emission Trading (Trial)	Normative
March 2021	Ministry of Ecology and the Environment	Interim Regulations on the Management of Carbon Emissions Trading (Draft)	Normative

Cstv significantly reduces haze pollution. Conversely, in key areas for air pollution prevention and control, Cstv shows no discernible effect. Cstv has a greater impact on non-key environmental protection cities than on key environmental protection cities. These findings provide us with a profound understanding of the role of Cstv in mitigating haze pollution, emphasizing its significance in environmental protection.

Literature Review

Industrial emissions are a primary source of haze pollution, with sulfur dioxide, nitrogen oxides, and particulate matter being the main components released during the combustion of fossil fuels in industrial activities. For instance, heavily polluting industries such as steel, cement, and chemicals emit significant amounts of waste gases and particulates during production, directly degrading air quality [24]. The contribution of industrial emissions to air pollution is particularly pronounced in highly industrialized regions [25, 26]. Furthermore, the energy structure significantly impacts haze pollution. China's coal-dominated energy structure results in high sulfur and high ash combustion emissions, which are critical factors in haze pollution [27]. Effective measures to reduce industrial emissions include promoting cleaner energy sources such as natural gas and renewable energy, improving industrial technology, and tightening emission standards.

Traffic emissions are another major source of urban haze pollution [28]. Vehicle exhausts emit nitrogen oxides, carbon monoxide, and volatile organic compounds, which undergo photochemical reactions under sunlight to form ozone and secondary organic aerosols, key components of haze. The rapid increase in motor vehicle numbers due to urbanization exacerbates the negative impact of urban traffic on air quality [29]. Additionally, accelerated urbanization results in substantial particulate matter emissions, further worsening haze pollution. The urban heat island effect is also considered a contributing factor to haze pollution. Changes in land cover and increased building density

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[2] Due to space limitations, the authors have only compiled national-level carbon sink policies in recent years. More carbon sink policies at the provincial level can be found at the following link: https://www.qianzhan.com/analyst/detail/220/240131-11f1be25.html.

associated with urbanization raise urban temperatures, reduce the dispersion of air pollutants, and make haze events more frequent and severe [30].

Natural factors play a critical role in the formation of haze pollution [31]. Meteorological conditions such as temperature inversions, low wind speeds, and high humidity can hinder the dispersion and dilution of pollutants, leading to their accumulation near the surface and forming haze [32]. For example, during the winter heating season, stable weather conditions combined with high pollution emissions and poor dispersion capacity lead to frequent haze events. Additionally, geographical factors are pivotal in haze formation. Mountainous terrain can obstruct air flow, causing localized pollutant accumulation, while plains facilitate better air circulation, aiding pollutant dispersion [33].

The formulation and enforcement of environmental policies and regulations are crucial in controlling haze pollution [34, 35]. Strict emission standards and effective pollution control policies can significantly improve air quality. For example, the Chinese government's "Ten Measures for Air" policy, implemented in recent years, has effectively reduced urban haze pollution by strictly controlling industrial emissions, optimizing the energy structure, promoting clean energy, and enhancing monitoring capabilities. However, the effectiveness of these policies varies significantly across different regions, and the results of cross-regional collaborative efforts to control haze pollution have been less than ideal [36]. Moreover, public participation and increased environmental awareness are also critical factors in haze management. Enhanced public engagement and awareness can support the implementation of policies and contribute to more effective haze pollution control [6].

The potential innovations of this paper are outlined as follows: Firstly, adopting an ecological perspective, the study primarily focuses on the impact of Cstv on haze pollution. By delving into the mechanisms through which Cstv mitigates haze pollution, this paper not only expands the understanding of Cstv in the field of ecology but also lays a theoretical foundation for the organic integration of ecology and environmental economics. Consequently, this paper offers a unique contribution to the collaborative development between these two disciplinary domains. Secondly, the paper extends the factors influencing haze pollution from an ecological standpoint. In prior research, traditional factors such as green innovation, industrial agglomeration, and environmental governance were widely regarded as key determinants of haze pollution [24, 36-38]. However, by focusing on the role of Cstv, this paper reveals the complex interplay between ecosystems and atmospheric environments, providing a novel perspective for addressing haze pollution. Furthermore, this paper utilizes satellite data as research evidence [39], providing us with more comprehensive and accurate data support. Satellite data offers extensive and continuous spatial coverage, capturing information that ground observations cannot attain. This enables a more precise estimation of the impact of vegetation carbon sequestration on haze pollution, thereby elevating the accuracy and reliability of the study.

Research Hypotheses

Vegetation plays a multifaceted role in the control of atmospheric pollution. Primarily, terrestrial vegetation's carbon sequestration contributes to the reduction of harmful gas concentrations in the atmosphere, thereby mitigating the risk of haze pollution [40, 41]. Plants also have the capacity to absorb other deleterious gases associated with haze formation, such as carbon monoxide and volatile organic compounds. Hence, terrestrial vegetation carbon sequestration aids in purifying the air and diminishing the occurrence of haze. Furthermore, terrestrial vegetation can ameliorate microclimatic conditions in the atmospheric environment. The crowns and leaves of vegetation form a natural filtering layer, intercepting and reducing suspended particles, organic matter, and other pollutants in the air. This not only directly lowers the concentration of particulate matter but also mitigates the diffusion of harmful substances, effectively reducing the formation and spread of haze [42]. Lastly, the release of oxygen during the carbon sequestration process of vegetation contributes to enhancing the oxygen content in the atmosphere, thereby improving air quality. The release of oxygen not only benefits human health but also aids in maintaining the balance of oxygen and carbon dioxide in the atmosphere, slowing the proliferation of air pollution [43, 44]. In summary, terrestrial vegetation carbon sequestration operates through various mechanisms, providing robust ecological support for the mitigation and prevention of haze pollution. Based on the aforementioned analysis, we propose Hypothesis 1:

Hypothesis 1: Cstv is beneficial for reducing haze pollution.

Vegetation plays a pivotal role in maintaining the stability of ecosystems. Through various mechanisms such as carbon sequestration, oxygen release, moisture retention, and provision of habitats for fauna and flora, vegetation profoundly influences the normal functioning of ecosystems [45, 46]. During the carbon sequestration process, vegetation absorbs atmospheric carbon dioxide and transforms it into organic matter. These organic substances serve as the foundation for plant growth and constitute significant carbon storage within the ecosystem. As plants grow and decay, this carbon is cyclically utilized, sustaining the continuous operation of the ecosystem [14]. In this process, vegetation releases a substantial amount of oxygen, a primary source for maintaining oxygen levels in the atmosphere. Therefore, enhancing the vegetation carbon sequestration process can elevate environmental performance, simultaneously creating more favorable conditions for the sustainable development of human society and the natural environment [47]. Furthermore, vegetation plays a

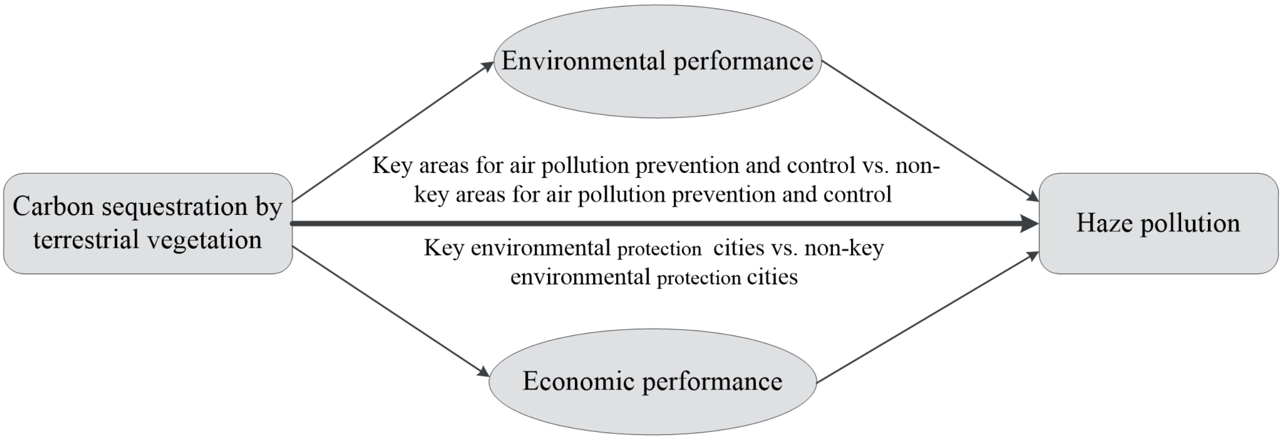

Fig. 1. Frame diagram.

crucial role in ecosystems by providing habitats for wildlife, reducing soil erosion, and promoting water resource protection. Plants not only contribute to improving soil quality but also mitigate water pollution [48, 49]. Consequently, vegetation carbon sequestration contributes to preserving the diversity and stability of ecosystems, upholding ecological balance and thereby enhancing environmental performance. Based on the aforementioned analysis, we propose hypothesis 2:

Hypothesis 2: Cstv may reduce haze pollution by enhancing environmental performance.

On the one hand, vegetation carbon sequestration assists in mitigating climate change risks, thereby alleviating economic losses related to climate change. Climate change poses significant risks to the global economy, including extreme weather events, rising sea levels, and losses in agriculture and fisheries. By absorbing atmospheric carbon dioxide, vegetation contributes to the reduction of greenhouse gas emissions, slowing the progression of climate change [50]. This not only safeguards agricultural yields and mitigates the impact of natural disasters but also reduces government spending on disaster response [51]. Consequently, vegetation carbon sequestration has the potential to lower climate-related risks, providing stability and sustainability to the economy [52]. These innovations not only promote the development of the relevant industrial chain but also provide new impetus and opportunities for economic growth [53]. Meanwhile, carbon sequestration also promotes forest growth, improves forest stock and timber quality, and brings higher economic benefits to forestry. This win-win situation helps to promote the sustainable development of agriculture and forestry and economic growth. Based on this analysis, we posit Hypothesis 3:

Hypothesis 3: Cstv can reduce haze pollution by enhancing economic performance.

Fig. 1 illustrates the concise research framework. The primary focus of this research centers on examining the influence of Cstv on haze pollution. Building upon this foundation, we conduct an investigation from the perspectives of environmental performance and economic performance to elucidate the underlying mechanisms through which Cstv interacts with haze pollution. Finally, we explore the heterogeneity of the baseline regression analysis based on urban categorizations, such as key environmental protection cities and non-key environmental protection cities. Air Pollution Prevention and Control Priority Areas are areas where the government has taken mandatory measures to address air quality issues, such as China's Beijing-Tianjin-Hebei and Yangtze River Delta regions, which are economically developed and heavily polluted. Pollution control is stronger in these areas, and measures such as industrial emissions and traffic control are generally stricter. In addition, key environmental protection cities are likely to have better environmental infrastructure, higher environmental awareness, and stronger government regulatory capabilities. The effect of Cstv is rather diluted due to the already existing environmental protection measures. Therefore, the marginal effect of Cstv may be lower in air pollution prevention and control in key regions and key environmental protection cities. Our study aims to contribute to a comprehensive understanding of Cstv and its effect on environmental-related outcomes, thus providing valuable insights for promoting sustainable development.

Experimental

Data and Sample

The data utilized in this study is sourced from multiple channels. Specifically, the data on haze pollution is obtained from the Atmospheric Composition Group at Dartmouth College. Data on Cstv is derived from the team led by Chen Jiandong at the Southwestern University of Finance and Economics [39]. The research team utilized the MOD17A3H product provided by the MODIS platform to estimate the net primary

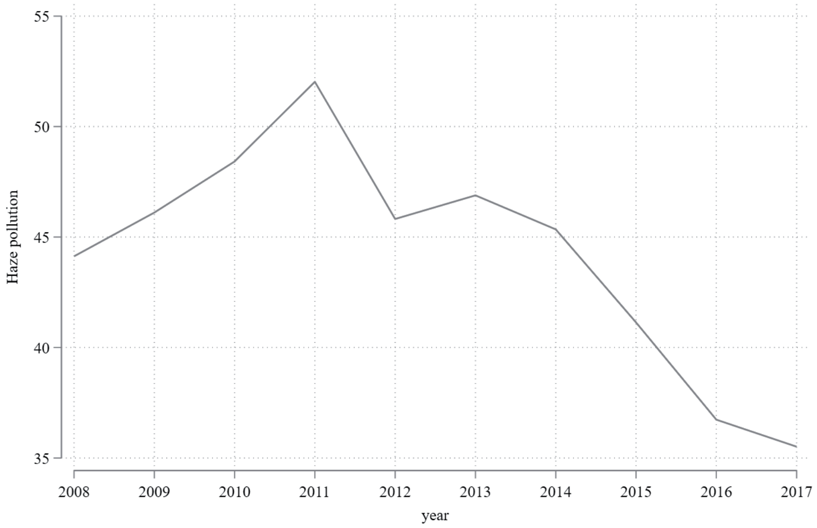

Fig. 2. Change trend of $PM_{2.5}$ concentration.

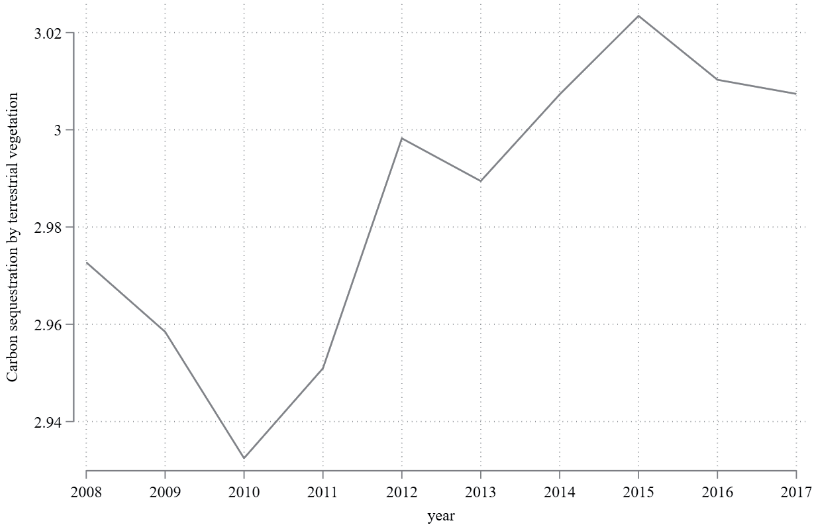

Fig. 3. Change trend of carbon sequestration by terrestrial vegetation.

productivity corresponding to Chinese counties from 2000 to 2017. Subsequently, Cstv was determined by employing the conversion coefficient between vegetation biomass and absorbed CO_2. The environmental regulatory indicator is sourced from urban government work reports. Total energy consumption is calculated by converting the annual electricity consumption (in 10000 kilowatt-hours), liquefied petroleum gas (in tons), and natural gas (in 10000 cubic meters) of each city into "10000 tons of standard coal" and summing them. Other control variables are derived from the EPS database. Ultimately, by amalgamating data from various sources, we obtained balanced panel data for 283 prefecture-level and above cities in China from 2008 to 2017.

Variable Definitions

Dependent Variable

Haze pollution *(Pm)*. In previous studies, conventional pollutants such as sulfur dioxide, particulate matter, and other indicators have often been used as proxy variables to measure the severity of air pollution. However, these indicators may not precisely reflect the regional conditions of haze pollution. $PM_{2.5}$ is commonly regarded as the primary contributor to haze weather and is the most frequently utilized metric in academia for measuring haze pollution. Building upon existing authoritative literature [54-56], this paper employs urban $PM_{2.5}$ concentrations as a measure of haze pollution. Due to a lack of emphasis on the collection of haze pollution data in the earlier stages of China's development, domestically monitored $PM_{2.5}$ data

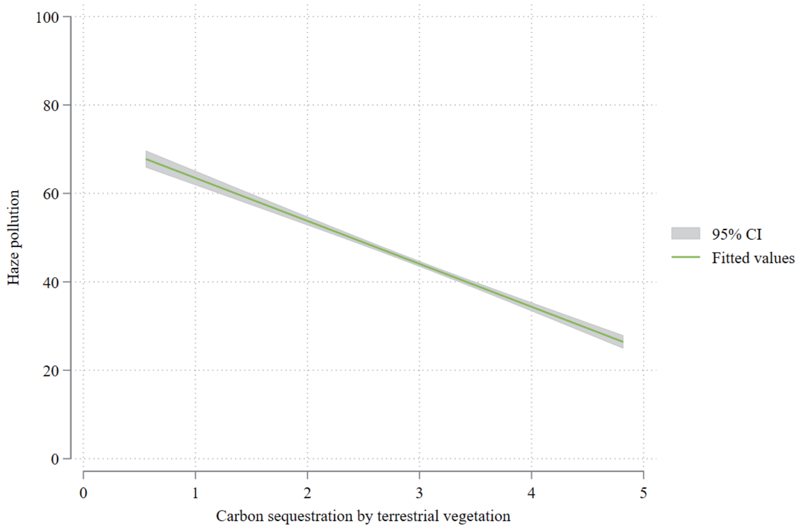

Fig. 4. Carbon sequestration by terrestrial vegetation and haze pollution.

only became officially effective in 2013. Additionally, there is suspicion that local governments, seeking higher promotion probabilities, may engage in 'data washing' and 'false disclosure' of pollution emissions in the process of reporting.

Given this context, the dependent variable in this study is represented by $PM_{2.5}$ data sourced from Dalhousie University. Leveraging NASA's publicly available gridded data, Dalhousie University's Atmospheric Composition Analysis Group further processed this information using ArcGIS software, yielding annual average $PM_{2.5}$ concentration data at the level of Chinese cities. This interdisciplinary team amalgamated both direct ground-level monitoring data and indirect satellite observations, enhancing the precision of measuring the extent of haze pollution in a given region to a considerable degree.

Fig. 2 illustrates the annual trend in $PM_{2.5}$ concentration across various cities in China. From 2008 to 2011, there was a consecutive annual increase in $PM_{2.5}$ concentration, reaching its peak in 2011. Subsequently, a general declining trend in $PM_{2.5}$ concentration has been observed post-2011.

Independent Variable

Carbon sequestration by terrestrial vegetation (*Cstv*). In the realm of ecology, Cstv is regarded as a pivotal ecosystem service. This service plays a crucial role in achieving long-term carbon storage, reducing greenhouse gas concentrations in the atmosphere, and regulating climate at both local and regional scales. Through photosynthesis, terrestrial vegetation has the capacity to absorb carbon dioxide from the atmosphere and convert it into organic matter, effectively fixing carbon. This process not only contributes to diminishing atmospheric carbon dioxide concentrations, thereby mitigating global climate change, but also mitigates the risks of haze pollution. Building on the research by [39], we aggregate the county-level Cstv to derive urban-level data on terrestrial vegetation carbon sequestration.

In contrast to industrial carbon sequestration, ecological restoration for carbon fixation exhibits significantly enhanced cost-effectiveness, emerging as a strategic focal point in the global response to climate change. By optimizing or restoring the structure and functionality of existing ecosystems and adjusting the spatial arrangement of regional ecosystems, substantial potential exists to effectively stimulate carbon storage in forests, grasslands, wetlands, and soils. This approach stands out as a pivotal pathway toward achieving carbon peak and neutrality objectives. Presently, it is widely recognized as the most economical, secure, and efficient means of carbon sequestration. Against the backdrop of global climate change, the strategic importance of ecological restoration is accentuated, providing critical support for global sustainable development and environmental conservation.

Fig. 3 depicts the annual trend in Cstv across various cities in China. From 2008 to 2010, Cstv exhibited a consecutive annual decline, reaching its minimum in 2010. Post-2010, the variation in Cstv has generally exhibited an "M"-shaped pattern.

Fig. 4 illustrates a significant negative correlation between Cstv and haze pollution. The markedly negative slope of the fitted line indicates that with an increase in terrestrial vegetation carbon sequestration, there is a clear downward trend in the concentration of $PM_{2.5}$. This further confirms the positive role of terrestrial vegetation carbon sequestration in mitigating haze pollution.

Control Variables

To eliminate the influence of other important factors on the estimation results. Referring to Gan et al. (2020) [55] and Zhou et al. (2019) [57], this paper also controls for the following factors in the model. Foreign trade (*Fdi*), measured by the natural logarithm of foreign

Table 2. Variable definitions.

Variables	Code	Definitions
Dependent variable	*Pm*	$PM_{2.5}$ concentration
Independent variable	*Cstv*	Carbon sequestration by terrestrial vegetation
Control variables	*Fdi*	Natural logarithm of foreign direct investment
	Pden	Total population of the city at the end of the year/administrative area
	Sci	The ratio of science expenditure to GDP
	Sec	Value added of the secondary industry/GDP
	Er	Environmental vocabulary in government work reports/total text vocabulary
	Ei	Total energy consumption/GDP

direct investment, and the technology spillover effects and economies of scale from foreign trade are usually beneficial in reducing pollution. Population density (*Pden*) and population gathering increase energy demand; this article uses the ratio of the total population at the end of the year to the administrative area to represent population density. The size of science expenditure (*Sci*) is measured as the ratio of urban science expenditure to GDP. Industrial structure (*Sec*) is measured by the proportion of value added by the secondary sector to GDP, and a higher proportion indicates that there may be higher energy consumption. Environmental regulation (*Er*), similar to Chen et al. (2018) [58], is represented by the proportion of environmental-related vocabulary in the urban government's work report. Energy intensity (*Ei)* is measured using the ratio of total urban energy consumption to GDP.

The definitions of the main variables are shown in Table 2.

Model Specification

This paper predicts that Cstv helps mitigate haze pollution after controlling for other factors that influence haze pollution (Hypothesis 1). To examine the impact of Cstv on haze pollution, referring to Rana and Sills (2024) [59], the following two-way fixed effects model is constructed. On the one hand, the two-way fixed effects model allows us to control for time-invariant unobserved heterogeneity at both the city and time levels, thereby mitigating potential biases arising from omitted variables. On the other hand, the two-way fixed effects model is well-suited for panel data analysis, allowing us to effectively examine the dynamic relationship between Cstv and haze pollution over time across multiple cities in China.

$$Pm_{it}=\alpha+\beta_1 Cstv_{it}+\Sigma\lambda Control_{it}+\mu_i+\upsilon_t+\varepsilon_{it} \quad (1)$$

In Equation (1), where Pm_{it} represents the $PM_{2.5}$ concentration of city *i* in year *t*; $Cstv_{it}$ denotes carbon sequestration by terrestrial vegetation; $Control_{it}$ denotes a set of urban characteristics; μ_i and v_t represent the city and time fixed effects; ε_{it} is the error term. α is a constant term; β_1 is the coefficient. β_1 is the coefficient we are most concerned about. If the estimate of β_1 is significantly negative, it means that Cstv is conducive to reducing haze pollution, thus supporting the basic view of this paper. If the estimate of $\beta 1$ is significantly positive, it means that Cstv exacerbates haze pollution.

To test whether Hypothesis 2 and Hypothesis 3 are valid, similar to Baron (2022) [60], we design the following mediating effects model:

$$Mech_{it}=\alpha+\beta_1 Cstv_{it}+\Sigma\lambda Control_{it}+\mu_i+\upsilon_t+\varepsilon_{it} \quad (2)$$

In Equation (2), $Mech_{it}$ refers to mechanisms, i.e., environmental performance and economic performance.

Results and Discussion

Descriptive Statistics

The descriptive statistics are presented in Table 3. It is evident that the minimum and maximum values for haze pollution (*Pm*) are 10.390 and 93.144, respectively, with a relatively large standard deviation. This suggests significant disparities in $PM_{2.5}$ concentrations among different cities, reflecting variations in air quality across regions. For *Cstv*, the minimum and maximum values are 0.556 and 4.819, respectively, with a minimal difference between the mean and median, indicating a relatively even distribution of *Cstv* overall. The substantial range between the minimum and maximum values for *Er* suggests slight variations in the intensity of environmental regulations among cities, possibly linked to the environmental preferences of local policymakers.

The Spatial Distribution of Haze Pollution and Carbon Sequestration by Terrestrial Vegetation

To visually display the spatiotemporal distribution of $PM_{2.5}$ concentration and Cstv in Chinese cities, we utilize ArcGIS software to create spatiotemporal

Table 3. Summary statistics.

Code	Mean	Std.dev	Min	Median	Max
Pm	44.212	19.271	10.390	41.050	93.144
Cstv	2.985	0.860	0.556	3.047	4.819
Fdi	11.713	1.912	6.236	11.794	16.364
Pden	0.042	0.030	0.002	0.036	0.136
Sci	0.227	0.183	0.031	0.171	1.138
Sec	48.967	10.230	19.760	49.290	74.570
Er	0.740	0.539	0.000	0.680	15.520
Ei	0.082	0.076	0.010	0.061	0.494

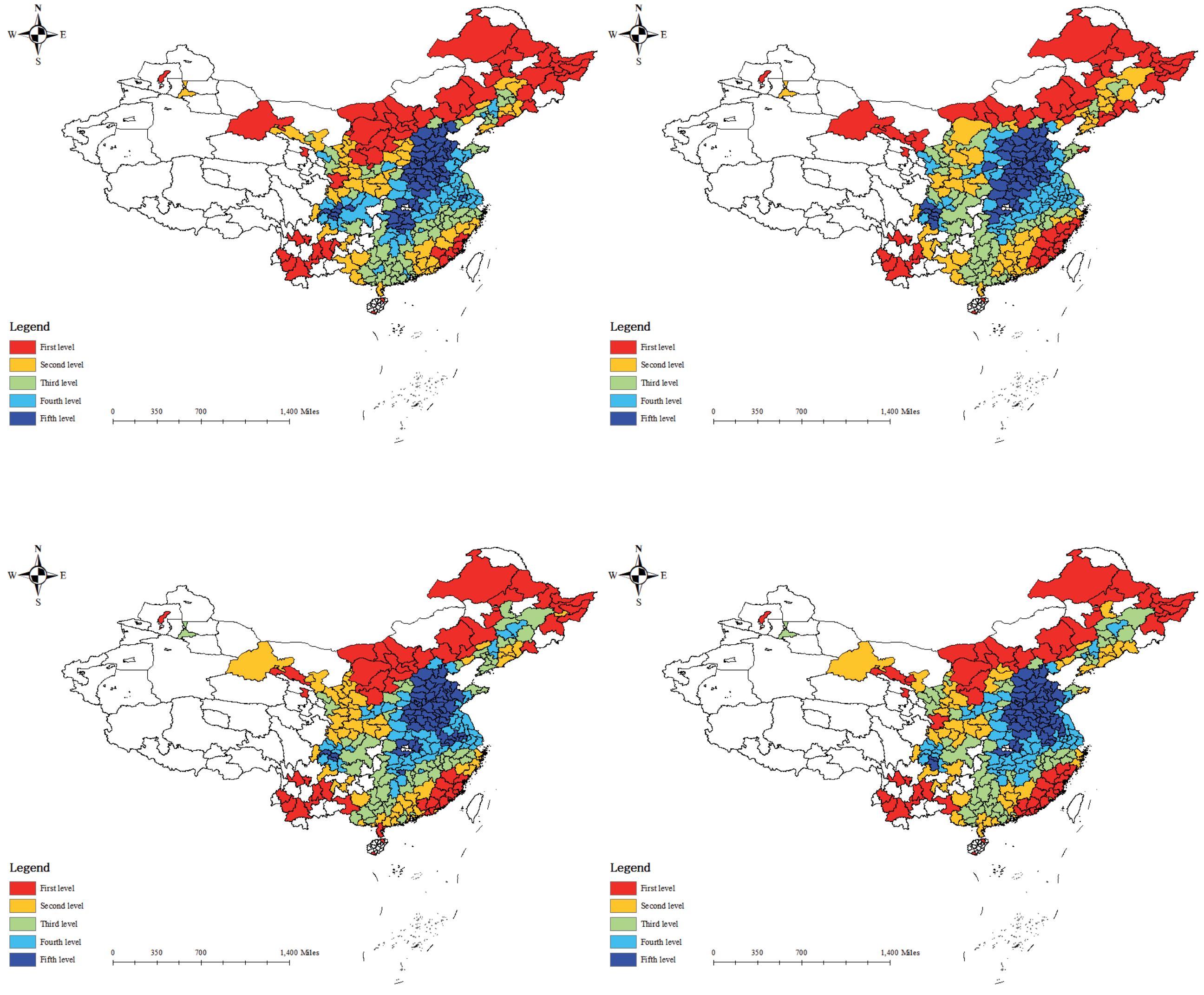

Fig. 5. The spatial and temporal distribution of $\text{PM}_{2.5}$ concentration in Chinese cities.
Note: The representative years, from left to right and top to bottom, respectively, are 2008, 2011, 2014, and 2017. The base map is from the Standard Map Service System of the Ministry of Natural Resources, and the base map audit number is GS(2019)1822.

distribution maps. As depicted in Fig. 5, this study showcases the spatial distribution of $PM_{2.5}$ concentration for the years 2008, 2011, 2014, and 2017, respectively. In the course of four distinct years, haze pollution ($PM_{2.5}$ concentration) has not exhibited pronounced fluctuations. Generally, cities with severe haze pollution are primarily concentrated in the Beijing-Tianjin-Hebei region, as well as provinces such as Shanxi, Henan, Shandong, Hubei, and Sichuan. Potential explanations for this pattern lie in the substantial proportion of heavy industries in these regions, with a predominant reliance on coal in their energy structures. Issues such as traffic congestion and emissions from vehicular exhaust are also prominent, all of which may contribute to an elevation in $PM_{2.5}$ concentrations.

As depicted in Fig. 6, our research showcases the spatial distribution of Cstv for the years 2008, 2011, 2014, and 2017, respectively. In different years, the distribution of Cstv exhibits a certain degree of similarity. Although there may be differences in absolute values, the overall trend shows no significant changes in distribution characteristics. This stability may stem from variations in vegetation coverage among different cities. Specifically, cities with higher levels of Cstv are spatially dispersed and do not exhibit clear clustering phenomena. This dispersion suggests that cities with high carbon sequestration do not depend on specific geographic locations or climatic conditions but are closely associated with their own vegetation coverage and management maintenance measures.

Benchmark Regression

Table 4 illustrates the impact of Cstv on haze pollution. In Column (1), we do not control for any fixed effects. In Column (2), no control variables are included in the model. Column (3) reports the result controlling only for year-fixed effects. Similarly, Column (4) reports the estimation result controlling only for city-fixed effects. Subsequently, we introduce all control variables into the model for a more comprehensive understanding of the influence of Cstv on haze pollution. The result in Column (5) shows that the coefficient of Cstv is significantly negative. This indicates that Cstv

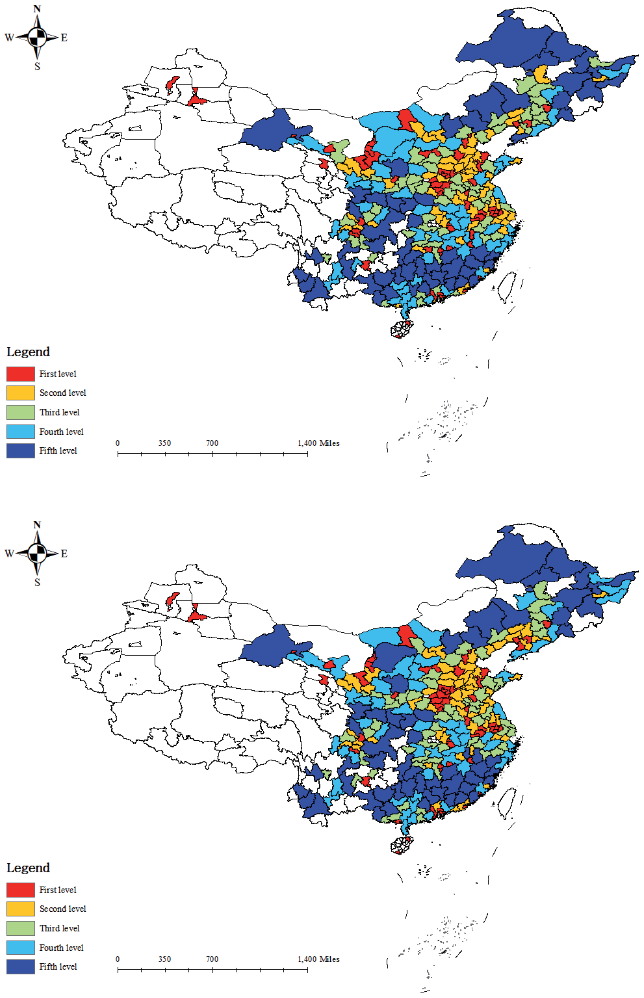

Fig. 6. The spatial and temporal distribution of Cstv in Chinese cities.
Note: The representative years, from left to right and top to bottom, respectively, are 2008, 2011, 2014, and 2017. The base map is from the Standard Map Service System of the Ministry of Natural Resources, and the base map audit number is GS(2019)1822.

significantly reduces haze pollution. With an increase in the amount of Cstv, the severity of haze pollution notably decreases. This outcome underscores the crucial role of vegetation in purifying the atmosphere and improving environmental quality, offering new insights and approaches for addressing haze pollution in China. Effectively lowering haze pollution levels can be achieved by preserving and expanding terrestrial vegetation, particularly in regions with severe haze pollution, such as urban and industrial areas. Hypothesis 1 is confirmed.

Robust Tests

A series of robustness checks are conducted to test the robustness of the baseline regression results. In the baseline regression, the dependent variable was not logged, which might lead to heteroscedasticity in the model. Therefore, we use the log-transformed $PM_{2.5}$ concentration as the dependent variable, and the result is presented in the Column (1) of Table 5. Subsequently, recognizing that green innovation technology encourages the development of low-carbon, environmentally friendly, and circular economies, thereby contributing to the reduction of environmental pollution at the source and minimizing environmental damage. Many studies also indicate that green innovation serves as a potent driving force for reducing haze [37, 61, 62]. Therefore, we incorporate urban green innovation as a crucial control variable into the model and re-estimate the regression. The corresponding result is displayed in Column (2), where the estimated coefficient of the independent variable remains significantly negative.

Thirdly, unlike other cities in China, Beijing, Shanghai, Tianjin, and Chongqing hold a "special status" as they are directly administered by the central government. The administrative level of municipalities is higher than that of ordinary cities, and the municipalities are able to receive more attention and importance from the central government. We remove four municipalities, and the regression test is re-run according to the baseline regression model. The result is shown in Column (3). Finally, considering that the double machine learning model combines the advantages of traditional causal inference methods and machine learning techniques, it can more accurately evaluate estimation results [63]. We use the double machine learning model for robustness testing, and the result is displayed in Column

Table 4. Benchmark regression results.

	(1)	(2)	(3)	(4)	(5)
Cstv	-6.020***	-13.368***	-6.100***	-25.408***	-13.250***
	(-3.740)	(-6.486)	(-3.778)	(-8.861)	(-6.861)
Fdi	0.220	-	0.227	-0.415*	-0.353*
	(0.459)		(0.480)	(-1.698)	(-1.965)
Pden	283.735***	-	284.640***	-108.712	22.739
	(4.604)		(4.606)	(-1.022)	(0.329)
Sci	-15.679***	-	-13.553***	-15.385***	-6.868***
	(-3.573)		(-2.961)	(-9.312)	(-5.114)
Sec	0.234***	-	0.140	0.446***	-0.151***
	(2.695)		(1.487)	(9.291)	(-3.702)
Er	-0.313	-	0.155	-0.704**	-0.073
	(-0.499)		(0.281)	(-2.051)	(-0.408)
Ei	-50.935***	-	-46.167***	-17.663***	3.846
	(-4.798)		(-4.269)	(-3.993)	(1.111)
City fixed effect	No	Yes	No	Yes	Yes
Year fixed effect	No	Yes	Yes	No	Yes
_cons	44.112***	84.117***	47.593***	113.166***	95.620***
	(5.253)	(13.672)	(5.613)	(11.487)	(14.248)
N	2830	2830	2830	2830	2830
R^2_a	0.422	0.933	0.457	0.897	0.935

Note: *** p<0.01, ** p<0.05, * p<0.1; T-values for clustering at the city level are shown in parentheses.

Table 5. The results of robust tests.

	(1)	(2)	(3)	(4)	(5)
Cstv	-0.177***	-13.408***	-13.496***	-4.734***	-13.259***
	(-5.041)	(-7.005)	(-6.948)	(-11.078)	(-6.889)
Gi	-	-0.897***	-	-	-
		(-4.079)			
Control variables	Yes	Yes	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes
Other policies	No	No	No	No	Yes
_cons	4.555***	95.117***	96.717***	-0.048	94.568***
	(33.914)	(14.476)	(14.373)	(-0.255)	(14.131)
N	2830	2830	2790	2830	2830
R^2_a	0.943	0.936	0.936	-	0.936

Note: *** p<0.01, ** p<0.05, * p<0.1; T-values for clustering at the city level are shown in parentheses.

(4). Finally, in recent years, the Chinese government has implemented a series of environmental regulatory policies, such as pilot carbon emissions trading, air pollution prevention and control action plans, pilot low-carbon cities, and pilot smart cities, which may have an impact on haze pollution. Similar to Zor (2023) [64], we include the above policies as control variables in the regression model. The results are shown in Column (5).

Endogenous Analysis

In this paper, the endogeneity is a fatal issue when discussing the impact of Cstv on haze pollution. That is, there may be an endogenous problem between Cstv and haze pollution, which can seriously interfere with the estimation results. Although this paper controls a range of control variables that may affect haze pollution, numerous unobservable factors may also affect air quality. Therefore, there may be endogenous problems caused by omitted variables in the econometric model. In view of this, our paper employs the instrumental variable approach, which is widely used in academia, to alleviate the authors' concerns regarding the endogeneity.

Table 6. Endogenous analysis.

	(1)	(2)
Rain	0.073***	-
	(4.726)	
Temp	-0.011**	-
	(-2.474)	
Cstv	-	-43.159***
		(-3.810)
Control variables	Yes	
City fixed effect	Yes	
Year fixed effect	Yes	
F-statistics of the first stage	24.720	
N	2830	

Note: *** p<0.01, ** p<0.05, * p<0.1; T-values for clustering at the city level are shown in parentheses.

In fact, a perfect instrumental variable is "God's gift". To be specific, the authors try to alleviate endogenous problems by using two-stage least squares (2SLS) regression. We utilize urban rainfall (*Rain*) and average annual temperature (*Temp*) as instrumental variables for Cstv. Both rainfall and average temperature are closely linked to the growth of terrestrial vegetation. Rainfall affects soil moisture, subsequently influencing the carbon absorption capacity of vegetation. Temperature impacts plant respiration and photosynthesis, and it is also associated with the carbon absorption capacity of vegetation. Therefore, the instrumental variables satisfy relevance. Moreover, rainfall and temperature are natural meteorological conditions generally unaffected by external factors. Hence, the instrumental variables satisfy exogeneity. The estimation results of 2SLS are shown in Table 6. The first-stage F-value is greater than 10, and the weak instrumental variable problem can be excluded. In the second stage, *Pm* is used as the dependent variable, and the Cstv still significantly decreases haze pollution. Thus, the benchmark regression results remain robust after mitigating the endogeneity.

Table 7. The results of impact mechanisms.

	(1) Environmental performance	(2) Economic performance
Cstv	-0.005***	0.126***
	(-3.510)	(3.375)
Control variables	Yes	Yes
City fixed effect	Yes	Yes
Year fixed effect	Yes	Yes
_cons	0.013**	8.834***
	(2.553)	(45.699)
N	2,830	2,830
R^2_a	0.759	0.977

Note: *** p<0.01, ** p<0.05, * p<0.1; T-values for clustering at the city level are shown in parentheses.

The Results of the Mechanism Analysis

Improving Environmental Performance

Hypothesis 2 posits that Cstv can reduce haze pollution by enhancing environmental performance. To test the validity of this hypothesis and draw on the methodology of [65], this study employs the ratio of industrial sulfur dioxide emissions to GDP as a measure of environmental performance (a lower ratio indicates higher environmental efficiency). Environmental performance is treated as the dependent variable, and the result is presented in Column (1) of Table 7, revealing that Cstv significantly reduces the intensity of industrial sulfur dioxide emissions at the 1% significance level. Thus, Cstv can mitigate haze pollution by improving environmental performance, confirming the validity of Hypothesis 2.

Enhancing Economic Performance

Hypothesis 3 predicts that Cstv can reduce haze pollution by improving economic performance. To test the validity of Hypothesis 3, we use urban per capita GDP to measure economic performance (the higher the per capita GDP, the higher the economic performance). Urban GDP per capita is widely recognized as a robust proxy for economic performance at the city level (e.g., Li et al., (2021) [66]; Ekeocha et al., (2021) [67]), as it reflects the overall economic output relative to the population size. We use economic performance as the dependent variable, and the result is shown in Column (2) of Table 7. Cstv significantly increased urban per capita GDP at the level of 1%. That is, Cstv can reduce haze pollution by improving economic performance. Therefore, Hypothesis 3 is validated.

The Results of Heterogeneity Analysis

Key Areas for Air Pollution Prevention and Control vs. Non-key Areas for Air Pollution Prevention and Control

Given that Cstv contributes to reducing haze pollution, it naturally prompts the question of whether the efficacy of Cstv differs between regions designated as key areas for air pollution prevention and control and those that are not. Typically, key areas for air pollution prevention and control are regions facing severe pollution issues where a series of robust measures have been implemented to mitigate pollution. Due to the substantial pollution burden in these areas, even if vegetation carbon sequestration exhibits some purifying effects, its impact might be relatively limited, and it may not significantly improve the pollution situation. In contrast, in non-key areas for air pollution prevention and control, pollution problems are generally less severe, allowing vegetation carbon sequestration to more significantly reduce pollutant concentrations. Key areas for air pollution prevention and control may receive greater government investment and measures, but these efforts might be concentrated on alternative pollution control methods rather than vegetation carbon sequestration. In non-key areas for air pollution prevention and control, the government might prioritize vegetation carbon sequestration as a method to reduce pollution. Based on the aforementioned analysis, we have reason to believe that the impact of Cstv on non-key areas for air pollution prevention and control is more pronounced. This nuanced understanding contributes to a more comprehensive assessment of the differential effects of vegetation carbon sequestration in distinct regions, providing specific and differentiated recommendations for future environmental governance decisions.

We stratify the sample into two groups: key areas for air pollution prevention and control (Air=1) and those outside this designation (Air=0). The results are presented in Columns (1)-(2) of Table 8, indicating that, in key areas for air pollution prevention and control, the impact of Cstv on haze pollution is not statistically significant. Conversely, in non-key areas for air pollution prevention and control, Cstv significantly reduces haze pollution at the 1% level. Also, the test for difference in coefficients between groups (*Diff*) was significant at the 1% level, indicating that the two groups were indeed significantly different. Key areas for air pollution prevention and control typically grapple with more severe pollution issues, prompting local governments to implement stringent control measures to mitigate pollution levels. Due to the substantial control measures in place and the progress made in environmental pollution control in these regions, the efficacy of Cstv in reducing haze pollution may be less pronounced. This finding underscores the importance of considering regional characteristics and diverse governance needs

Table 8. The results of heterogeneity analysis.

	(1) Air=1	(2) Air=0	(3) Key=1	(4) Key=0
Cstv	2.280	-15.567***	-10.095***	-15.574***
	(0.734)	(-7.328)	(-3.489)	(-6.209)
Control variables	Yes	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes
_cons	42.256***	103.962***	81.500***	104.493***
	(3.790)	(14.312)	(8.106)	(12.121)
N	590	2240	1120	1710
R²_a	0.957	0.934	0.928	0.940
Diff	-17.848***		-5.479***	

Note: *** $p<0.01$, ** $p<0.05$, * $p<0.1$; T-values for clustering at the city level are shown in parentheses.

when formulating targeted policies and measures in environmental management strategies.

Key Environmental Protection Cities vs. Non-key Environmental Protection Cities

In November 2007, the Ministry of Ecology and Environment issued the "Eleventh Five-Year Plan for National Environmental Protection[3]".This plan identified a list of 113 key environmental protection cities, prompting an inquiry into whether there are differences in the haze reduction effects of Cstv between key environmental protection cities and non-key environmental protection cities. Key environmental protection cities allocate more resources and policies towards environmental protection, potentially resulting in higher green coverage and carbon sequestration capacity. The vegetation in these cities may have reached a certain saturation point in its inhibitory effect on haze pollution, thus suggesting a relatively smaller impact of Cstv on haze pollution. Additionally, the industrial structure and energy consumption in environmentally protected key cities are subject to greater restrictions and regulations, further potentially limiting the effectiveness of Cstv in reducing haze. In contrast, non-key environmental protection cities may have more space and potential in terms of land use. These cities might possess more undeveloped land suitable for tree planting, green space creation, and increasing forest coverage, thereby enhancing the effectiveness of Cstv. Unlike key environmental protection cities, which may have invested significantly in the past, resulting in relatively high vegetation coverage, the growth potential of Cstv may be limited. Based on the analysis above, we anticipate that the haze reduction effect of Cstv may be greater in non-key environmental protection cities.

In accordance with the "Eleventh Five-Year Plan for National Environmental Protection", our sample is categorized into key environmental protection cities (Key=1) and non-key environmental protection cities (Key=0). The results, as depicted in Columns (3)-(4) of Table 8, unmistakably reveal a more pronounced inhibitory effect of Cstv on haze pollution in non-key environmental protection cities. Also, the test for difference in coefficients between groups (*Diff*) was significant at the 1% level, indicating that the two groups were indeed significantly different. This result underscores the heterogeneity between different city types. Non-key environmental protection cities typically confront more severe environmental challenges, including industrial emissions, high traffic density, and urban expansion, factors that may exacerbate issues related to haze pollution. In such circumstances, non-key environmental protection cities may urgently need to take action to alleviate the impact of haze pollution. Cstv has been demonstrated as a promising strategy capable of significantly improving air quality. This finding not only provides valuable insights for urban environmental management and policy formulation but also raises a series of thought-provoking questions.

Conclusions

Delving into the impact of Cstv on haze pollution not only enhances our understanding of the functions and roles of ecosystems but also provides scientific insights and effective pathways for addressing the current environmental challenges. This research holds significant practical implications for advancing ecological civilization and achieving sustainable

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[3] Due to space limitations, the authors have only compiled national-level carbon sink policies in recent years. More carbon sink policies at the provincial level can be found at the following link: https://www.qianzhan.com/analyst/detail/220/240131-11f1be25.html.

development. Utilizing balanced panel data from 283 cities across China at the municipal level spanning from 2008 to 2017, we employed the two-way fixed effects model to empirically test the influence of Cstv on air pollution. The available evidence leads us cautiously to the following conclusions:

First, Cstv significantly reduces haze pollution. This finding remains stable and reliable after a series of rigorous robustness tests. This finding holds paramount significance for addressing global climate change, safeguarding ecological environments, and enhancing human quality of life.

Secondly, the mechanism analysis results indicate that Cstv effectively alleviates haze pollution through two pathways: improving environmental performance and enhancing economic efficiency. On one hand, the increase in terrestrial vegetation improves soil quality, maintains water and soil, purifies air, and regulates climate, thereby enhancing environmental performance. On the other hand, the increased terrestrial vegetation also boosts income in agriculture, forestry, tourism, and other sectors, contributing to improved economic efficiency. These findings provide theoretical support for the formulation of scientifically sound environmental protection policies and economic development strategies.

Thirdly, the reduction effect of Cstv on haze pollution varies in different regions. In non-key areas of air pollution prevention and control, Cstv can significantly reduce haze pollution. In key areas for air pollution prevention and control, the role of Cstv is not significant. This may be related to the adoption of other stricter environmental protection measures in key areas for air pollution prevention and control. Meanwhile, compared to key environmental protection cities, Cstv has a greater impact on non-key environmental protection cities, which may be related to the insufficient environmental capacity and ecological construction of non-key environmental protection cities.

Based on the above conclusions, this article proposes the following policy recommendations:

First, it is imperative to strengthen urban greening planning to enhance urban vegetation coverage. Governments can encourage the inclusion of green spaces in urban planning, particularly in industrial and densely populated areas, by introducing vegetation protection policies and formulating greening indicators. Enhancing the management and maintenance of urban vegetation not only contributes to improving air quality but also elevates residents' quality of life. Additionally, governments can promote the installation of green roofs and vertical greening on buildings to maximize urban vegetation coverage, effectively reducing the formation of haze. The establishment of a carbon sequestration incentive mechanism can encourage businesses and individuals to participate in carbon sequestration efforts. Governments can incentivize businesses to undertake greening within their premises by providing tax incentives and economic rewards. This approach facilitates ecological development in industrial zones. Simultaneously, the creation of a carbon sequestration project fund supports individual and community involvement in carbon sequestration activities, fostering broader societal engagement in vegetation protection and augmentation.

Second, environmental protection policies, particularly those pertaining to vegetation carbon sequestration, should be enhanced. The government can incentivize regions to increase vegetation coverage, especially in areas heavily affected by haze, through the refinement of regulations, establishment of environmental standards, and implementation of incentive mechanisms. Establishing a robust management system for vegetation carbon sequestration, coupled with the monitoring and assessment of environmental performance, ensures that vegetation carbon sequestration efforts yield the anticipated environmental benefits. Simultaneously, the formulation of economic incentive policies can encourage businesses and individuals to engage in vegetation carbon sequestration projects. The government may implement measures such as tax incentives, financial support, and reward funds to economically motivate vegetation carbon sequestration initiatives, thereby encouraging active participation from enterprises and individuals. This approach not only contributes to enhanced economic performance but also provides an economically viable avenue for addressing haze-related challenges.

Third, in addressing key areas for air pollution prevention and control, the government must judiciously assess the actual effectiveness of vegetation carbon sequestration and consider potentially adopting more comprehensive governance strategies. Given the limited efficacy of vegetation carbon sequestration in such urban areas, the government may prioritize alternative and more impactful measures for mitigating haze, such as industrial emission controls and reductions in vehicular exhaust. This approach ensures the comprehensiveness and efficiency of haze mitigation efforts. By intensifying policy support and economic incentives for cities that are not key environmental protection cities, through initiatives such as project funding and tax exemptions, the government can encourage these cities to augment vegetation coverage and thereby reduce the extent of haze pollution. Simultaneously, the government can initiate vegetation carbon sequestration demonstration projects in key environmental protection cities, providing experiential insights and technical support for non-key environmental protection cities. Strengthening collaboration between key environmental protection cities and non-key environmental protection cities and fostering the exchange of experiences and resources can stimulate environmental protection initiatives in non-key environmental protection cities and enhance the positive role of Cstv.

Although this study provides valuable insights into the relationship between carbon sequestration and haze pollution, there are still some limitations and room for improvement. First, although a two-way fixed-effects model was used to analyze the data in this paper, this model may not be able to fully capture the nonlinear relationship between carbon sequestration and haze pollution. The use of nonlinear modeling or machine learning methods may better reveal the complex relationship between the variables. Second, the conclusions of this study are mainly based on data from specific regions in China, so their generalizability may be limited. Future studies can test the generalizability of these findings through cross-country or cross-regional comparative studies, for example, by selecting countries or regions with different environmental policies and levels of economic development for comparative studies to explore the effects of carbon sequestration on haze pollution in different contexts. This will not only validate the findings of existing studies but also identify new influencing factors and mechanisms. Finally, future studies could further use more refined data, such as county-level data, to validate our conclusions. While city-level data can provide valuable macroscopic perspectives, county-level data can reveal more subtle regional differences and localized factors, thereby improving the precision of the analysis and the reliability of the conclusions.

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Conflict of interest

The authors declare no conflict of interest.

Data Availability Statement

The datasets used during this research are available from the corresponding author upon reasonable request.

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