ARTICLE IN PRESS

Economic Systems xxx (xxxx) xxx

Contents lists available at ScienceDirect

Economic Systems

journal homepage: www.elsevier.com/locate/ecosys

Do vertical ecological compensation policies promote green economic development: A case study of the transfer payments policy for China's National Key Ecological Function Zones

Qiuyue Yang

School of Marxism, Anhui University, No. 111, Jiulong Road, Economic-tech Development Zone, 230601 Hefei City, Anhui Province, China

ARTICLE INFO

Keywords:
Vertical ecological compensation
Transfer payments
National Key Ecological Function Zones
Green economic efficiency
Green economic development

ABSTRACT

The transfer payment policy for National Key Ecological Function Zones is a typical vertical ecological compensation (VEC) policy that has been in place in China since 2008. This study treats this VEC policy as a quasi-natural experiment and utilises a slack-based measure model to calculate each county's green economic efficiency based on China's county-level data for the period 2003–2020. Then, the difference-in-differences method is used to evaluate the impact of the VEC policy on green economic efficiency and to verify its possible mechanisms. The results indicate that the VEC policy significantly improves the green economic efficiency of compensated areas, demonstrating that this policy promotes regional green economic development. Moreover, we find that the VEC policy may improve green economic efficiency by reducing the pollution caused by industrial development, promoting eco-industrial development and accelerating technological innovation. From the perspective of realising its three policy goals, the VEC policy not only improves the compensated areas' ecological environment quality, but also promotes economic growth and optimises public services in the compensated areas. Furthermore, an inverted U-shaped curve relationship between the scale of VEC and green economic efficiency is identified.

1. Introduction

In recent decades, China has promoted industrialisation by investing heavily in physical capital, labour, energy resources, and other factors, thereby contributing to the extensive economic growth of the country (Wang et al., 2009). However, this form of extensive economic growth has generated a series of problems, including environmental pollution, resource consumption, ecological deterioration, etc. According to the *Bulletin of China's Ecological Environment* published in 2021, the national ecological environment index value was 59.77, and the overall ecological environment quality was rated as general. Promoting ecological progress and strengthening environmental pollution controls are not only fundamental plans related to China's sustainable development, but also are important paths for China to improve its green economic efficiency and realise its green development goals. Chinese governments at all levels attach great importance to environmental protection and pollution control. The 18th and 19th National Congresses of the Communist Party of China (CPC) called for efforts to promote green, circular, and low-carbon development, and designated the establishment and improvement of the ecological compensation mechanism as one of the most crucial aspects of ecological

E-mail address: yueshiyqy@163.com.

https://doi.org/10.1016/j.ecosys.2023.101125
Received 16 February 2023; Received in revised form 3 May 2023; Accepted 8 May 2023
Available online xxxx
0939-3625/

Please cite this article as: Q. Yang, Do vertical ecological compensation policies promote green economic development: A case study of the transfer payments policy for China's National Key Ecological Function Zones, Economic Systems, https://doi.org/10.1016/j.ecosys.2023.101125

civilisation construction. The 20th National Congress of the CPC highlighted the importance of "promoting green development and the harmonious coexistence of humanity and nature" as one of the main tasks on China's path to modernisation, and explicitly stated the importance of establishing an ecological product value realisation mechanism and improving the ecological compensation mechanism. Significantly, green economic efficiency refers to the economic operational efficiency attained after considering environmental costs, indicating that improving green economic efficiency is the key to achieving green development. Therefore, promoting green economic efficiency is an important goal of China's development in the new era. Additionally, as one of the "four beams and eight pillars" of its ecological civilisation system, establishing and perfecting an ecological compensation mechanism is an important tool in China's overall plan to improve its green economic efficiency.

Since the 1980s, the Chinese government has explored and implemented various vertical ecological compensation (VEC) policies in several ecological fields, which have presently achieved positive results. Among these, the transfer payment policy for National Key Ecological Function Zones (NKEFZs) is the most representative and extensive VEC policy in China. NKEFZs transfer payment (hereafter 'the VEC policy') is a VEC policy, wherein the central government provides economic compensation via financial transfer payments to areas that are rich in ecological resources but relatively undeveloped in terms of their economies to compensate for the opportunity costs of development related to environmental protection. The goals of this policy include protecting the ecological environment, improving people's livelihoods and alleviating ecological poverty, which may help to improve the green economic efficiency of compensated areas. According to previous literature, although several scholars have extensively discussed the conceptual connotations, theoretical basis, framework construction and implementation strategies related to ecological compensation (Guan et al., 2016; Jing and Zhang, 2018), there are relatively few theoretical and empirical studies on the effects of ecological compensation policies. Prior studies have primarily evaluated the policy effects of VEC along two dimensions: environmental benefits (Xu and Zhang, 2017; Gong et al., 2021) and economic benefits (Hegde and Bull, 2011; Li and Li, 2021). However, these studies did not examine the impacts and mechanisms of VEC policy on green economic efficiency. Based on China's county-level data for the period 2003–2020, this paper takes the NKEFZs transfer payments policy as an example, and utilises the difference-in-differences (DID) model to conduct an empirical analysis of the green economic development effects associated with the policy. This paper contributes to current studies in two ways. Theoretically, it is the first to analyse the effects and internal mechanisms of the VEC policy from the perspective of green economic efficiency, and it examines the policy effects of VEC along three aspects: environmental protection, ecological poverty alleviation, and livelihood improvement. Methodologically, based on China's county-level data, the slack-based measure (SBM) model is adopted to estimate each county's green economic efficiency. Subsequently, the DID model is applied to comprehensively evaluate the green economic development effect of the VEC policy. Furthermore, this paper confirms that the VEC policy can promote compensated areas' green economic development by weakening polluting industrial development, promoting eco-industrial development, and triggering technological innovation.

The remaining sections are organised as follows. Section 2 summarises the definitions of ecological compensation, and discusses related literature. Section 3 analyses the background and theoretical basis of the VEC policy administered to the NKEFZs. Section 4 measures the green economic efficiency of each county in China. Section 5 describes the empirical models, sample method, and data sources used in this research. Section 6 reports and analyses the empirical results. Section 7 concludes this study and puts forward policy recommendations.

2. Literature review

2.1. The definitions of ecological compensation

According to Cuperus et al. (1996), the goal of ecological compensation was to restore ecological functions and natural values that continued to be affected despite undertaking every effort to minimise external impacts. Moreover, the ideas of ecological compensation were described as embodied in the construction of Dutch highway projects and summarised in specific implementation methods utilised for this compensation. Subsequently, Cuperus et al. (1999) and Cuperus et al. (2001) defined ecological compensation as compensation provided to replace the ecological function or ecological quality damaged by development. These studies also examined the specific measures, application fields and typical cases of ecological compensation projects. Additionally, Wunder (2005) and Engel et al. (2008) proposed the ecological compensation concepts of "payments for environmental/ecosystem services", and introduced the relevant characteristics, types and efficiency assessment methods of these concepts. They emphasised that "payments for environmental services" was an extremely useful environmental protection method that not only benefited the providers and buyers of ecological services, but also improved the resource base. Furthermore, many researchers incorporated ecological compensation into the concept of environmental (ecosystem) service supply, and conducted extensive research on relevant aspects of environmental service supply. Li and Liu (2010) and Xie et al. (2015) expanded the connotation of ecological compensation based on the actual developmental situation in China. Thus, ecological compensation includes not only "payments for environmental services", but also the economic compensation provided by individuals or units that contributes to environmental protection and ecological functions restoration.

Based on the administrative subordination relationship between compensators and recipients, ecological compensation can be divided into two types: vertical and horizontal ecological compensation. This paper focuses on the VEC policy, which means that the superior government provides ecological compensation to the subordinate government through financial transfer payments, including payments from the central government to local governments, from provincial governments to municipal governments, etc. The NKEFZs transfer payments policy studied in this research is the largest VEC policy implemented in China, and is guided by the central government. Specifically, this policy views the fiscal revenue and expenditure gaps as compensation standards, and replaces the horizontal ecological compensation implemented by local governments via financial transfer payments. Notably, this policy has three goals, environmental protection, people's livelihood improvement and ecological poverty alleviation (Xu and Zhang, 2017).

2.2. Theoretical research on ecological compensation policies

After a review of prior literature, it is evident that extensive theoretical research has been conducted on ecological compensation policies mainly in terms of their theoretical bases, mechanism construction, and standard setting. An analysis of relevant literature is presented below.

First, prior literature has primarily utilised auction theory, incomplete contract theory, principal-agent theory, and game theory to analyse the theoretical basis of ecological compensation. Ajayi et al. (2012) stated that the application of auction mechanisms to environmental service payment projects could resolve the information asymmetry that exists between environmental service providers and buyers. Li and Li (2014) and Li et al. (2014) constructed a VEC contract model for NKEFZs utilising a principal-agent theoretical framework that included the central and local governments. It analysed the optimal behaviour choices of different government levels under the condition of asymmetric information. Similarly, Ito (2022) employed the principal-agent model to discuss the design of ecological compensation incentive mechanisms and ecological service providers' behavioural responses. It concluded that if ecological compensation policies are effectively implemented, then ecosystem service providers are more likely to actively participate in environmental protection.

Second, the construction of ecological compensation mechanisms. Jack et al. (2008) indicated that the design of ecological compensation mechanisms should comprehensively consider the principle of equity and the coordination of environmental benefits and cost-effectiveness. Subsequently, Sattler and Matzdorf (2013) divided the ecological compensation mechanism into four stages: exploration, development, pilot and operation. Based on the policy objectives of environmental protection and poverty alleviation, Engel (2016) further analysed the design principles of the ecological compensation mechanism from the aspects of payment methods, preconditions, location selection, spatial coordination, etc. In response to problems existing in Chinese VEC systems, Mu (2013), Li and Sun (2014) suggested corresponding actions, such as increasing financial subsidies, imposing ecological compensation taxes, establishing an ecological product transaction compensation mechanism, exploring the market-oriented compensation mechanism, etc.

Third, current studies have utilised various methods to identify the compensation standards of ecological compensation policies in different regions, which may serve as a guide for implementing ecological compensation policies. Specifically, in terms of design principles, Gastineau et al. (2021) and Lu et al., (2021) believed that ecological compensation policies should adhere to the principles of minimising the total costs of ecological restoration and maintaining social welfare. Next, standardised methods were utilised to scientifically evaluate ecological compensation standards. Regarding ecological compensation standards accounting, Li and Li (2017) estimated the opportunity costs and ecological benefits of the VEC policy for the period 2009–2014 by using market comparison and conditional value methods, and compared them with the number of transfer payments observed. The estimation results highlighted the existence of a significant gap between ecological benefits and the number of ecological transfer payments, thereby indicating that the transfer payments failed to meet the requirements of the reasonable range of compensation standards.

2.3. Research on the effect of ecological compensation policy

2.3.1. The impact of ecological compensation policy on pollution reduction

Most prior studies suggested that ecological compensation policies improve compensated areas' ecological environment quality (Zhang, 2015; Gong et al., 2021). Zhang and Li (2015) and Zhang (2015) respectively constructed the principal-agent and game theory models, regarding environmental governance between the central and local governments. Through theoretical analysis, they concluded that the VEC policy significantly improved local environmental quality. Zhu and Chen (2020), Gong et al. (2021) regarded the VEC policy as an exogenous shock, and applied the DID model to test its pollution reduction effect. They similarly concluded that the policy significantly improved the ecological environment of NKEFZs. This effect was seen to increase over time. In contrast, a few scholars believed that, due to multiple factors, it may be difficult for ecological compensation policies to achieve the goals of pollution reduction and ecological environment quality improvement. For instance, Bennett (2008) found that China's Sloping Land Conversion Programme failed to significantly improve the ecological quality of forests and watersheds owing to significant issues with the compensation mechanism design and policy implementation. The specific reasons for the programme's failure included low compensation standards, archaic technologies, insufficient implementation budget, etc.

2.3.2. The impact of ecological compensation policy on economic development

Most scholars believed the VEC policy could reduce residents' poverty rates and promote regional economic development. In terms of theoretical research, Li and Shi (2017) introduced environmental factors and human capital into an economic growth model called the RCK model, and conducted a theoretical analysis of the internal relationship between ecological compensation and economic growth. The results demonstrated that ecological compensation could promote economic growth by improving capital growth rates. In terms of empirical research, Hegde and Bull (2011) concluded that Mozambique's Carbon Sequestration Plan contributed to increasing local households' cash income and consumption based on household survey data. Yuan et al. (2017), Li and Li (2021) respectively utilised the structural model and the DID model to investigate the poverty reduction effect of the VEC policy applied to the NKEFZs. They found that the policy reduced individuals' poverty by improving their sustainable livelihood ability, perfecting ecological environment quality, raising labour employment rates, etc.

2.3.3. Impacts of ecological compensation policy on green economic development

Few previous studies have systematically investigated the effects of ecological compensation policies on green economic development. Relevant research can be classified into two categories. First, some researchers have examined the internal relationship between ecological compensation and green economic development by simultaneously evaluating the environmental and economic benefits of ecological compensation policies (Ola et al., 2019; Pham et al., 2021). For example, Ola et al. (2019) used qualitative literature analysis and quantitative binary logistic regression methods to test the impact of ecological compensation policies on the economy, the environment and the coordinated development of the economy and environment. They found that the ecological compensation policies helped create a win-win situation between environmental protection and economic growth. Pham et al., (2021) and Truong (2022) found that Vietnam's Forest Ecological Compensation policy contributed to accelerating economic sustainable development, improving local ethnic minority residents' income, and promoting public infrastructure construction. Second, some researchers evaluated the internal relationship between ecological compensation and green economic development by establishing a comprehensive evaluation index system of environmental and economic benefits (Li and Li, 2018; Sun et al., 2021). Sun et al. (2021) constructed an evaluation system for ecological security and economic development, and calculated the degree of coordination between ecological security and economic development to compare the green development status of NKEFZs and non-NKEFZs in Southwest China. They found that, after implementing the ecological compensation policy, the ecological security level of the NKEFZs exceeded that of the non-NKEFZs, but the economic development level of the NKEFZs remained relatively low. Li and Li (2018) and Jin (2021) constructed a green poverty reduction index system based on the pressure state response model and entropy weight method to evaluate the effect of the VEC policy on green economic development and green poverty reduction. The former found that the poverty reduction effect of implementing VEC policy in the NKEFZs was poor. In contrast, the latter believed that the policy significantly improved the green poverty reduction index of NKEFZs, and that the larger the scale of ecological compensation was, the more obvious the green poverty reduction effect of this policy was.

2.4. Brief conclusion

According to the above analysis, the current research has the following deficiencies. First, while literature related to the VEC policy primarily focuses on various concepts, theoretical basis, mechanism designs, and compensation standards, relatively few theoretical studies examine the impacts of the VEC policy or the relationship between the VEC policy and green economic development. Second, while the transfer payments policy for NKEFZs is the most representative VEC policy in China, few empirical studies have examined its policy effects. More importantly, while previous empirical studies examined the pollution reduction and economic growth effects of the VEC policy based on city-level data, they have not examine the impact of the VEC policy on the compensated areas' green economic efficiency. Particularly, the internal mechanism of how the VEC policy affects green economic development has not been accurately identified. Given these limitations, this paper clarifies the relationship between the VEC policy and green economic development. Then, based on China's county-level panel data from 2003 to 2020, it employs the DID model to investigate the effects of the VEC policy on green economic development.

3. Institutional background and theoretical hypothesis

3.1. Institutional background

The NKEFZ refers to a region that undertakes important ecological functions, such as maintaining biodiversity, wind prevention and sand fixation, and water and land conservation. The goals of establishing the NKEFZs include providing ecological products, and protecting and restoring ecosystems. In the NKEFZs, high-intensity and large-scale urbanisation and industrialisation development activities should be restricted, and the supply capacity of ecological products should be strengthened (Li et al., 2014). To effectively improve the ecological environment of the NKEFZs and the quality of fundamental public service levels, and to promote regional green development, China's Ministry of Finance has implemented a VEC pilot programme in 211 counties since 2008. Subsequently, the Ministry of Finance promulgated the *Transfer Payment (Pilot) Measures for NKEFZs in 2009*, and revised the basic principles, distribution methods, incentive and restraint mechanisms, and policy objectives of ecological compensation for subsequent years.

In terms of transfer payment scope, the VEC policy provides ecological compensation for the following four areas: prohibited and restricted development areas in the main functional areas, deep poverty areas or regions with important ecological functions, major ecological engineering construction areas, and ecological civilisation pilot demonstration areas. The VEC policy adheres to the principles of "fairness, openness, transparency, step-by-step, incentives and constraints". Its original objectives include improving ecological environment quality and public service levels. In response to the national development goals of high-quality economic development and poverty alleviation, the Ministry of Finance has introduced "ecological poverty alleviation" into the objectives of the VEC policy since 2016. From an assessment mechanism perspective, the VEC policy has a strict performance assessment mechanism. Specifically, areas with notable achievements in environmental protection and poverty alleviation should be given corresponding compensation and rewards. In contrast, measures like deductions in the provision of compensation funds should be implemented in areas where the ecological environment has deteriorated due to unnatural reasons. Furthermore, the implementation of the negative list regarding industrial access is ineffective, and the effectiveness of ecological poverty alleviation is not obvious. Regarding policy evolution, during the period 2008–2021, the pilot scope and compensation scale of the VEC policy was expanding. The Ministry of Finance allocated 6918.11 billion yuan for NKEFZs, and the number of counties obtaining VEC reached 818. This change trend of the scope and scale of ecological compensation is shown in Fig. 1.

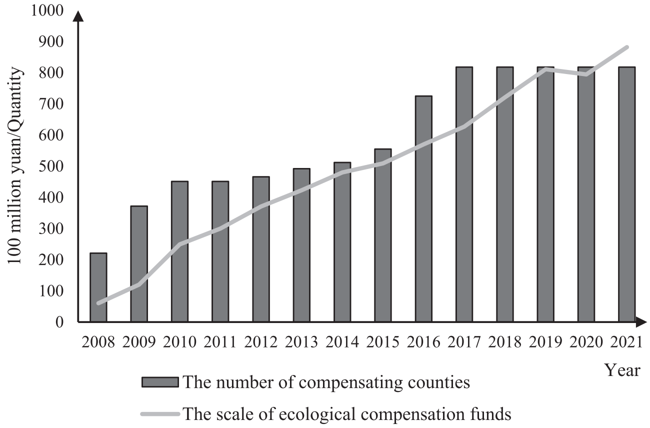

Fig. 1. Changes in the scope and scale of ecological compensation subsidies from 2008 to 2021. (Notes: The data are derived from the website of the Ministry of Finance).

NKEFZs transfer payment is an organic combination of transfer payment policy and ecological compensation policy. It is a new compensation mechanism implemented by the central government for NKEFZs under the original institutional framework of financial transfer payments. It compensates for the opportunity costs involved in restricting or prohibiting NKEFZs' development and the economic costs of ecological environment protection. As a typical VEC policy, the transfer payment policy for NKEFZs not only optimises the compensated areas' ecological environment quality (Xu and Zhang, 2017), but also significantly reduces residents' poverty rates (Li and Li, 2021). Thus, this policy may help to improve compensated areas' green economic efficiency.

3.2. Theoretical hypothesis

3.2.1. Policy effect

In recent decades, NKEFZs have played a key role in resource supply, improving environmental and ecological security as well as maintaining China's ecosystem stability. Against this background, the economic development level of NKEFZs may be somewhat adversely affected, with some regions even falling into the trap of "ecological poverty". The public good attributes and externalities of the ecological environment are important causes of "ecological poverty", and this problem can be solved by the government providing subsidies and levying Pigouvian taxes (Li and Li, 2021). Given this situation, China implemented the NKEFZs transfer payment policy in 2008, which is the most typical VEC policy in China. According to this VEC policy, the central government provides certain subsidies via financial transfer payments to local governments of the areas in which the NKEFZs are located to encourage local governments. These are meant to achieve the goals of environmental protection, ecological poverty alleviation, and residents' livelihood improvement, thus promoting green economic development in the compensated areas. In other words, the VEC policy can effectively improve compensated areas' green economic efficiency, which is embodied in three factors: environmental governance, economic growth and public service effects. In terms of environmental governance effects, the VEC policy improves the environmental governance level and ecological environment quality in compensated areas. The policy establishes a strict system for assessing ecological environment quality and assigns rewards and punishments to areas based on the assessment of their ecological environment quality. In this case, implementing an ecological compensation policy urges local governments to focus on environmental governance and ecological restoration, and to fulfil ecological assessment requirements by lowering pollution emission intensities and expanding the scale of natural resources (such as forests, wetlands and grasslands) in compensated areas. To obtain more ecological compensation, local governments may insist on environmental pollution control and ecologically fragile areas restoration for a long time, thereby improving the local overall ecological environment quality. In terms of its economic growth effect, the VEC policy improves compensated areas' economic development level and promotes ecological economic development. The ecological compensation fund increases the financial budget revenue of local governments. Using these funds they may directly provide some economic compensation to the residents of compensated areas, thereby increasing their income and promoting regional economic growth. Furthermore, the VEC policy improves and enhances compensated areas' environmental quality and productivity, which is conducive to promoting the simultaneous increases in the quantity and quality of agricultural products, thereby increasing residents' income. Additionally, the VEC policy encourages compensated areas to fully utilise their ecological resource advantages so that these areas can broaden their income channels by developing eco-agriculture and eco-tourism to achieve their economic growth goals. Regarding the public service effect, the VEC policy helps to improve compensated areas' public service levels. To satisfy the demand for public services, local governments spend a portion of the ecological compensation funds towards the constructions of fundamental public services, and focus on increasing the expenditure on infrastructure construction, medical services, social security, culture, and education to increase the supply of public services. These efforts serve to effectively improve local public service levels. Therefore, the following hypothesis is proposed.

H1. The VEC policy can improve compensated areas' green economic efficiency. From the perspective of realising the triple policy goals, the VEC policy not only improves ecological environmental quality, but also promotes economic growth and optimises public service quality in compensated areas.

3.2.2. Mechanisms

The VEC policy may improve compensated areas' green economic efficiency by weakening polluting industrial development, promoting eco-industrial development, and accelerating technological innovation. A detailed analysis is as follows.

The first mechanism is to reduce the pollution caused by industrial development. After implementing the VEC policy, the central government formulated a strict ecological environment quality assessment system, requiring compensated areas to improve the effectiveness of their ecological environment governance. Additionally, the central government assigns benefits and implements penalties based on the assessment results. Industrial pollution is not only an important source of environmental pollution, but also a key factor in destroying the ecological balance. To achieve their environmental assessment objectives, local governments may reduce industrial pollution emissions intensity by strengthening environmental regulations, such as shutting down polluting enterprises, levying environmental taxes, reducing subsidies, etc. According to the "Pollution Heaven Hypothesis", strict environmental regulations compel some polluting industrial enterprises to withdraw from their ecological function zones and migrate to development zones with low-intensity environmental regulations. Some less polluting industrial enterprises may continue to exist by reducing production and improving pollutant treatment efficiency. This leads to a significant reduction in the number of polluting industrial enterprises and total industrial output value in the compensated areas. Therefore, the VEC policy could improve compensated areas' green economic efficiency by weakening polluting industrial development. This leads to the second hypothesis.

H2. The VEC policy improves green economic efficiency by weakening polluting industrial development.

The second mechanism is to promote eco-industrial development. The VEC policy encourages compensated areas to utilise their rich ecological resources so that these areas can promote the realisation of ecological products' value through ecological industrialisation, thus improving their green economic efficiency. Additionally, ecological compensation helps to promote the development of eco-agriculture. In particular, the VEC policy improves environmental productivity in compensated areas and encourages residents of these areas to explore and develop green ecological agricultural products. The quality and price of eco-agricultural products tend to be higher than those of traditional agricultural products, thus, increased quantity and quality of agricultural products may transform the ecological advantages of compensated areas into economic advantages, further facilitating their green economic development. Furthermore, the VEC policy may promote industrial development related to eco-tourism. Specifically, the VEC policy is conducive to improving the ecological environment quality of subsidised areas and restoring ecologically fragile areas. More importantly, harmonious ecosystems and beautiful natural environments can serve as incentives for eco-tourism development. The development of eco-tourism industries not only protects the environment, but also increases residents' income, thereby improving their green economic efficiency. Hypothesis 3 is therefore proposed.

H3. The VEC policy improves green economic efficiency by promoting eco-industrial development.

The third mechanism involves promoting technological innovation. Under the triple goals of environmental protection, ecological poverty alleviation, and improving people's livelihood, governments can achieve green development by improving corporate technological innovation capacity. Specifically, local governments can provide financial and tax policy support to facilitate enterprises' technological innovation. This may encourage enterprises to improve their pollution treatment efficiency, reduce pollution emissions, and guide enterprises to produce high-tech products and green ecological products. Moreover, the VEC policy may result in "Potter effect". To be precise, local governments may formulate strict environmental regulation policies, which can force enterprises to improve their technological innovation capacities by increasing their research and development inputs and introducing high-end talent. The improvement of firms' technological innovation abilities not only improves the quality of the regional ecological environment, but also increases regional economic benefits. Therefore, the VEC policy can promote compensated areas' green economic efficiency by encouraging them to improve corporate technological innovation capacity. As such, the fourth hypothesis can be proposed.

H4. The VEC policy improves green economic efficiency by accelerating technological innovation.

4. Measurement of green economic efficiency

4.1. SBM model with undesirable output

In this study, each county is set as a production decision unit (DMU). Supposing that each DMU needs inputs $x = (x_1, \cdots, x_m) \in R_+^m$ for its production and produces both desirable outputs $y = (y_1, \cdots, y_n) \in R_+^n$ and undesirable outputs $b = (b_1, \cdots, b_k) \in R_+^k$, the production possibility set can be defined as follows:

$$P^t(x^t) = \left\{ \left(y^t, b^t \right) \middle| x_{im}^t \geq \sum_{i=1}^{I} \lambda_i^t x_{im}^t, y_{in}^t \leq \sum_{i=1}^{I} \lambda_i^t y_{in}^t, b_{ik}^t \geq \sum_{i=1}^{I} \lambda_i^t b_{ik}^t; \lambda_i^t \geq 0, \forall\ m, n, k \right\} \tag{1}$$

where λ_i^t is the weight vector and the above equation corresponds to the constant returns to scale technology.

According to Tone (2003), we construct a SBM model with desirable outputs and undesirable outputs. Its formula is presented as follows:

$$\rho^* = \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^x}{x_{i0}}}{1 + \frac{1}{n+k}\left(\sum_{r=1}^{n}\frac{s_r^y}{y_{r0}} + \sum_{l=1}^{k}\frac{s_l^b}{b_{l0}}\right)}$$

$$s.t.\begin{cases} x_{i0} = \sum_{j=1}^{J}\lambda_j x_j + s_i^x \\ y_{r0} = \sum_{j=1}^{J}\lambda_j y_j - s_r^y \\ b_{l0} = \sum_{j=1}^{J}\lambda_j b_j + s_l^b \\ s_i^x \geq 0,\ s_r^y \leq 0,\ s_l^b \geq 0,\ \lambda_j \geq 0,\ \forall\ i, j, r, l \end{cases} \tag{2}$$

where ρ^* is the efficiency value of DMU, reflecting the green economic efficiency of different counties, and its value satisfies $0 < \rho \leq 1$. The vectors $s_m{}^x$ and $s_k{}^b$ correspond to the excesses in inputs and undesirable outputs, respectively. $s_n{}^y$ represents shortages in desirable outputs. When $\rho^* = 1$, it means $s_m{}^x = s_n{}^y = s_k{}^b = 0$, indicating that there is no redundancy of inputs and unexpected outputs, and no shortage of the expected output, i.e., the DMU is efficient. $\rho^* < 1$ indicates a loss of efficiency in the DMU.

4.2. Variables and data source

Green economic efficiency represents the comprehensive economic efficiency after considering production factors, resource consumption and environmental costs. The input and output variables are described as follows.

4.2.1. Input

Labour and capital are important components of the production function. Therefore, this paper sets labour force and capital stock as input factors.

Labour input (*Labour*) is measured by the number of employees in each county at the year-end.

Capital stock (*Capital*). This paper draws on research by Ke and Xiang's (2012) to estimate the capital stock of each county in China using provincial and county-level data on fixed assets. The first step is to calculate the fixed asset investment price index. The average construction period of fixed assets is assumed as three years. According to the investment of the three types of capital goods, i.e., construction and installation work, purchase of equipment and other expenses, the investment proportion of each province is calculated according to its composition over the years. Next, the price indexes of the three types of capital are weighted by the investment proportion, and the total weighted price index based on 2002 can be obtained. The second step is to calculate the depreciation rate. Assuming that the residual value rate of all equipment is 5 %, the depreciation life of construction and installation work is 38 years, the depreciation life of machinery and equipment is 16 years, and the depreciation rates for these assets calculated by the geometric decline mode are 7.58 % and 17.08 %, respectively. Other expenses are amortised to the first two types of capital goods in proportion to their investment. According to the investment ratio of construction and installation work or purchase of equipment, we obtain the depreciation rate of construction and installation work or the purchase of equipment weighted by their ratio of investment in different regions. The third step is to calculate the capital stock of the base period according to Eqs. (3)–(4), and this paper further calculates the capital stock of other years based on Eq. (5).

$$I_t' = (I_t + I_{t-1} + I_{t-2})/3 \tag{3}$$

$$K_0 = I_0\left(\frac{1-\delta}{1+g}\right) \tag{4}$$

$$K_t = K_{t-1}(1-\delta) + I_t' \tag{5}$$

where I_t, I_{t-1}, I_{t-2} represent fixed assets investments in year t, t-1 and t-2, respectively. I_0 is the amount of new fixed assets investments, and I_t' is the new fixed assets in the year t. K_t and K_{t-1} are the capital stock in the period t and t-1, respectively. g is the average growth rate, and δ is the depreciation rate.

4.2.2. Output

The calculation of green economic efficiency must include both desirable and undesirable outputs.

Desirable outputs. According to Liu and Xin (2019), this paper selects regional economic development level (*GDP*) and residents' savings capacity (*Deposit*) as expected outputs, which are measured by real GDP and the balance of savings deposits for urban and rural residents, respectively. Moreover, this study uses the consumer price index based on 2002 to calculate real GDP.

Undesirable outputs. Most scholars have used industrial wastewater emissions, sulphur dioxide emissions (Fang et al., 2021), chemical oxygen demand (Liu and Xin, 2019), and carbon dioxide emissions (Xie et al., 2021) as unexpected outputs. Due to the scarcity of environmental quality data at the county level, PM2.5 concentrations and industrial wastewater discharge per unit of gross industrial output values are selected as undesirable outputs. Specifically, this paper uses the grid data of the global annual PM2.5 concentrations based on satellite monitoring published by the Atmospheric Composition Analysis Group, and uses ArcGIS software to

Table 1
The variables and definitions of green economic efficiency.

Input/Output	Variable	Definitions	Data source
Input	*Labor*	The number of employees at the year-end	*China Statistical Yearbook*
	Capital	Estimation of capital stock based on perpetual inventory method	*China County/City Statistical Yearbook*
Desirable output	*GDP*	Real GDP	*China County/City Statistical Yearbook*
	Deposit	The balance of savings deposits for urban and rural residents	
Undesirable output	*PM25*	PM2.5 concentrations	*Atmospheric Composition Analysis Group*
	Pwater	Industrial wastewater discharge	*China County/City Statistical Yearbook*

parse it into county-level annual average PM2.5 concentrations (*PM2.5*) in China from 2003 to 2020. Due to the unavailability of county-level water pollution emissions data in China, this paper calculates the proportion of the county-level GDP to the city-level GDP to construct an index *P*. Subsequently, city-level industrial wastewater emissions data is distributed to each county to estimate county-level industrial water pollution intensity. The calculation method is as follows:

$$P_{it} = GDP_{it} / \sum_{i=1}^{K} GDP_{it} \tag{6}$$

$$Pwater_{it} = P_{it} * waterpollution_{it} \tag{7}$$

where P_{it} refers to the proportion of GDP of a county i in year t to the GDP of the city where the county is located. $Pwater_{it}$ represents county-level industrial wastewater emissions. $Waterpollution_{it}$ represents city-level industrial wastewater discharge.

Based on the above models and data, we utilise MATLAB 2021a to measure each county's green economic efficiency. Table 1 shows the definitions and measurement methods of all variables.

5. Methodology and data

5.1. Model

Based on the characteristics of the VEC policy, this paper uses a multi-stage DID model to examine whether this policy drives the improvement of green economic efficiency in compensated areas. DID estimation equation is specified as follows:

$$GEE_{it} = \alpha_0 + \alpha_1 Policy_{it} + \alpha_2 CV_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{8}$$

where subscript '*i*' and '*t*' represent a specific county and a year, respectively. *GEE* is the green economic development level of each county, measured by green economic efficiency. $Policy_{it}$ is a dummy variable that equals one for the years following a county's selection as a pilot region, and zero otherwise. The coefficient α_1 indicates the impact of the VEC policy on regional green economic efficiency. *CV* represents a series of control variables, including industrial structure, education level, population density, government intervention degree, and health welfare. μ_i is the county fixed effect, capturing counties' time-invariant characteristics, and λ_t measures the year fixed effect. ε_{it} is a random error term.

5.2. Data and variables

The dependent variable is green economic efficiency (*GEE*). The SBM model is used to calculate the county-level *GEE* to characterise the regional green economic development level. The specific calculation methods and data sources are described in Section 4.

The core independent variable is the VEC policy (*Policy*), which estimates differences in the outcome variable (*GEE*) between pilot and non-pilot counties before and after establishing the VEC policy in the NKEFZs. *Policy* is a dummy variable, whose values for *Policy* in the control and treatment groups are equal to 0 before the treatment year, and 1 if a county is selected as a pilot county, *Policy* value becomes 1.

The control variables include industrial structure (*Stru*), education level (*Edu*), population density (*Popdensity*), government intervention degree (*GI*), and health welfare (*Medical*), which are measured by the ratio of the added value of the third industry to that of the second industry, the proportion of primary and secondary school students to the total population, total population divided by urban construction land area, the proportion of government financial expenditure to GDP, the ratio of the number of hospital beds in medical institutions to the total population, respectively. Relevant data are derived from the *China County Statistical Yearbook*. Additionally, considering the existence of a few extreme values among the control variables, a 1% bilateral tailing of the control variables is conducted.

5.3. Sample selection

In 2008, the VEC policy was officially implemented in China. To compare the differences in compensated areas' green economic efficiency before and after implementing the VEC policy, this paper sets the research period as 2003–2020. Many counties were selected as the NKEFZs, so the utilisation of county-level data may comprehensively reflect the policy effect. Hence, this paper takes

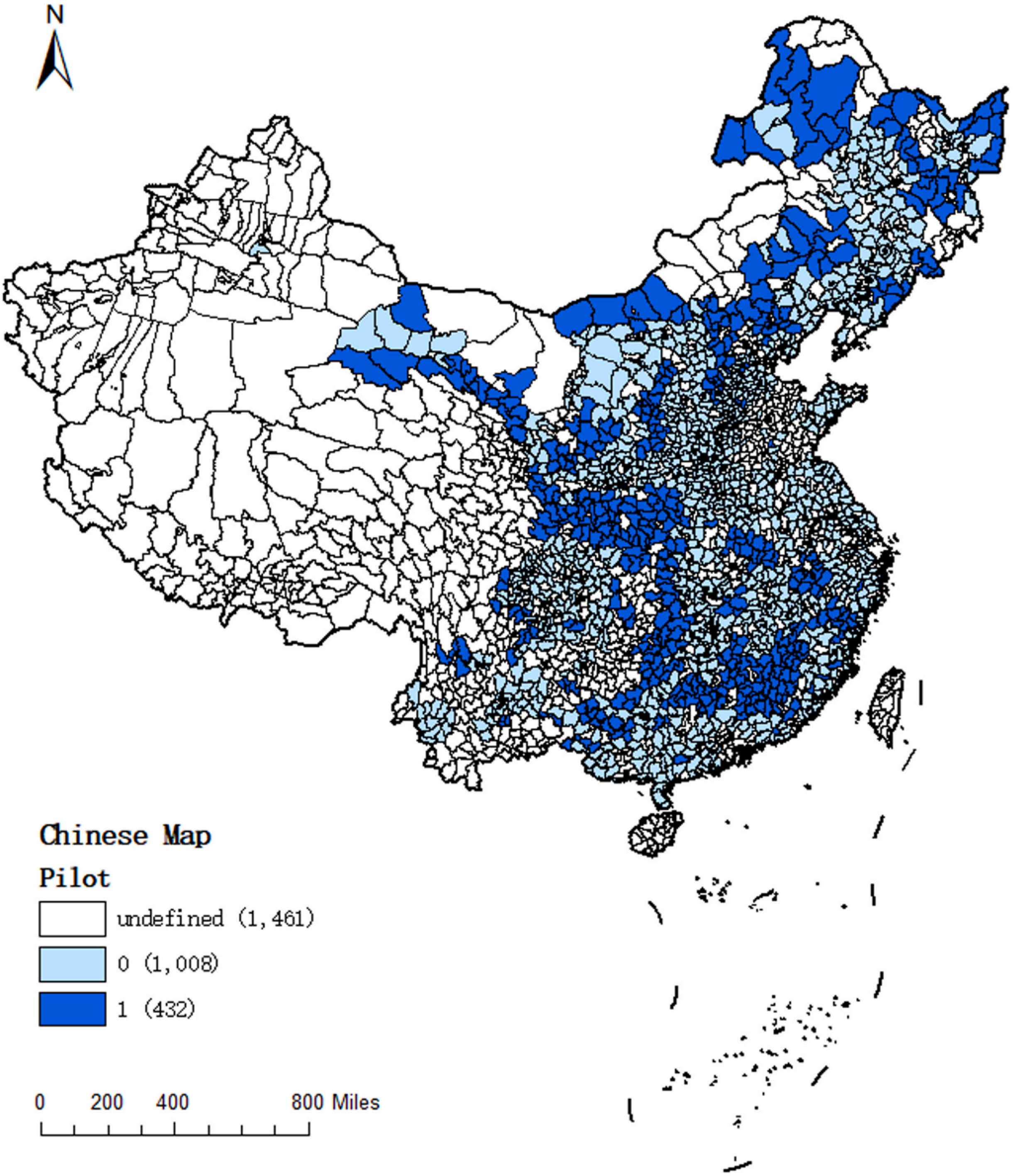

Fig. 2. The locations of pilot and non-pilot counties. (Notes: Blank areas on the map indicate undefined areas. Light blue and dark blue areas on the map represent non-pilot and pilot counties, respectively.).

counties (districts) as the research object, excluding the areas that lack economic and environmental data (such as Haidian District and Chaoyang District in Beijing), and excluding areas without continuous ecological compensation (such as Qingshuihe County, Liuzhi Special Economic Zone, and Shuicheng County). In detail, this paper selects the counties (districts) that have obtained VEC since 2008 as the treatment group, and defines other counties (districts) that have not implemented the policy as the control group. Finally, this paper selects the data of 1440 counties from 2003 to 2020 as the research sample, including 432 pilot counties and 1008 non-pilot counties. It is clear from Fig. 2 that pilot counties are concentrated in the Northeast and Midwest regions. Table 2 presents

Table 2
Descriptive statistics.

Variable	Treatment group			Control group		
	Obs	Mean	Std. Dev	Obs	Mean	Std. Dev
GEE	7776	0.304	0.161	18144	0.367	0.191
Policy	7776	0.512	0.500	18144	0.000	0.000
Stru	7776	1.325	0.974	18144	0.929	0.640
Edu	7776	0.121	0.037	18144	0.127	0.037
GI	7776	0.540	0.474	18144	0.444	0.395
Pop	7776	0.016	0.013	18144	0.042	0.028
Medical	7776	0.003	0.002	18144	0.003	0.002

the descriptive statistical results of the treatment and control groups. As shown, the average values of green economic efficiency, education level, and population density in the treatment group are lower than those in the control group, while the average values of industrial structure and government intervention in the treatment group are higher than those in the control group.

6. Results and discussion

6.1. Analysis of basic regression results

According to Eq. (8), this paper sets the dependent variable as *GEE*, and uses the multi-stage DID model to test the impact of the VEC policy on compensated areas' green economic efficiency. As seen in Table 3, the following conclusions can be obtained. First, when time-fixed effects are ignored, the estimated coefficients of *Policy* in columns (1)-(2) are 0.058 and 0.015, respectively, which are significant at the 1% level. In columns (3)-(4), the coefficients of *Policy* are 0.009 and significant at the 5 % level, indicating that after controlling time dummy variables, the policy improves compensated areas' green economic efficiency by 0.9 %. This demonstrates that the VEC policy significantly improves compensated areas' green economic efficiency, which is conducive to promoting regional green economic development. Therefore, H1 is supported. Moreover, after controlling for county and year effects, the industrial structure and population density are shown to be helpful in significantly improving regional green economic efficiency, while increasing government intervention degrees, improving education level and medical construction services have no significant impacts on regional green economic efficiency.

6.2. Parallel trend and dynamic effects

The precondition for obtaining unbiased estimation by DID method is that the control and treatment groups satisfy the parallel trend assumption. Precisely, in the absence of exogenous policy intervention, the variation trends of dependent variables in the

Table 3
The impact of the VEC policy on green economic efficiency.

Variable	(1)	(2)	(3)	(4)
	GEE	*GEE*	*GEE*	*GEE*
Policy	0.058***	0.015***	0.009**	0.009**
	(0.004)	(0.004)	(0.004)	(0.004)
Stru		0.004***		0.006***
		(0.001)		(0.001)
Edu		-0.569***		-0.022
		(0.056)		(0.066)
GI		0.017***		0.001
		(0.005)		(0.004)
Pop		0.002**		0.006***
		(0.001)		(0.001)
Medical		8.257 ***		1.303
		(1.251)		(1.366)
Constant	0.339***	0.379***	0.254***	0.248***
	(0.001)	(0.009)	(0.005)	(0.012)
County	Yes	Yes	Yes	Yes
Year	No	No	Yes	Yes
N	25,920	25,920	25,920	25,920
R^2	0.018	0.069	0.122	0.123

Notes: The parentheses are the clustered standard errors at the city-year level. * , ** and *** indicate 10 %, 5 % and 1 % significant levels, respectively. *County* and *Year* represent county and year fixed effects, respectively.

Table 4
Parallel trend and dynamic effects.

Variable	(1)	(2)
	GEE	*GEE*
Pre_4	0.001	0.001
	(0.007)	(0.007)
Pre_3	0.003	0.003
	(0.008)	(0.008)
Pre_2	0.004	0.004
	(0.008)	(0.008)
Pre_1	-0.002	-0.002
	(0.008)	(0.008)
Post_1	-0.000	-0.001
	(0.008)	(0.008)
Post_2	-0.000	-0.000
	(0.009)	(0.009)
Post_3	0.009	0.009
	(0.009)	(0.009)
Post_4	0.008	0.008
	(0.010)	(0.010)
Post_5	0.029***	0.029***
	(0.010)	(0.010)
Post_6	0.035***	0.035***
	(0.013)	(0.013)
Post_7	0.022**	0.021**
	(0.010)	(0.010)
Post_8	0.020*	0.019
	(0.012)	(0.012)
Post_9	0.023**	0.020*
	(0.011)	(0.011)
Post_10	0.034***	0.031***
	(0.011)	(0.011)
CV	No	Yes
County	Yes	Yes
Year	Yes	Yes
N	25,920	25,920
R^2	0.124	0.125

Notes: This regression sets 2008 as the base year. *Pre* refers to the year before the policy is implemented, and *Post* refers to the year after the policy is implemented.

control and treatment groups are consistent. Referring to Beck et al. (2010), this paper tests the parallel trend and dynamic effects of the VEC policy and verify the feasibility of DID model by the event study approach. The relevant model is set as follows:

$$GEE_{it} = \alpha_0 + \sum\nolimits_{t=m}^{n} \theta_t D_t + \alpha_2 CV_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{9}$$

where D_t is the dummy variable of the year before and after implementing the VEC policy. When the VEC policy is implemented in the current year, D_t equals one, and equals zero otherwise. θ_t indicates the impact of the VEC policy on green economic efficiency before and after implementing the pilot policy. This paper treats policy implementation year as the base year for event analysis. The parallel trend assumption requires that the difference regarding the policy effects of pilot areas and non-pilot areas in the year before policy implementation (*Pre*) are insignificant. The regression results of Eq. (9) are shown in Table 4. At the same time, this paper sets the first batch of pilots in 2008 as the cut-off point for policy implementation, and divides the research year into non-pilot period (2003–2007) and pilot period (2008–2020).

According to Table 4, the following conclusions can be drawn. First, before implementing the VEC policy, the coefficients of D_t (*Pre_1*-*Pre_4*) are not significantly different from zero. This indicates that there is no significant difference in green economic efficiency between treatment and control groups before implementing the VEC policy, satisfying the parallel trend hypothesis. Second, after implementing the policy, the coefficients of D_t (*Post_1*-*Post_10*) gradually changed from negative to positive, and the coefficients continue to increase. This means that the VEC policy contributes to improving compensated areas' green economic efficiency, and with the continuous expansion of the pilot scope, the policy effects show an upward trend. Third, from the fifth year after implementing the policy, the coefficients of D_t are significantly positive, indicating that the VEC policy has lagging effects on compensated areas' green economic efficiency. The possible reasons are as follows. At the initial stage, ecological compensation standards and environment quality assessment systems are not perfect, and the pilot scope is relatively limited, so the effect of the VEC policy at this stage is not obvious. With the continuous promotion of the policy and the expansion of transfer payments scale, the effect of VEC policy on green economic efficiency began to appear.

6.3. Robustness checks

6.3.1. Propensity score matching (PSM)

The prerequisite for using DID is that the dependent variables of treatment and control groups have the same variation trends before implementing the VEC policy. While the selection of pilot areas for VEC policy is not random, it is determined by the Ministry of Finance and the Ministry of Environmental Protection based on the ecological environment and geographic location. This paper uses the PSM method to further examine the influence of the VEC policy on green economic efficiency to avoid sample selection bias and improve the comparability between control and treatment groups. Considering that the VEC policy has multi-stage characteristics, this paper matches non-pilot counties with pilot counties year by year (Cao, 2020). Specifically, this paper utilises the K-nearest neighbour matching method and selects *GDP*, *Stru*, *Edu*, *Popdensity*, *GI*, and *Medical* as covariates to match the individuals in the treatment group with those in the control group.[1]

The prerequisite of using the PSM-DID method should satisfy the co-supporting hypothesis, so this paper conducts covariate imbalance testing and reports the results in Table 5. It concludes that almost all P values of covariates are insignificant, that is, there is no significant difference in the mean of covariates between the treatment and control groups after PSM treatment, which confirms the rationality of using PSM-DID. Additionally, Fig. 3 shows the test results of PSM matching effects, and specifically that the propensity score probability density of treatment and control groups are relatively close after matching, indicating that our PSM matching effects are good. Table 6 presents the results of the PSM-DID method. As shown, the regression results are consistent with the baseline regression results after adopting different PSM methods, implying that the VEC policy helps to promote regional green economic development. Therefore, the regression results of this research can be considered robust.

6.3.2. Further treatment of potential sample selection bias

Considering that compensated areas' green economic efficiency may be affected by regional economic development level and other environmental policies, this section adopts the following two methods to eliminate potential sample selection bias. First, this paper excludes municipality samples from the full sample to eliminate the impact of urban characteristics. There seems to be a huge gap in environmental protection levels and economic conditions between counties and districts under their jurisdiction. Therefore, this paper removes the relevant data of counties and districts directly under the central government from the whole sample, and retests the green economic development effect of the VEC policy. It can be seen from Table 7 that after excluding the samples of counties and districts under the jurisdiction of municipalities, the coefficients of *Policy* are still significantly positive, and the regression results are basically consistent with Table 3. Second, eliminate the impact of trans-provincial watershed horizontal ecological compensation policies. Considering that some regions are influenced by the vertical and horizontal ecological compensation policies at the same time, this section further excludes the county-level regions affected by tans-provincial watershed horizontal ecological compensation policies (including Xin'an River, Wei River, Jiuzhou River, Ting-Han River, Dong River, and Luan River). The results show that after excluding the areas affected by the horizontal ecological compensation policy, the coefficients of *Policy* are still significantly positive, indicating that the results of this paper are relatively robust.

6.3.3. Alternative measurement of dependent variables

Considering that using a single indicator to measure regional green economic development level may lead to some errors in the regression results, this paper replaces the dependent variable with green economic efficiency (*GEE1*) calculated by super-SBM model (Cheng, 2014), and re-test Eq. (8). As seen in Table 8, when the dependent variable is *GEE1*, the coefficients of *Policy* are significantly positive. This indicates that changing the measurement methods of regional green economic efficiency fails to change the policy effect of VEC, i.e., the policy can effectively improve compensated areas' green economic efficiency.

6.3.4. Alternative estimation method

Considering the potential bias in the coefficients of the multi-stage DID model estimated with fixed effects due to the time-varying policy treatment effects, this paper utilises the two-stage DID method for additional robustness tests (Gardner, 2021). Table 9 shows clearly that the coefficients of *Policy* are significantly positive at the 5 % level, implying that changing the estimation method does not affect the impact of vertical ecological compensation policies on green economic efficiency.

6.3.5. Placebo test

The placebo test is often used to test whether the regression results are affected by other unobservable factors such as economy, environment, and politics. Although this paper controls regional and time characteristics in the baseline model, the regression results may still be affected by unobserved factors. According to Wang et al. (2020), this paper constructs a virtual VEC policy variable (*Policy1*), and assumes that this dummy variable has an impact on randomly selected counties. Then, this paper regresses *GEE* on *Policy1*, and conducts this random data generating process 500 times to avoid contamination by any rare events. Random selection ensures that the artificial term *Policy1* has no impact on green economic efficiency, i.e., the estimation coefficient of *Policy1* is not statistically significant. Fig. 4 depicts the estimated distribution of *Policy1* coefficients from the 500 times of randomisation. The results show that the distributions of coefficients' kernel density of green economic development effect almost obey normal

[1] According to Cao (2020), this paper selects control variables and GDP as covariates and uses Stata command "psestimate" to verify the effectiveness of covariates.

Table 5
The mean difference between the treatment and control groups after matching.

Year	*GDP*	*Stru*	*Edu*	*GI*	*Medical*	*Pop*
2003	0.758	0.297	0.661	0.506	0.709	0.965
2004	0.590	0.587	0.140	0.088	0.014	0.175
2005	0.433	0.932	0.029	0.479	0.596	0.875
2006	0.577	0.542	0.660	0.333	0.078	0.738
2007	0.822	0.202	0.897	0.940	0.719	0.573
2008	0.940	0.511	0.509	0.483	0.715	0.751
2009	0.915	0.553	0.448	0.504	0.723	0.812
2010	0.829	0.674	0.887	0.240	0.056	0.411
2011	0.403	0.266	0.002	0.106	0.940	0.683
2012	0.895	0.669	0.886	0.999	0.273	0.712
2013	0.983	0.910	0.405	0.842	0.355	0.744
2014	0.309	0.284	0.353	0.241	0.197	0.482
2015	0.548	0.429	0.113	0.324	0.064	0.365
2016	0.540	0.805	0.346	0.036	0.506	0.665
2017	0.485	0.430	0.553	0.650	0.097	0.974
2018	0.638	0.121	0.985	0.121	0.046	0.714
2019	0.868	0.635	0.500	0.043	0.849	0.946
2020	0.154	0.819	0.651	0.123	0.156	0.777

Notes: The P values reported in the table are the differences in the mean values between the treatment and control groups.

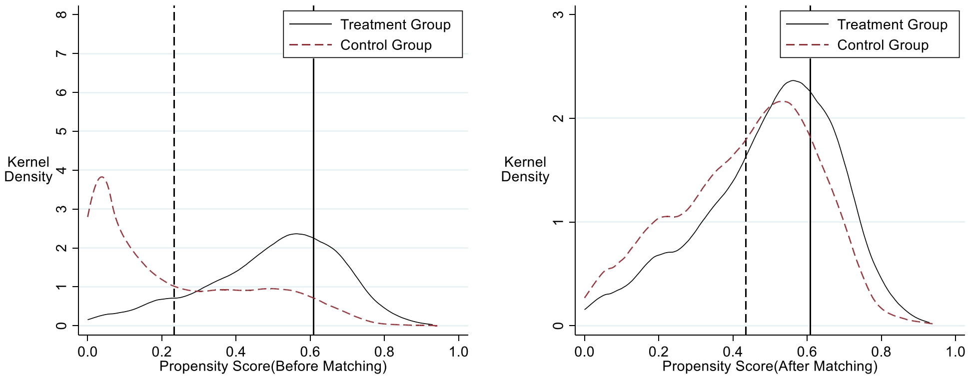

Fig. 3. Probability distribution density function of the propensity score.

Table 6
Robustness check 1: PSM treatment.

Variable	(1)	(2)
	GEE	*GEE*
Policy	0.009**	0.008**
	(0.004)	(0.004)
CV	No	Yes
County	Yes	Yes
Year	Yes	Yes
N	24,264	24,264
R^2	0.130	0.132

Notes: The parentheses are the clustered standard errors at the city-year level. *, ** and *** indicate 10 %, 5 % and 1 % significant levels, respectively.

distribution. This indicates that our results are less affected by other unobservable factors. Therefore, the regression results of this paper are robust.

6.4. Mechanism analysis

Theoretical analysis shows that the VEC policy may influence regional green economic efficiency by weakening polluting industrial development, promoting eco-industrial development and accelerating technological innovation. To verify the internal

Table 7
Robustness check 2: Further treatment of potential sample selection bias.

Variable	Excluding municipality samples	Eliminate the impact of trans-provincial watershed horizontal ecological compensation policy
	(1)	(2)
	GEE	*GEE*
Policy	0.013***	0.013***
	(0.004)	(0.004)
CV	Yes	Yes
County	Yes	Yes
Year	Yes	Yes
N	22,560	21,712
R^2	0.262	0.254

Notes: The parentheses are the clustered standard errors at the city-year level. *, ** and *** indicate 10 %, 5 % and 1 % significant levels, respectively.

Table 8
Robustness check 3: Alternative measurement of dependent variables.

Variable	(1)	(2)
	GEE1	*GEE1*
Policy	0.009**	0.009**
	(0.004)	(0.004)
CV	No	Yes
County	Yes	Yes
Year	Yes	Yes
N	25,920	25,920
R^2	0.114	0.116

Notes: The parentheses are the clustered standard errors at the city-year level. *, ** and *** indicate 10 %, 5 % and 1 % significant levels, respectively.

Table 9
Robustness check 4: Alternative estimation method.

Variable	(1)	(2)
	GEE	*GEE*
Policy	0.015**	0.013**
	(0.011)	(0.025)
CV	No	Yes
County	Yes	Yes
Year	Yes	Yes
N	25,920	25,920

Notes: The parentheses are the clustered standard errors at the city-year level. *, ** and *** indicate 10 %, 5 % and 1 % significant levels, respectively.

mechanism regarding the impact of VEC policy on regional green economic development, this paper replaces the development variables with mechanism variables (Jing and Zhang, 2021), and uses the following econometric model for testing:

$$M_{it} = \gamma_0 + \gamma_1 Policy_{it} + \gamma_2 CV_{it} + \lambda_i + \mu_t + \varepsilon_{it} \tag{10}$$

where M represents mechanism variables, including polluting industrial development level, eco-industrial development level, and technological innovation capacity.

This paper primarily adopts the following methods to construct mechanism variables. First, considering that heavily polluting industrial enterprises are more likely to be affected by environmental policies, this paper sorts the scope of heavily polluting industries based on the *Standards of Industrial Classification of China's Listed Companies* and *Heavily Polluted Industry Standards 2012* issued by the China Securities Regulatory Commission (Wang and Chen, 2018). Then, based on data from *Chinese Industrial Enterprise Database* (2003–2013), this paper calculates the sum of the industrial output value of heavily polluting enterprises and the ratio of heavily polluting industrial output value to GDP in different counties to measure counties' industrial development level. Second, due to limited relevant data on eco-industries at the county level, this paper selects agricultural product output (*Agri1*) and agricultural technology level (*Agri2*) as the proxy variables of eco-industrial development level, measured by the natural logarithm of total grain output and total power of agricultural machinery, respectively. Third, this paper adopts the Malmquist DEA model to measure counties' total factor productivity, and decomposes it into technical

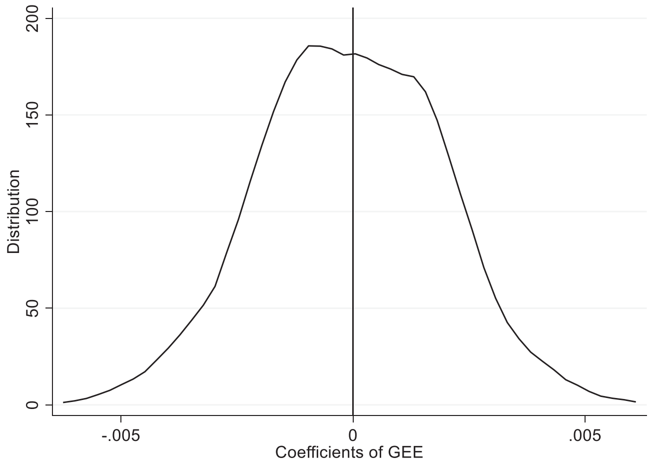

Fig. 4. Placebo test.

Table 10
Mechanism analysis.

Variable	Polluting industrial development		Eco-industrial development		Technological innovation
	(1)	(2)	(3)	(4)	(5)
	Heavy1	*Heavy2*	*Agri1*	*Agri2*	*Tech*
Policy	-0.075***	-1.247***	0.063***	0.121***	0.014***
	(0.005)	(0.173)	(0.017)	(0.017)	(0.004)
CV	Yes	Yes	Yes	Yes	Yes
County	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
N	14,308	14,308	25,920	25,920	24,480
R^2	0.313	0.364	0.139	0.428	0.740

Notes: The parentheses are the clustered standard errors at the city-year level. *, ** and *** indicate 10 %, 5 % and 1 % significant levels, respectively.

advancement and technical efficiency change. Furthermore, this paper utilises technical advancement change (*Tech*) to measure counties' production technological progress.

As seen in Table 10, the following conclusions can be obtained. First, when the dependent variable is *Heavy1* or *Heavy*2, the coefficients of *Policy* are significantly negative at the 1% level, indicating that the VEC policy significantly reduces heavily polluting industrial output value and its proportion to GDP in the compensated areas. Specifically, after being affected by the VEC policy, polluting industrial enterprises may avoid administrative penalties by reducing production, increasing efficiency or relocating factories. Additionally, polluting firms may work toward achieving cleaner production and industrial transformation. This effectively inhibits polluting industrial development, reduces pollution emissions intensity, and promotes regional economic development, thereby improving compensated areas' green economic efficiency. Second, when the dependent variable is *Agri1* or *Agri2*, the coefficients of *Policy* are positive at the 1 % level, indicating that the VEC policy increases agricultural product outputs and improves agricultural machinery technological levels, thus promoting eco-industrial development in the compensated areas. The positive effect of the policy on compensated areas' eco-industrial development compensates for the negative effect of the policy on industrial development, thereby improving regional green economic efficiency. Third, when the dependent variable is *Tech*, the coefficient of *Policy* is positive at the 1 % level. This shows that the VEC policy promotes compensated areas' technological innovation to a certain extent, i.e., the policy improves compensated areas' green economic efficiency by promoting technological innovation. Therefore, the VEC policy can improve compensated areas' green economic efficiency by inhibiting polluting industrial development, promoting eco-industrial development, and accelerating technological innovation. Overall, H2-H4 are validated.

6.5. Further analysis

Based on the analysis in the previous sections, the effects of environmental governance, economic growth, and public services of the VEC policy have not been investigated, and the effect of changes in ecological compensation scale on green economic efficiency is also ignored. In view of this, this section further analyses the impact of the VEC policy on compensated areas' green economic efficiency from the following two aspects: the decomposition effects of the VEC policy and the impact of changes in ecological compensation scale on green economic efficiency.

Table 11
The decomposition effects of the VEC policy.

Variable	Environmental protection effect	Economic growth effect	Public service effect
	(1)	(2)	(3)
	EPI	*EGI*	*PSI*
Policy	0.007**	0.002***	0.002*
	(0.003)	(0.001)	(0.001)
CV	Yes	Yes	Yes
County	Yes	Yes	Yes
Year	Yes	Yes	Yes
N	25,920	25,920	25,920
R^2	0.279	0.536	0.128

Notes: The parentheses are the clustered standard errors at the city-year level. *, ** and *** indicate 10 %, 5 % and 1 % significant levels, respectively.

6.5.1. Environmental protection, economic growth, and public service effects

The goals of the VEC policy include environmental protection, ecological poverty alleviation, and people's welfare improvement. Therefore, this section respectively replaces dependent variables with environmental protection, economic growth, and public service levels to further investigate the policy effect of VEC by the DID model. The specific model is set as follows:

$$EPI_{it}(EGI_{it}, PSI_{it}) = \delta_0 + \delta_1 Policy_{it} + \delta_2 CV1_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{11}$$

where *EPI*, *EGI* and *PSI* represent environmental protection, economic growth, and public service levels, respectively. *CV1* refers to control variables, including industrial structure (*Stru*), population density (*Pop*), government intervention degree (*GI*), and fixed assets investments rate (*Invest*).[2] The measurements of indicators are listed in Appendix.

According to Table 11, we can conclude that the coefficients of *Policy* are significantly positive at least at the 10 % level when the dependent variables are *EPI*、*EGI*, and *PSI*. This demonstrates that the VEC policy is helpful to improve ecological environment quality, promote economic growth and improve public service levels, thus promoting the improvement of green economic efficiency of compensated areas. This further confirms H1.

6.5.2. The impact of ecological compensation scale on green economic growth

Different scales of ecological compensation funds may have different effects on regional green economic efficiency. In detail, regions receiving more ecological compensation may have higher green economic efficiency, but high ecological compensation may reduce the enthusiasm that governments promote green economic development. Considering that the Ministry of Finance only disclosed the total compensation scale of each province, this paper empirically examines whether the changes in VEC scale affects compensated areas' green economic efficiency by using the fixed effect model based on the data of China's 31 provinces from 2008 to 2020.

$$GEE_{pt} = \rho_0 + \rho_1 Transfer_{pt} + \rho_2 Transfer_{pt}^2 + \rho_3 CV2_{pt} + \mu_p + \lambda_t + \varepsilon_{pt} \tag{12}$$

where *p* and *t* represent a specific province and year, respectively. *Transfer* refers to ecological compensation scale, measured by the logarithm of the number of ecological transfer payments received by provinces. *CV2* represents control variables, including industrial structure, education level, government intervention degree, population density, and medical construction level. The data for ecological compensation scale come from the information disclosure of the Ministry of Finance, and the rest of the data are collected from the National Bureau of Statistics.

According to Table 12, when *Transfer* is introduced into the model, the coefficients of *Transfer* are positive but basically not significant. When *Transfer* and *Transfer2* are simultaneously introduced into the model, the coefficients of *Transfer* are significantly positive, while the coefficients of *Transfer2* are significantly negative. Simply, whether the dependent variable is *GEE* or *GEE1*, there is an inverted U-shaped curve relationship between ecological compensation scale and green economic efficiency. The possible reason is that ecological compensation funds compensate for economic losses caused by environmental protection in the NKEFZs, which is conducive to promoting compensated areas' green economic development. However, if ecological compensation scale exceeds a certain limit, the NKEFZs may be overly dependent on financial subsidies given by the central government, which reduces their efforts in environmental protection and economic construction, and is ultimately detrimental to compensated areas' green economic development.

[2] This paper selects the ratio of fixed assets investments to GDP to measure the fixed assets investments rate at the county level. The data are derived from the *China County Statistical Yearbook*.

Table 12
The effect of VEC scale on green economic efficiency.

Variable	(1)	(2)	(3)	(4)
	GEE	*GEE*	*GEE1*	*GEE1*
Transfer	-0.000	0.014*	0.004	0.018**
	(0.008)	(0.008)	(0.009)	(0.009)
Transfer^2		-0.009**		-0.009**
		(0.004)		(0.004)
CV	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	372	372	372	372
R^2	0.212	0.228	0.185	0.200

Notes: The parentheses are the clustered standard errors. *, ** and *** indicate 10 %, 5 % and 1 % significant levels, respectively. *Province* and *Year* represent province and year fixed effects, respectively.

7. Conclusions

Based on China's county-level data from 2003 to 2020, this paper adopts the SBM model to calculate each county's green economic efficiency. This paper treats NKEFZs transfer payments policy as a quasi-natural experiment, and uses the DID model to evaluate the impact of the VEC policy on regional green economic development and verify its possible mechanisms. According to the above analysis, the following conclusions can be obtained. First, China's green economic efficiency kept an upward trend with some fluctuations from 2003 to 2020, and showed obvious spatial agglomeration characteristics. Second, the VEC policy significantly improves compensated areas' green economic efficiency, indicating that the policy promotes regional green economic development. Third, the VEC policy may improve green economic efficiency by weakening polluting industrial development, promoting eco-industrial development and accelerating technological innovation. Fourth, from the perspective of realising triple policy goals, the VEC policy not only improves ecological environment quality, but also promotes economic growth and optimises public service quality in compensated areas. However, there is an inverted U-shaped curve relationship between the scale of VEC and green economic efficiency.

This study provides important policy implications for China in terms of improving ecological compensation systems and promoting regional green economic development. First, the government should perfect the VEC policy and actively promote the construction of a diversified ecological compensation mechanism. The specific approach requires the formulation and development of flexible ecological compensation standards and the improvement of corresponding ecological compensation performance evaluation system considering both fairness and efficiency to improve the effectiveness of the VEC policy. The findings of this study also indicate that there is an inverted U-shaped curve relationship between ecological compensation scale and green economic efficiency. Therefore, the government should not only expand the ecological compensation scale, but also improve and revise ecological compensation standards according to local governments' financial income and ecological environment quality. The market and the government should work together to promote the construction of diversified ecological compensation mechanisms. Under the existing government-led ecological compensation system, the central government should gradually build a more diversified ecological compensation programme with market-oriented operation and public participation, mobilise the enthusiasm for local environmental governance and green development, and broaden the source of ecological compensation funds. Second, the central government should establish a long-term incentive-and-constraint mechanism to promote compensated areas' green economic development. Local governments should improve the incentive-and-constraint mechanisms that link the ecological protection effect with fund allocation, and formulate ecological compensation mechanisms integrating vertical and horizontal compensation to promote compensated areas' green economic development. Specifically, the central government should meaningfully improve the national plan for developing functional zones and the NKEFZs transfer payment policy under the consideration of the principles of fairness and efficiency to promote the two environmental policies to form a long-term incentive-and-restraint mechanism for green economic development. The central government should insist on the principle of "local compensation as the main part and central compensation as the supplementary part". It should also construct a horizontal ecological compensation mechanism that complements the existing ecological compensation mechanism. Therefore, the integration of vertical and horizontal ecological compensation models can promote regional green economic development.

Appendix A

1. Spatial and temporal evolution characteristics of green economic efficiency

According to the county-level green economic efficiency calculated in the Section 4, this section analyses the spatial and temporal evolution characteristics of China's green economic efficiency. Fig. A1 illustrates the average changing trend of green economic efficiency in China and different regions from 2003 to 2020. Table A1 shows global *Moran's I* index of China's green economic efficiency at the provincial and county levels. Accordingly, we can draw the following conclusions. First, the average value of

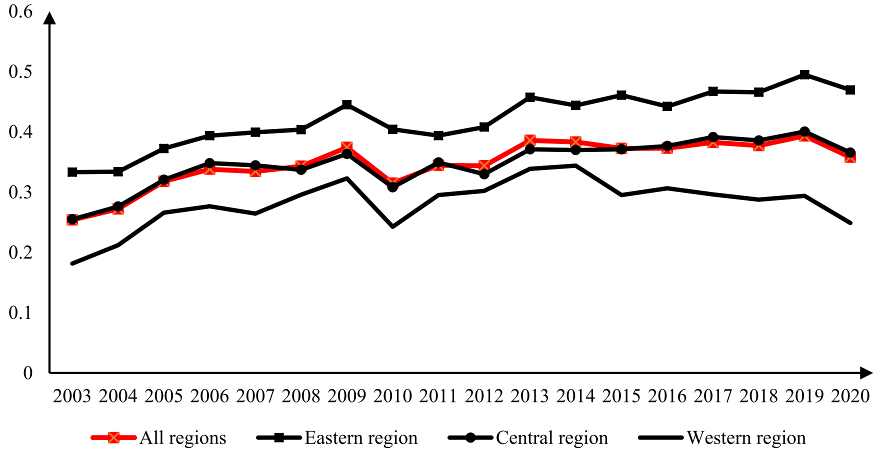

Fig. A1. Average changing trend of green economic efficiency in different regions from 2003 to 2020.

Table A1
Moran's I index of China's green economic efficiency.

Year	Provincial level			County level		
	Moran's I	Z value	P value	*Moran's I*	Z value	P value
2003	0.583	5.235	0.000	0.505	20.457	0.000
2004	0.468	4.302	0.000	0.510	20.679	0.000
2005	0.477	4.320	0.000	0.570	23.080	0.000
2006	0.434	3.968	0.000	0.556	22.492	0.000
2007	0.359	3.426	0.000	0.517	20.915	0.000
2008	0.353	3.345	0.000	0.512	20.724	0.000
2009	0.260	2.574	0.005	0.574	23.244	0.000
2010	0.276	2.706	0.003	0.600	24.283	0.000
2011	0.352	3.314	0.000	0.521	21.089	0.000
2012	0.350	3.298	0.000	0.523	21.164	0.000
2013	0.341	3.224	0.001	0.517	20.926	0.000
2014	0.369	3.454	0.000	0.498	20.167	0.000
2015	0.384	3.575	0.000	0.548	22.190	0.000
2016	0.336	3.181	0.001	0.534	21.607	0.000
2017	0.229	2.218	0.013	0.580	23.471	0.000
2018	0.382	3.560	0.000	0.581	23.507	0.000
2019	0.339	3.249	0.001	0.634	25.637	0.000
2020	0.237	2.333	0.010	0.618	25.005	0.000

national green economic efficiency exhibited an upward trend with some fluctuations, indicating that green economic development level in China maintained a steady growth trend. Second, during the period from 2003 to 2020, the average green economic efficiency is the highest in the eastern region, followed by the central region and the western region. Third, the *Moran's I* index at the provincial and county levels passed the significance test of 1 % in all years, indicating that China's green economic efficiency has significant spatial correlations at the provincial and county levels. Also, there are obvious spatial agglomeration characteristics in China's green economic efficiency.

Measurements of EPI, EGI, and PSI

This paper constructs comprehensive index system and utilises the entropy weight method to measure county-level environmental protection, economic growth, and public service levels. The specific methods are listed as follows. First, this paper introduces three indicators, including industrial wastewater discharge (*Pwater*), PM2.5 concentrations (*PM25*), and the proportion of artificial afforestation areas to administrative areas (*Forest*) to measure counties' environmental protection level. Second, this paper uses the following five indicators to measure county-level economic growth level, including real GDP (*GDP*), per capita fiscal income (*Fincome*), the proportion of residents' savings balance (*Deposit*), the proportion of secondary industry output value to GDP (*Second*), and the proportion of tertiary industry output value to GDP (*Third*). Third, this paper constructs a comprehensive public service index (*PSI*) from three aspects of basic education (*Primary*), medical services (*Medical*), and communication services (*Phone*). Finally, the entropy weight method is used to calculate environmental protection index (*EPI*), economic growth index (*EGI*), and public service index (*PSI*). The relevant data mainly come from *China Urban Statistical Yearbook*, *China County Statistical Yearbook*, *China Forestry Statistical Yearbook*, and *Atmospheric Composition Analysis Group*. The definitions and attributes of indicators are shown in Table A2.

Table A2
Environmental protection, economic growth and public service levels comprehensive index systems.

Comprehensive index	Basic index	Abbreviation	Attributes
Environmental protection index (*EPI*)	Industrial wastewater discharge (10000 tons)	*Pwater*	-
	PM25 concentrations (μg/m^3)	*PM25*	-
	The proportion of artificial afforestation areas in administrative areas (%)	*Forest*	+
Economic growth index (*EGI*)	Real GDP (yuan)	*GDP*	+
	The proportion of residents' savings balance in GDP (%)	*Deposit*	+
	Per capita fiscal revenue (yuan/person)	*Fincome*	+
	The proportion of output value of secondary industry in GDP (%)	*Second*	+
	The proportion of output value of tertiary industry in GDP (%)	*Third*	+
Public service index (*PSI*)	The proportion of primary school students in the total population (%)	*Primary*	+
	The number of beds in medical and health institutions per capita (bed/person)	*Medical*	+
	The number of telephone users (family)	*Phone*	+

References

Ajayi, O.C., Jack, B.K., Leimona, B., 2012. Auction design for the private provision of public goods in developing countries: lessons from payments for environmental services in Malawi and Indonesia. World Dev. 40 (6), 1213–1223.
Beck, T., Levine, R., Levkov, A., 2010. Big bad banks? The winners and losers from bank deregulation in the United States. J. Financ. 65 (5), 1637–1667.
Bennett, M.T., 2008. China's sloping land conversion program: institutional innovation or business as usual? Ecol. Econ. 65 (4), 699–711.
Cao, Q., 2020. Driving effects of national new zone on regional economic growth: evidence from 70 cities of China. China Ind. Econ. 7, 43–60.
Cheng, G., 2014. Data Envelopment Analysis and MaxDEA Software. Intellectual Property Publishing House.
Cuperus, R., Canters, K.J., Piepers, A.A.G., 1996. Ecological compensation of the impacts of a road. Preliminary method for the A50 road link (Eindhoven-Oss, The Netherlands). Ecol. Eng. 7 (4), 327–349.
Cuperus, R., Canters, K.J., De Haes, H.A.U., et al., 1999. Guidelines for ecological compensation associated with highways. Biol. Conserv. 90 (1), 41–51.
Cuperus, R., Bakermans, M.M.G.J., De Haes, H.A.U., et al., 2001. Ecological Compensation in Dutch Highway Planning. Environ. Manag. 27 (1), 75–89.
Engel, S., 2016. The devil in the detail: a practical guide on designing payments for environmental services. Int. Rev. Environ. Resour. Econ. 9, 131–177.
Engel, S., Pagiola, S., Wunder, S., 2008. Designing payments for environmental services in theory and practice: an overview of the issues. Ecol. Econ. 65 (4), 663–674.
Fang, C., Cheng, J., Zhu, Y., et al., 2021. Green total factor productivity of extractive industries in China: an explanation from technology heterogeneity. Resour. Policy 70, 101933.
Gardner, J., 2021. Two-stage differences in differences. Working paper.
Gastineau, P., Mossay, P., Taugourdeau, E., 2021. Ecological compensation: how much and where? Ecol. Econ. 190, 107191.
Gong, C., Zhang, J., Liu, H., 2021. Do industrial pollution activities in China respond to ecological fiscal transfers? Evidence from payments to national key ecological function zones. J. Environ. Plan. Manag. 64 (7), 1184–1203.
Guan, X., Liu, W., Chen, M., 2016. Study on the ecological compensation standard for river basin water environment based on total pollutants control. Ecol. Indic. 69, 446–452.
Hegde, R., Bull, G.Q., 2011. Performance of an agro-forestry based payments-for-environmental-services project in Mozambique: a household level analysis. Ecol. Econ. 71, 122–130.
Ito, J., 2022. Program design and heterogeneous treatment effects of payments for environmental services. Ecol. Econ. 191, 107235.
Jack, B., Kousky, C., Sims, K., 2008. Designing payments for ecosystem services: lessons from previous experience with incentive-based mechanisms. Proc. Natl. Acad. Sci. USA 105, 9465–9740.
Jin, S., 2021. The Impact of Transfer Payment in Key Ecological Function Areas on Green Poverty Reduction: Take Jiangxi Province as an Example. Jiangxi University of Finance and Economics,.
Jing, S., Zhang, J., 2018. Can Xin'an River basin horizontal ecological compensation reduce the intensity of water pollution. China Popul., Resour. Environ. 28 (10), 152–159.
Jing, S., Zhang, J., 2021. Trans-provincial basin horizontal ecological compensation and enterprise total factor productivity. J. Financ. Econ. 47 (5), 139–152.
Ke, S., Xiang, J., 2012. Estimation of urban fixed capital stock in China from 1996 to 2009. Stat. Res. 29 (7), 19–24.
Li, G., Li, H., 2018. Evaluation of green poverty reduction in national key ecological functional areas. Soft Sci. 32 (12), 93–98.
Li, G., Li, X., 2017. Ecological compensation standard, payment amount and adjustment target in national key ecological function areas. J. Xi' Jiaotong Univ. (Soc. Sci.) 37 (2), 1–9.
Li, G., Shi, H., 2017. The relationship between GTFP and regional economic growth based on Ramsey-Cass-Koopmans modeling. Resour. Sci. 39 (9), 1712–1724.
Li, G., Zhang, W., Li, X., 2014. Design and analysis of ecological compensation contract to national key ecological function zone. Bus. Manag. J. 36 (8), 31–41.
Li, W., Liu, M., 2010. Several strategic thoughts on China's eco-compensation mechanism. Resour. Sci. 32 (5), 791–796.
Li, X., Li, G., 2014. Governance of the hold-up in ecological compensation based on incomplete contract: taking national key ecological function area as a case. Financ. Trade Res. 25 (6), 87–94.
Li, X., Sun, B., 2014. System design and path selection for environmental pollution liability insurance under the perspective of ecological compensation. Insur. Stud. (5), 13–20.
Li, Y., Li, J., 2021. Does ecological compensation help winning the tough battle against poverty: Quasi-natural experiment research based on transfer payment in key ecological function zone. Financ. Trade Res. 32 (5), 23–36.
Liu, Z., Xin, L., 2019. Has China's belt and road initiative promoted its green total factor productivity: evidence from primary provinces along the route. Energy Policy 129, 360–369.
Lu, S., Zhong, W., Li, W., et al., 2021. Regional non-point source pollution control method: a design of ecological compensation standards. Front. Environ. Sci. 9, 724483.
Mu, L., 2013. Study on the innovation of ecological compensation mechanism in main functional areas of China. Res. Financ. Econ. Issues (7), 103–108.
Ola, O., Menapace, L., Benjamin, E., et al., 2019. Determinants of the environmental conservation and poverty alleviation objectives of payments for ecosystem services (PES) programs. Ecosyst. Serv. 35, 52–66.
Pham, V.T., Roongtawanreongsri, S., Ho, T.Q., et al., 2021. Can payments for forest environmental services help improve income and attitudes toward forest conservation? Household-level evaluation in the central highlands of Vietnam. For. Policy Econ. 132, 102578.
Sattler, C., Matzdorf, B., 2013. PES in a nutshell: from definitions and origins to PES in practice-approaches, design process and innovative aspects. Ecosyst. Serv. 6, 2–11.
Sun, M., Yang, R., Li, X., et al., 2021. Designing a path for the sustainable development of key ecological function zones: a case study of Southwest China. Glob. Ecol. Conserv. 31 (9), e01840.
Tone, K., 2003. Dealing with undesirable outputs in DEA: a slacks-based measure (SBM) approach [R]. GRIPS Research Report Series I 2003–0005:1–18.

Truong, D.D., 2022. Impacts of payment for forest environmental service policy in Vietnam: a case study of Muong Nhe protected area. Trees, For. People 7, 100198.

Wang, B., Mo, Q., Qian, H., 2020. The diffusion models and effects of the local environmental policy innovation: a micro-econometric evidence from the diffusion of River Chief Policy. China Ind. Econ. (8), 99–117.

Wang, F., Chen, F., 2018. Board governance, environmental regulation and green technology innovation: empirical test based on listed companies in China's heavy polluting industry. Stud. Sci. Sci. 36 (2), 361–369.

Wang, X., Fan, G., Liu, P., 2009. Transformation of growth pattern and growth sustainability in China. Econ. Res. J. 44 (1), 4–16.

Wunder S. Payments for environmental services: some nuts and bolts. CIFOR Occasional Paper No.42. 2005, 24.

Xie, G., Cao, S., Lu, C., et al., 2015. Current status and future trends for eco-compensation in China. J. Resour. Ecol. 6, 355–362.

Xie, R., Fu, W., Yao, S., et al., 2021. Effects of financial agglomeration on green total factor productivity in Chinese cities: insights from an empirical spatial durbin model. Energy Econ. 9, 105449.

Xu, H., Zhang, W., 2017. Study on the ecological protection effect of the transfer payment of national key ecological function areas: an empirical study based on Shaanxi data. China Popul., Resour. Environ. 27 (11), 141–148.

Yuan, L., Zhang, G., Huo, X., 2017. Study on the effect of ecological compensation on the residents' sustainable livelihoods in the national key ecological functional areas: based on the perspective of "targeted poverty alleviation. Theory Pract. Financ. Econ. 38 (6), 119–124.

Zhang, W., Li, G., 2015. Dynamic incentive effect analysis of transfer payment in national key ecological function zone. China Popul., Resour. Environ. 25 (10), 125–131.

Zhang, Y., 2015. The supervision of transfer payment to national key ecological function zone. China Econ. Stud. (6), 87–96.

Zhu, Y., Chen, H., 2020. Did the transfer payment in key eco-functional areas improve the eco-environment: based on PSM. South China J. Econ. (10), 125–140.