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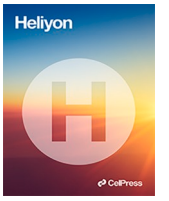

Research article

The impact and mechanism of vertical fiscal imbalance on green development efficiency: An empirical analysis based on city-level samples in China

Ruichao Liu, Kenong Sun, Hongjie Cao *

School of Economics, Qingdao University, Qingdao, 260071, China

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ABSTRACT

Green development has become a prevalent theme due to the tightening of resource constraints. This article explores the institutional factors that may contribute to the slow pace of green modernization in prefecture-level cities during the new era through the examination of the central-local fiscal relationship that local governments in China must navigate. A two-way fixed-effects model is used to theoretically analyze the impact of the increase in vertical fiscal imbalance (VFI) on green development efficiency (GDE) based statistical data from 270 cities between 2007 and 2020. The research shows that the increase in VFI has an N-shaped nonlinear effect on GDE, which is supported by various robustness and endogeneity tests. The greening process is significantly affected by the fluctuating dynamics of China's central-local fiscal relations. The VFI values of 0.2801 and 0.8892 are important transition points along the GDE curve, representing its peak and valley, respectively. At the end of the study period, only 12.13% of the studied cities experienced a higher quality facilitation effect. Streamlining the relationship between central and local finance is urgently needed for the widespread implementation of greening. The stock and supply of scientific and technological personnel play crucial roles in shaping the impact of the central-local fiscal relationship on green modernization. Specifically, VFI has an inverted U-shaped nonlinear impact on the level of scientific and technological human resources (S&TL). The inflection point occurs at VFI = 0.2710, which is close to the point of GDE. Furthermore, heterogeneity tests indicate that the institutional dividend of VFI is more pronounced in economically developed regions, eastern coastal areas, and regions with a more developed industrial structure. The study provides valuable insights for the government to promote green development. However, the lack of indicators and specific samples, as well as the reliance on limited assumptions, constrains the ability of this study to draw meaningful research conclusions. These limitations highlight the necessity for further related research in the future.

1. Introduction

Since the launch of reform and opening up, China's economic strength has grown by a significant margin. Moreover, the ecological environment has been significantly impacted by the increasing number of enterprises involved in resource exploitation and factor input [1], leading to various kinds of pollution and ecological damage. The cost of ecological degradation skyrocketed from 51.1

* Corresponding author.
E-mail address: jaytsoo@qdu.edu.cn (H. Cao).

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billion (RMB) in 2004 to 189.2 billion (RMB) in 2017 [2]. The constraints of environmental resources have become markedly tighter [3], which poses a threat to the progress of Chinese society and the well-being of its people [4]. Therefore, improving the coordination in the field of ecological civilization, building an ecological civilization system and constructing a beautiful China were established as important goals for future development in the 14th Five-Year Plan. China announced the "carbon neutral" strategy to the world and issued a series of policies in the following year, such as the "Carbon Neutral Action Plan by 2030″, "Opinions on Deepening the Battle of Pollution Prevention and Control", and "Opinions on Strict Energy Efficiency Constraints to Promote Energy Saving and Carbon Reduction in Key Areas". Harmony between human beings and nature has been one of the key points of Chinese modernization [4], and the continuous and in-depth promotion of green development has been the main theme of the current era.

The factors affecting green development have been discussed from the perspectives of financial development [5], environmental regulation [6], and foreign investment [7], but the importance of vertical fiscal imbalance in the context of the tax sharing system has rarely been mentioned. The fiscal relationship between the central and local governments is crucial for both macroeconomic control and regional development strategies, particularly in the context of China's modernization. This article examines the link between the institutional framework of fiscal decentralization and the level of regional green development in China. It seeks to determine the most effective level of vertical fiscal imbalance that can drive and support green development. The findings not only provide scientifically grounded answers for realizing China's high-quality development and for reforming the fiscal and taxation system but also offer decision-making reference for establishing a more complete and modern national governance system.

China's fiscal and tax system has undergone comprehensive and intensified reforms over the past decade since the Third Plenary Session of the 18th Central Committee. This has resulted in a more prominent fiscal trend of the upward transfer of fiscal power and the decentralization of administrative power. China's fiscal and taxation system is undergoing a critical period of socialist modernization and continuous development. Fiscal imbalances, which arise from balancing decentralized local autonomy and centralized state management, inevitably impact the efforts of central and local governments to promote green policies. The fiscal pattern of decentralization and devolution clearly limits the incentives for local governments and has largely contributed to the serious fiscal imbalance between the central and local governments. The "extrusion effect", "common pool effect", "flypaper effect" and other undesirable phenomena have intensified with the deepening of the imbalance, leading to the uneven development of various sectors within regions. Environmental pollution has also become more difficult to control, to the detriment of green and sustainable regional development [8]. Moreover, local governments, motivated by the "promotion tournament", not only favor high-priced, high energy-consuming, high-emission and high-pollution industries but also relax access conditions and environmental regulation constraints to compete for factors from outside the region, further worsening the local environmental governance situation and causing a loss of efficiency in local green development. However, "Chinese modernization is the modernization of material and cultural-ethical advancement" [4]. Improving the efficiency of green development is essential for promoting green modernization. It is necessary to optimize the relationship between central and local finances to implement eco-friendly growth.

This study makes three potential marginal contributions. (1) At the theoretical level, the article offers insights into the government's role in promoting green development within the framework of intergovernmental fiscal relations. This study provides a systematic analysis of the nonlinear impact of deepening vertical fiscal imbalance (VFI) on green development efficiency (GDE), addressing a research gap in this area and expanding the theoretical horizons of green development research by linking new institutional economics, finance, and environmental economics. (2) In the empirical study, the introduction of a higher power term of VFI confirms its nonlinear effect on GDE. It also identifies the optimal degree of VFI that enables local governments to maintain peak levels of green development. Additionally, this study verifies the nonlinear role of scientific and technological human resources in this context. These significant findings offer important policy references and data support for institutional mechanisms to effectively promote green modernization and development. (3) Three additional heterogeneity tests conducted regarding the effect of VFI on GDE verify the generalizability and variability of the impact and expand the exploration of specific impact scenarios. The results provide evidence for further reform of the fiscal system to promote green and sustainable economic development [9].

The remainder of this paper is organized as follows. The second section summarizes the relevant literature, based on which the impact of VFI on GDE is theoretically analyzed. The third section outlines the model design, defines variables, and conducts descriptive statistical analysis. The fourth section empirically tests the effect and mechanism of the impact of VFI on GDE at the city level. Finally, the last section summarizes the research conclusions and policy recommendations.

2. Literature review

2.1. Quantifying green development and analyzing influencing factors

In recent years, the concept of green development has gained significant attention as the global community recognizes the importance of sustainable and environmentally friendly practices.

In terms of research tools, green development efficiency serves as a crucial metric for gauging the harmonious interaction between humans and the environment, as guided by the principles of sustainable development. It provides a holistic assessment of how effectively resources are allocated and utilized within the constraints of prevailing scientific and technological capabilities, resource carrying capacity, and ecological limits [10]. As such, the measurement system for green development efficiency should encompass both anticipated and unanticipated inputs and outputs, as well as the total input value [10]. In addition to using the indicator evaluation methods of the Organization for Economic Co-operation and Development (OECD) and the United Nations Environment Programme (UNEP), researchers used a directional distance function (DDF) with weak disposability assumptions to consider undesirable outputs. The data envelopment analysis (DEA) method [11], specifically the SBM model, is widely recommended because it can

operate without requiring specific functional forms, price information, or behavioral assumptions. However, this approach has the drawback of slack improvement partial efficiency bias. On the other hand, the EBM model, which combines radial and nonradial characteristics, not only addresses this problem but also enhances the precision of the DEA measurement [12]. This makes it more suitable for accurately measuring green development efficiency.

Extensive research within the framework of the Environmental Kuznets Curve (EKC) hypothesis has brought to light the non-linear relationship between economic growth and environmental degradation [13]. Foreign direct investment (FDI) commonly leads to increased carbon emissions while driving rapid economic growth. However, the influence of FDI on both economic output and carbon emissions undergoes significant changes once it crosses the threshold, showing a nonlinear characteristic [14]. The impact of the digital economy on carbon dioxide emissions also shows an inverted U-shaped relationship when natural resource rent is used as the threshold variable [15]. Furthermore, the impact of trade openness on carbon emissions in global international trade is asymmetric [16], and even triggers a nonlinear change in in the energy consumption of information technology in countries with different levels of development [17]. These findings highlight the complexity of the relationship between economic growth and environmental degradation.

2.2. Impact of vertical fiscal imbalance

Currently, there are many studies on the impact of vertical fiscal imbalance on regional development, and the research findings are mixed. In general, studies can be roughly categorized into three distinct viewpoints.

One perspective holds that moderate vertical fiscal imbalances can be advantageous. Vertical fiscal imbalance, a natural occurrence in both developing and developed nations, serves as a crucial tool for decentralized governance [18], as it optimizes the distribution of public spending and enhances the efficiency of public goods provision. Via the appropriately transfer of fiscal power and decentralization of responsibilities, local governments are incentivized to compete on an individualized basis, optimizing resource allocation within limited revenue autonomy. This approach utilizes the economic leverage of taxation [19], complemented by well-structured vertical management policies and incentive mechanisms, to enable the central government to effectively oversee local governments and improve their overall efficiency in fulfilling their responsibilities [20].

From the perspective of input and output efficiency in science, technology, and innovation (STI), fiscal decentralization can enhance the independence of local public spending and empower local governments to foster and advance regional creative endeavors [21]. Additionally, the transfer payment system, which is essential for the central government to orchestrate fiscal allocation, can effectively manage the distribution of resources and guarantee the fair provision of public services in all regions [22,23].

The empirical evidence overwhelmingly supports the irrationality of vertical fiscal imbalances. Countries with higher imbalances are more susceptible to fiscal instability and soft budget constraints. For instance, excessive fiscal spending by local governments in Indonesia has resulted in reduced incentives for developing important areas such as education, health, and infrastructure services [24].

As vertical fiscal imbalances deepen, the revenue and expenditure behaviors of local governments become distorted, impacting operational efficiency [25]. This distortion weakens support for industrial green transformation and green industry cultivation, significantly inhibiting local environmental governance and green output efficiency [26].

Furthermore, the "fiscal insurance" behavior of central transfer payments impacts local government affairs and expenditure responsibilities to varying degrees [27]. The moral hazard generated by ex post relief also poses significant challenges [28]. This not only eases the local government's budgetary constraints in the long term [29] but also shifts the burden of funding local public goods to other regions through the "common pool," ultimately impeding the qualitative and quantitative advancement of regional development [30]. Therefore, these policies are not conducive to the overall enhancement of regional development.

The current literature on green development addresses a wide variety of fields and complex influencing factors, but there is still a noticeable gap in the comprehensive exploration of the fiscal relationship between the central and local governments. Research has focused mainly on the linear relationship between VFI and its impact while neglecting the nonlinear correlation with green development. Most scholars analyze the impact of vertical fiscal imbalance on green development through governmental actions, such as public expenditure preferences or transfers between central and local governments. However, other important pathways, such as the factor market or human capital structure, are often overlooked.

Therefore, this paper aims to thoroughly analyze the impact of vertical fiscal imbalance on green development efficiency by studying three aspects to enhance and supplement the existing related research.

3. Hypotheses development

3.1. The impact of vertical fiscal imbalance on the efficiency of green development

China's economic and social development typically follows a "government-led" model, entrusting local governments to enact the policies and directives proposed by the central government while also obligating them to take responsibility for their respective economic and social development. The fiscal and taxation system has recently undergone extensive modernization, resulting in the centralization of financial power at the national level. The vertical fiscal imbalance makes challenging for local governments to advance green development while addressing their own fiscal constraints. The dilemma arises from the need to balance decentralized local autonomy with centralized government management. Therefore, according to theory regarding fiscal decentralization, externalities, and public goods, it is argued that a vertical fiscal imbalance could have both favorable and unfavorable effects on the efficiency of green development.

After the Third Plenary Session of the 18th Central Committee of the Communist Party of China (CPC), the fiscal and taxation system commenced modernization and reform. The "high degree of freedom" experienced under decentralization encourages local governments to utilize their subjective initiative while operating within a moderate level of vertical fiscal imbalance [31]. This is intended to gradually enhance the efficiency of green development among various jurisdictions. Related analysis can be broken down into three key points: (1) Regional competition and incentive effects. The moderate upward transfer of financial power and reasonable decentralization of affairs among governments can establish an optimal vertical imbalance, under which local governments have the opportunity to autonomously exercise their initiative within a limited scope of revenue autonomy, optimize resource allocation by exploiting their information advantage according to local conditions, and reduce market predation. The same level of government can also provide higher quality public services due to the positive demonstration effect. The efficiency of city government services with low agency costs drives up the output levels of enterprises in the region and contributes to the improved efficiency of green development [32,33]. (2) The leadership role of the central government. In the transition to modernization undergone by China's social development and financial system, the central government has strong macrocontrol capabilities. Local governments are inclined to more effectively allocate funds to carry out their functions and increase the proportion of expenditure on green factors, such as environmental regulation and pollution supervision. This can contribute to the achievement of the green development goals set by higher levels of government. (3) The facilitating effect of transfer payments. The transfer payment strategy is an important means for the central government to compensate for the differences in horizontal development between regions. Central government transfers can reduce the scale and risk of local government debt, alleviate regional financial pressure, and promote equitable access to social welfare [34]. Special funds have also been set up to support local economic and social initiatives regarding aspects such as infrastructure, education and science, social security and environmental protection. Financial assistance to local governments is aimed at promoting environmentally friendly production.

A vertical fiscal imbalance exceeding a certain limit will inevitably distort the behavior of local government revenue collection and expenditure [35], resulting in a decline in operational efficiency. This is detrimental to the long-term development of the jurisdiction in the following ways. (1) Crowding out effect. Under severe vertical fiscal imbalance, local governments constantly search for sources of funding to reduce fiscal constraints. To achieve significant short-term GDP growth, they often exploit tax incentives or allocate overconcentrated financial resources to finance "short and quick" projects, such as infrastructure investment and real estate sector development [36,37]. This behavior, which prioritizes GDP, detracts from local government financial investment in green development and impedes the government's efforts to transition traditional industries into more environmentally friendly industries and to foster the growth of green enterprises. (2) Deregulation and cost shifting. To expand or maintain their tax bases, local governments often relax environmental regulations, which leads to harmful effects, such as the formation and concentration of polluting industries. Furthermore, corruption can further exacerbate the negative environmental impacts by intensifying and perpetuating the undermining effects of previously mentioned behaviors, such as the misallocation of funds and resources for environmental protection initiatives, as well as the inefficient implementation of energy efficiency projects [38]. The negative externalities of environmental pollution force local governments to transfer the costs of environmental protection through public resource pools. This may create "pollution havens" in neighboring underdeveloped regions, which could ultimately undermine the effectiveness of green development and produce significant amounts of undesired output [37]. (3) Moral hazard. Due to the existence of transfer payments and other underwriting policies, local governments maintain high expectations of financial support from the central government. This can soften government budget constraints, disconnect government behavior from budget limitations [35] and trigger the "flypaper " effect. The conventional performance appraisal system prioritizes local GDP, creating a scenario in which local officials may be incentivized to accept bribes from heavily polluting enterprises. As a result, financial resources are disproportionately allocated to the productive sector, while cleaner industries are marginalized [39]. In addition, the "free-rider" mentality may result in inadequate investment in education, innovation, and ecological maintenance [37]. This detrimental approach weakens the motivation of enterprises to pursue green transformation in the long term, ultimately compromising the sustainability of local ecological resources.

The above elaboration and literature review show that vertical fiscal imbalance can have a positive incentive effect and a negative inhibitory effect on the efficiency of green development. The EKC hypothesis suggests that there is a threshold variable in the relationship between economic growth and environmental pollution [13] Prior to reaching this threshold, economic growth brings about structural changes and a rise in energy consumption, contributing to environmental pollution. once the threshold is surpassed, continued economic growth promotes technological advancements and the implementation of environmentally friendly policies, ultimately leading to environmental improvement [39]. Given the significant role of regional economic development, the financial revenue and expenditure of local governments are directly tied to the regional economy. As a result, the interaction between incentive and inhibition effects can have a non-linear impact on the distribution of institutional dividends. In this context, we propose the following hypothesis.

Hypothesis 1. There is a significant nonlinear impact of vertical fiscal imbalance on the improvement in green development efficiency at the urban city level in China.

3.2. Analysis of mechanisms based on the level of human resources for science and technology

The high pressure on local revenues and expenditures under vertical fiscal imbalance often leads local governments to limit their efforts to economic construction within their jurisdictions and, in the process, neglect areas that affect long-term development, such as the introduction and cultivation of talent. The introduction and cultivation of talent can improve the quantity and quality of the regional labor force, which in turn can reduce the instability associated with foreign pollution control technology and clean production

[40] and provide the necessary support for reducing pollution emissions, saving energy and enhancing the green technology innovation capacity in the region. This yields a synergistic effect with technological innovation and promotes the transformation and upgrading of the regional industrial structure [41] and green total factor productivity [42].

However, in this transmission process, different degrees of vertical fiscal imbalance have different impacts on the level of scientific and technological human resources. When the degree of vertical fiscal imbalance is low, local governments have the ability to increase the absolute and relative scale of public spending on education and thus have the corresponding funds to improve talent policies and solidify the human capital foundation for green development. The free flow of scientific and technological talent improves the efficiency of resource allocation and promotes the green growth potential and the multiplier effect of scientific and technological talent. In contrast, an "economy-oriented" development strategy with excessive imbalance has a "crowding-out effect" on talent cultivation and introduction [43]. In this scenario, local governments shift focus away from scientific and technological talent and high-quality labor and reduce related financial support. This accelerates the loss of the general talent resources needed to break through bottlenecks and is not conducive to the improvement in regional green efficiency.

Given the above, this article proposes the following hypothesis.

Hypothesis 2. Vertical fiscal imbalances affect the green development efficiency of various cities in China through the transmission of technological human resources.

4. Methodology and data

4.1. Research methods and model design

4.1.1. Green development efficiency measurement model

Green development aims to balance economic benefits with ecological costs. When measuring green development in a region, it is important to consider the potential impact of pollution. The superefficient EBM model provides a way to measure the efficiency of economic production by incorporating pollutant outputs. This approach addresses the issues associated with variables and mixed radial characteristics, enabling a thorough analysis of trends and differences among evaluation units. The chosen model aligns with the present state of green development [44,45], which can be articulated as follows.

This paper takes each city as a decision unit and constructs the optimal frontier of green development efficiency inputs and outputs for different cities. Assuming that in period t ($t = 1, \ldots, T$), there are n decision units DMU_j ($j = 1, \ldots, n$), each with m inputs x_{ij} ($i = 1, \ldots, m$), s desired outputs $y_{\xi k}$ ($\xi = 1, \ldots, s$), and q undesirable outputs b_{pj} ($p = 1, \ldots, s$), to provide a clearer representation of the model, the specific super-efficient EBM model considering the undesirable output constraint is presented in equation (1):

$$\varphi^* = \min \frac{\alpha - \beta_x \sum_{i=1}^{m} \frac{w_i^- s_i^-}{x_{ik}}}{\rho + \beta_y \sum_{\xi=1}^{s} \frac{w_\xi^+ s_\xi^+}{y_{\xi k}} + \beta_b \sum_{p=1}^{q} \frac{w_p^{b-} s_p^{b-}}{b_{pk}}} \quad s.t. \begin{cases} \sum_{j=1, j\neq k}^{n} \lambda_j x_{ij} + s_i^- = \alpha x_{ik} \quad i = 1, 2, 3, \cdots m \\ \sum_{j=1, j\neq k}^{n} \lambda_j y_{\xi j} - s_\xi^+ = \rho y_{\xi k} \quad \xi = 1, 2, 3, \cdots s \\ \sum_{p=1, j\neq k}^{n} \lambda_j b_{pj} + s_p^{b-} = \rho b_{pk} \quad p = 1, 2, 3, \cdots q \\ \lambda_j \geq 0, s_i^- \geq 0, s_\xi^+ \geq 0, s_p^{b-} \geq 0 \end{cases} \tag{1}$$

where φ^* denotes the combined efficiency of the decision unit; x_{ij}, $y_{\xi j}$ and b_{pj} denote the inputs, desired outputs and undesirable outputs of the predicted decision unit k ($k = 1, \ldots, n$), respectively; s_i^-, s_ξ^+, and s_p^{b-} are the slack variables of the input indicator i, desired output indicator ξ, and undesirable output indicator p, respectively; α and ρ are the input and output planning parameters of the radial component; w_i^- denotes the importance of each input indicator i; w_ξ^+ and w_p^b are the importance of desired and undesirable outputs (ξ and p), respectively; β_x, β_y, and β_b denote the importance of the nonradial components of inputs, desired outputs and undesirable outputs in the efficiency value calculation, respectively; and λ_j is the coefficient of the linear combination.

4.1.2. Modeling the effect of vertical fiscal imbalance on the efficiency of green development

As shown above, the total effect of vertical fiscal imbalance on regional green development efficiency needs to be further clarified, and few related studies have been conducted at the microlevel of cities. Therefore, equation (2) is tested using city-level panel data.

$$GDE_{it} = \gamma_1 VFI_{it} + c_l Control_{it}^l + \mu_i + \eta_t + \varepsilon_{it} \tag{2}$$

In the formula, *GDE* denotes regional green development efficiency, *VFI* denotes vertical fiscal imbalance, and *Control* denotes a set of control variables, including financial development (Finance), fixed asset investment (Fixed inv), population density (Density), competition for political performance (Compete), level of scientific and technological human resources (S&TL), urbanization rate (Urbanization), and openness to the outside world (Open consumption). γ and c are the coefficients to be estimated, reflecting the effect of the explanatory variable on the explained variable; ε is the random disturbance term; i is the city; and t is the year.

Notably, the dispersion of prefecture-level cities may lead to differing levels of green development within each city. This could

result in individual effects or time effects, such as omitted variables that do not vary over time or individual heterogeneity. To address this issue, a two-way fixed effects model is adopted, where μ represents city fixed effects and η represents time fixed effects. This model effectively mitigates the impact of omitted variables that differ between individuals but remain constant over time, allowing a more accurate observation of the relationship between VFI and GDE.

This article aims to investigate the potential nonlinear effect of vertical fiscal imbalance on green development efficiency. To achieve this, the model gradually introduces higher power terms of the core explanatory variables [46] and sets up equations (3) and (4).

$$GDE_{it} = \gamma_1 VFI_{it} + \gamma_2 VFI_{it}^2 + c_l Control_{it}^l + \mu_i + \eta_t + \varepsilon_{it} \tag{3}$$

$$GDE_{it} = \gamma_1 VFI_{it} + \gamma_2 VFI_{it}^2 + \gamma_3 VFI_{it}^3 + + c_l Control_{it}^l + \mu_i + \eta_t + \varepsilon_{it} \tag{4}$$

In the above model, γ_1, γ_2 and γ_3 are the core explanatory parameters of interest in this paper, and the impact of *VFI* on *GDE* can be identified by the positivity and the significance of their coefficients: that is, when γ_1, γ_2 and γ_3 are not significant, they are not related; when γ_2 and γ_3 are not significant, γ_1 is significant and greater than zero, they are positively related; conversely, if γ_1 is significant and less than zero, they are negatively related; when γ_3 is not significant, γ_2 is significant and greater than zero, and they have a positively U-shaped relationship; if γ_2 is significant and less than zero, they have an inverted U-shaped relationship; when γ_3 is significant and greater than zero, they have an N-shaped relationship, and when γ_3 is significant and less than zero, they have an inverted N-shaped relationship.

4.1.3. A mechanism test model based on the level of science and technology human resources

Equation (5) is used to test the transmission mechanism of the level of scientific and technological human resources.

$$S\&TL_{it} = \gamma_1 VFI_{it} + c_l Control_{it}^l + \mu_i + \eta_t + \varepsilon_{it} \tag{5}$$

In the above model, *S&TL* indicates the level of scientific and technological human resources as the explained variable, and the remaining definitions are consistent with models (2) to (4).

Then, to verify the above nonlinear effect of vertical fiscal imbalance on the level of human resources in science and technology, equations (6) and (7) are constructed by gradually adding the higher-power terms of the core explanatory variables in model (5).

$$S\&TL_{it} = \gamma_1 VFI_{it} + \gamma_2 VFI_{it}^2 + c_l Control_{it}^l + \mu_i + \eta_t + \varepsilon_{it} \tag{6}$$

$$S\&TL_{it} = \gamma_1 VFI_{it} + \gamma_2 VFI_{it}^2 + \gamma_3 VFI_{it}^3 + c_l Control_{it}^l + \mu_i + \eta_t + \varepsilon_{it} \tag{7}$$

4.2. Variable description

4.2.1. Explained variables

In the process of economic development, the cost of resources and the environment must be considered, ecological benefits must be a priority, and resources and the ecological environment must be treated as hard constraints to maximize the utilization rate of resources, reduce pollution emissions, and maximize economic benefits with the lowest ecological costs [47].

In this paper, GDE is defined as the ability to simultaneously reduce resource consumption and pollution emissions from undesirable outputs while increasing desired outputs. It represents the comprehensive economic efficiency achieved after considering resource and environmental costs and is a comprehensive measure of a region's green development level.

To ensure the scientific and rational nature of the selected input indicators, a refined input–output combination (Table 1) is defined in this paper based on a review of the relevant literature [48] as well as the formula of the superefficient EBM model. MaxDEA software was used to systematically measure the green development efficiency of each city.

Table 1
Green development efficiency measurement indicators.

Variable Properties	Variable Name	Quantitative indicators	Symbol	Unit
Input variables	*Labor*	*Total number of employees in three types of industries*	*TNE*	10000 persons
	Capital	*Capital stock*	*CS*	100 million yuan
	Land	*Urban construction land*	*UCL*	square kilometres
	Natural resources	*Water supply*	*WS*	10000 cubic meters
	Energy	*Total energy consumption*	*TEC*	10000 tons of standard coal
Output variables	*Desired output*	*Gross Domestic Product*	*GDP*	100 million yuan
	Nondesired output	*Wastewater discharge*	*Wwd*	10000 tons
		Sulfur dioxide emissions	SO_2	
		Dust emission	*Dust*	
		Carbon dioxide emissions	CO_2	
		pm2.5	*pm*2.5	μg/m^3

Note: The capital stock in the data used is derived by referring to the calculation method of Shan H. J. (2008) using the perpetual inventory method (2006 as the base period), with a depreciation rate of 10.96%.

4.2.2. Core explanatory variables

Vertical fiscal imbalance (*VFI*). Combining the institutional causes of vertical fiscal imbalance with the characteristics of asymmetric fiscal decentralization following China's tax reform, we use the method proposed by Eyraud and Chu [49,50] to quantitatively measure the degree of vertical fiscal imbalance (equation (8)).

$$VFI = 1 - \frac{Fqr}{Fqs} \times (1 - Lbd) = 1 - \frac{Lcpr/(Lcpr + Lppr + Cpr)}{Lcpe/(Lcpe + Lppe + Cpe)} \times \left(1 - \frac{Lce - Lcr}{Lce}\right) \tag{8}$$

*Fq*r and *Fqs*are local fiscal revenue and expenditure decentralization, respectively, and *Lbd* is the local fiscal self-sufficiency gap rate. Given that city-level data are used in the empirical evidence, the decentralized degrees are measured by referring to the steps of Lv Wei [51]. *Lcp*, *Lpp* and *Cp* correspond to the per capita public budgets at the city level, provincial level and central level, and the suffixes *r* and *e* represent revenues and expenditures; *Lcr* and *Lce* are the revenues and expenditures of municipal public budgets. To ensure the standardization and accuracy of the data, the final value range is standardized to (0, 1) with reference to the definition of vertical fiscal imbalance [52], indicating that the local government's revenue at the local level cannot cover the local fiscal expenditure.

The formula provides a clear measurement of the vertical fiscal imbalance and elucidates its root causes. This approach calculates the specific vertical fiscal imbalance value of each city based on readily available fiscal indicators and offers the potential for empirical analysis to explore the heterogeneity of imbalances in small and medium-sized cities.

4.2.3. Mediating variables

Level of scientific and technological human resources (*S&TL*). An increase in the amount of scientific and technological human resources available can effectively drive up the local innovation level and have a positive impact on the efficiency of green development. In this study, the total number of employees in the scientific research, technical services, and geological exploration industries is selected to measure the amount of scientific and technological human resources in a city [53], and its share of the total number of employees is set to indicate the level of scientific and technological human resources in the city.

4.2.4. Control variables

To accurately estimate the effect of vertical fiscal imbalance on regional green development efficiency, the following seven control variables are selected.

(1) Foreign direct investment: This variable not only plays an important role in regional economic development but also has a strong link with environmental regulations in each region [7]. It is expressed as the logarithm of FDI after conversion to constant RMB.
(2) Openness to the outside world: An increase in this variable implies that localities are better able to receive or disseminate new green technologies, thus promoting the efficiency of local green development. This variable is expressed as the ratio of the total value of imports and exports (in RMB) to the GDP of each locality in the current year.
(3) Fixed asset investment and financial development, denoting regional investment efficiency and financing constraints, are key indicators of industrial and financial growth in a region. The restructuring of the industrial sector is crucial for China's transition toward a more sustainable economy. A more efficient and advanced industrial structure not only enhances the coordination between different sectors but also leads to better utilization of resources, directly contributing to green development [10]. These variables are evaluated based on the total current investment in fixed assets and the year-end loan balance from financial institutions as a percentage of the year's GDP, with adjustments made for excessive volatility in the latter.[1]
(4) Although the performance appraisal system has been optimized several times and local officials face different competitions for performance under the pressure of promotion mechanisms, GDP growth remains the most easily measured key component. When local governments anticipate unpromising assessment results, they may let more polluting companies enter the market, inhibiting the efficiency of regional green development [54], expressed by the annual real GDP growth rate of each region.
(5) Population density is a crucial indicator of the relative size of a region's population and plays a significant role in shaping social demand and factor supply. It is also a fundamental requirement for regional development and construction. The level of population density not only affects the rate of energy consumption and labor costs in a region but also has implications for the transformation and upgrading of local industries, ultimately influencing green development [55]. This paper compares the total year-end resident population with the area of the jurisdiction, with logarithmic treatment.
(6) Urbanization rate: An increase in the urbanization level has many positive effects, such as promoting economies of scale, reducing transaction costs, improving overall work efficiency, and increasing the growth potential of green development efficiency [56]. The ratio of the urban resident population to the total resident population at the end of the year in each region is chosen to represent this variable.

[1] The formula for normalizing this variable is $X_{it}^* = (X_{it} - X_{\min})/(X_{\max} - X_{\min})$, where X_{it} represents the year-end loan balance of financial institutions as a percentage of GDP for city i in year t, X_{it}^* is the normalized value of X_{it}, and $X_{\max}$ and $X_{\min}$ represent the maximum and minimum values in the data set, respectively.

4.3. Data sources

The study period for this paper is limited to 2007–2020 due to changes in the quantification of terms and statistics on central and local finance provided by the China Bureau of Statistics in 2007 and the lag in updating the statistical yearbook. The empirical analysis is based on a sample of 270 cities at the prefecture level and above in China, excluding cities without vertical fiscal imbalance or with incomplete data. The raw data were obtained from the *China Urban Statistical Yearbook*, *China Statistical Yearbook*, *Local Statistical Yearbooks*, and *Wind Database*,[2] and some missing data were added using the interpolation method.[3] Table 2 displays the statistical characteristics of each variable.

This paper utilized the annual average exchange rate to convert economic data from USD to RMB, ensuring accuracy in the currency conversion process. To eliminate the impact of inflation, the economic data were deflated using the price index with 2007 as the base period. Furthermore, for the purpose of empirical analysis, certain data sets were transformed by applying the natural logarithm.

5. Empirical analysis

5.1. Basic regression

A panel regression test was conducted on the model using Stata 17 software, and the results can be found in Table 3. The coefficients of *VFI* are positive in the primary term, negative in the quadratic term and positive in the cube term, at least at the 5% significance level, confirming the existence of an N-type nonlinear relationship between *VFI* and *GDE*, with curve inflection points at approximately 0.2801 and 0.8892, respectively. This validates Hypothesis 1, which states that the impact of vertical fiscal imbalance on green development efficiency can be divided into three stages. When VFI<0.2801, green development efficiency is at stage 1, and increasing the degree of vertical fiscal imbalance can promote green development efficiency. Stage 2 occurs when 0.2801<VFI<0.8892; at this stage, the deepening of the vertical fiscal imbalance inhibits green development efficiency. Stage 3 begins when VFI>0.8892, at which point the increase in vertical fiscal imbalance again promotes green development efficiency.

For convenience, the first- and second-stage demarcation points are referred to as inflection point 1, and the second- and third-stage demarcation points are referred to as inflection point 2. The formula for calculating the critical point of the N-shaped curve is as follows:

$$\partial GDE_{it} \Big/ \partial VFI_{it} = \gamma_1 + 2\gamma_2 VFI_{it} + 3\gamma_3 VFI_{it}^2$$

Set it to zero: $\gamma_1 + 2\gamma_2 VFI_{it} + 3\gamma_3 VFI_{it}^2 = 0$.

To solve this equation: $VFI_{it} = (-2\gamma_2 \pm \sqrt{4\gamma_2{}^2 - 12\gamma_1\gamma_3})/6\gamma_3$.

Throughout the study period, the stage 2 urban sample, although fluctuating over time, maintained an overall upward trend as a proportion of the total sample, first falling from 72.05% in 2007 to 69.53% in 2008, then rising to 75.73% (2016), and after a small drop to 75.12% the following year, finally reaching 76.47% in 2020. The share of cities in stage 1 showed an inverted N-shaped downward trend, falling from 21.32% in the first period to 19.85% (2009) and continuing to climb and reach a peak in 2014 (23.16%), after which it continued to decline to 12.13% at the end of the period. The cities in stage 3 represented the lowest percentage, and the overall change over the study period presented a flat N-shape.

When the degree of vertical fiscal imbalance is less than 0.2801, a slight increase may be beneficial, as it has the potential to promote greater output and efficiency. As rational actors, local governments are influenced by regional competition and incentive effects, the leadership role of the central government, and the auxiliary function of transfer payments. They inevitably seek to fully utilize the output potential of their jurisdictions and invest their limited financial resources in low-risk, high-yield, and stable industries. Concurrently, the central government coordinates the allocation of financial resources at all levels to compensate for the costs in the supply process and address imbalances in local governments' responsibilities. This supports the achievement of coordinated and equitable regional development without introducing any new content. Furthermore, subsidies for energy conservation and emission reduction and other special environmental protection transfer payment programs, not only provide financial assistance for environmental protection measures but also effectively mitigate regional pollution. The progress made in green development and stable economic growth results in a decrease in input costs and undesirable outputs.

If the degree of vertical fiscal imbalance is between 0.2801 and 0.8892, the mismatch between financial and administrative powers can easily lead to a vicious cycle, discouraging local output and leading to a decline in the efficiency of green development. A high vertical fiscal imbalance usually means that local governments have very limited financial resources at their disposal. In response to increasing financial constraints and external pressures, local officials may be inclined to gradually loosen environmental regulations, which could lead to crowding out effects and moral hazard. On the one hand, local governments may overinvest limited funds in high-output economic construction; on the other hand, there may be overfinancing, land finance and other imprudent expansions of local financial resources [57]. Although industrial production has obvious short-term benefits, it produces much greater amounts of undesirable outputs, such as emissions and wastewater, than other industries. In this case, it is important to consider the potential

[2] https://www.wind.com.cn/portal/zh/WDS/database.html.

[3] The formula for the interpolation method is $a_1 = a_0 + (a_2 - a_0) \times (t_1 - t_0)/(t_2 - t_0)$, where a_1 denotes the missing value for the current period, a_0 and a_2 are the unmissing data for the previous and subsequent periods, and t denotes the year.

Table 2
Descriptive statistics of each variable.

Variable	Symbol	Obs	Mean	Std.Dev.	Min	Max
Green Development Efficiency	*GDE*	3780	0.6499	0.1788	0.2266	1.1622
Vertical Fiscal Imbalance	*VFI*	3780	0.5623	0.2664	0.0078	0.9842
Foreign direct investment	*ln_FDI*	3780	11.5259	1.9716	2.7526	18.3149
Financial development	*Finance*	3780	0.6438	0.0395	0	1
Fixed asset investment	*Fixed inv*	3780	0.5545	0.3795	0.0965	5.1235
Population density	*Density*	3780	5.7329	0.9329	1.5735	9.9839
Competition for political performance	*Compete*	3780	1.0858	0.0981	0.1431	1.8418
Level of scientific and technological human resources	*S&TL*	3780	0.0154	0.0153	0.0057	0.2068
Urbanization Rate	*Urbanization*	3780	0.5204	0.1524	0.1641	1
Openness to the outside world	*Open*	3780	0.3263	1.6415	0.0100	34.3579

Table 3
Regression results for the effect of vertical fiscal imbalance on green development efficiency.

Variable	(1)	Variable	(1)
	GDE		GDE
VFI	0.4951*** (2.96)	*Finance*	0.2733* (1.70)
VFI^2	−1.1621*** (−2.93)	*Open*	0.0025 (1.15)
VFI^3	0.6626** (2.38)	*Urbanization*	0.1432 (1.51)
S&TL	0.8079** (2.60)	*_cons*	−0.2270 (−1.28)
ln_FDI	0.0065** (2.09)	*City- fixed effect*	Yes
Density	0.0270*** (3.30)	*Year-fixed effect*	Yes
Fixed inv	−0.0568*** (−4.02)	R^2	0.1649
Compete	0.2410*** (6.75)	*N*	3780

Note: The values in parentheses are t values, and * * *, * *, and * represent significance at the 1%, 5%, and 10% levels, respectively.

long-term impacts of natural resource costs and undesired outputs in society's operations. The transient benefits are likely to be overshadowed by negative consequences in the future, ultimately leading to a decline in overall efficiency.

When the vertical fiscal imbalance is greater than 0.8892, the central government provides most of the funding sources for local fiscal expenditures, and local governments' fiscal expenditures are highly dependent on subsidies from the central government, especially in poor regions with relatively low income. In this situation, the central government should give full play to the advantages of its management system and actively mobilize resources to help while holding on to the bottom line of ecological security. The government should first support the market with fiscal allocation to prevent the profit-taking effect of the market economy and alleviate the wealth gap between regions, then subsidize residents with income allocation to guarantee the quality of life of the poor, and finally guide the inflow of capital with tax preferences and transfer payments. On the other hand, although these measures can alleviate the economic pressure of the region to a greater extent and local governments have more incentive to promote the development of other fields, local governments should also carefully control the degree of dependence on the central government's financial support and pay attention to the externalities caused by their own actions.

In terms of the control variables, the coefficient of fixed asset investment is significantly negative, while the coefficient of financial development is significantly positive. Given the multiplier effect and strong development inertia of fixed asset investment, localities are more inclined to expand production than to reduce capacity, which delays the pace of industrial restructuring and limits green development. In contrast, financial development not only expands the scale of financing and capital liquidity to achieve progress in resource allocation efficiency but also effectively diversifies risks, improves investment rationality, and promotes R&D and technological innovation, thus accelerating high-level green development in a multipronged manner. The coefficients of population density and the level of scientific and technological human resources are significantly positive, indicating that the scale and agglomeration effects of the labor force enhance the efficiency of green development and that the rising level of scientific and technological human resources supports scientific and technological progress and accentuates green development. The effect of "Compete" on the efficiency of green development is significantly positive at the 1% level, and the GDP growth rate is not only a measure of local officials' competition for promotion but also an important component of green development. To test the impact of the previous year's performance assessment, "Compete" is taken with a one-period lag, and the conclusion still holds. Extensive and close domestic and foreign exchanges ensure reasonable returns for capital owners, increasing economic agents' advanced production technology and management experience. "*FDI*" can significantly contribute to progress in green development efficiency, but due to the obvious differences in foreign trade between regions, the positive and negative effects of the economic-environmental utility of opening up to the outside world offset each other. Positive but insignificant coefficients for external openness and the urbanization rate indicate the potential to promote green development, but they are irrelevant in the current state of affairs.

5.2. Robustness tests

Given that the results of the baseline regression may be affected by variable selection bias, which could interfere with the scientific

validity of the study findings, this article focuses on the following three aspects to test the robustness of the N-shaped relationship between vertical fiscal imbalance and green development efficiency. First, both the steps of Chu [58] and the method of Jia [25] are applied according to the interpretation of Li [59] to replace the explanatory variable *VFI*, and the measurement results are presented in columns (2) and (3) in Table 4. Second, the green development efficiency of the sample cities is recalculated using the superefficient SBM model, and the test results after replacing the explanatory variables are shown in column (4) of Table 5. Finally, considering the special status of municipalities directly under the central government, provincial capitals and subprovincial cities and the difference from other cities in terms of development conditions, the article excludes the abovementioned cities, and the test results after changing the sample size are shown in column (5) of Table 4. The multiple robustness tests show that although the coefficients and significance of the core and control variables differ slightly from those of the baseline regressions, the overall direction remains unchanged. This supports the robustness of the finding that vertical fiscal imbalance presents N-type nonlinearities that affect the efficiency of green development and suggests that the control variables are accurately selected.

5.3. Endogeneity analysis

This article uses two-stage least squares (2SLS) regression to address the possible endogeneity of the empirical model due to the bidirectional causal relationship between vertical fiscal imbalance and green development efficiency. First, the VFI with a one-period lag is chosen as the instrumental variable for *VFI*, and its square and cube for VFI^2 VFI^3 are used as the core explanatory variables [60]. The results are shown in column (6) in Table 5. The one-stage regression F values are greater than the 5% critical value of the Stock–Yogo weak identification test. Thus, the 2SLS method used in this article is reasonable and feasible, and the estimation results are plausible.

The test results reveal that the coefficient of the primary term of VFI is positive, the coefficient of the quadratic term is negative, and the coefficient of the cube term is positive at least at the 10% level of significance. Therefore, an N-shaped nonlinear relationship is observed. These findings are consistent with the previous findings and indicate that the potential endogeneity problem does not interfere with the empirical results.

5.4. Heterogeneity analysis

The large differences in economic volume and development rate among cities lead to significant differences in fiscal growth and governance capacity. To capture the heterogeneity of the effect of vertical fiscal imbalance on green development, this article introduces dummy variables into equation (4) and conducts analysis on the following three aspects.

(1) Economic development level. Cities are ranked from largest to smallest by average GDP per capita in the previous 3 years. The median is used as the benchmark to define the group of sample cities with high values as developed regions, with a value of $dum = 0$ and the group with low values as less-developed regions, with a value of $dum = 1$. This enables us to identify the difference in the influence of *VFI* on *GDE* at different economic levels.
(2) Geographical location conditions. The cities located on the eastern coast of China are defined as coastal areas and assigned the value $dum = 1$, and other cities are defined as inland areas and assigned the value $dum = 0$ to indicate heterogeneity under different geographical constraints.
(3) Industrial structure. Industrial structure upgrading not only has significant energy-saving and emission-reducing effects but also contributes to the green transformation of local industries [61]. Therefore, the cities are arranged in descending order according to the average value added of the tertiary industry in the last three years and divided into two groups by the median value. Cities with values higher than the median are considered to have a higher-level industrial structure and attributed a value of $dum = 0$, while cities with lower values are attributed a value of $dum = 1$. This variable is used to judge the influence of the change in *VFI* on *GDE* under different industrial structures.

Table 4
Regression results of robustness and endogeneity tests.

Variable	(2)	(3)	(4)	(5)	(6)
	Replace Core Explanatory Variables		Replace Explained Variables	Reduce Sample	2SLS
VFI	0.7427*** (2.66)	0.7481*** (2.65)	0.5409** (2.44)	0.4709** (2.23)	0.7175*** (3.36)
VFI^2	−1.6323** (−2.53)	−1.6450** (−2.53)	−1.2495** (−2.45)	−1.0710** (−2.28)	−1.7431*** (−3.88)
VFI^3	0.9211** (2.02)	0.9313** (2.03)	0.7354** (2.11)	0.6155* (1.95))	0.9717*** (3.38)
_cons	−0.2979 (−1.49)	−0.2886 (−1.50)	−0.3750 (−1.58)	−1.3904*** (−2.99)	–
Control variable	Yes	Yes	Yes	Yes	Yes
City- fixed effect	Yes	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes	Yes
R^2	0.1674	0.1671	0.1094	0.1633	0.1652
N	3780	3780	3780	3360	3510
Kleibergen-Paap rk LM	–	–	–	–	113.413***
Cragg-Donald Wald F	–	–	–	–	314.954***

Note: The values in parentheses are t values, and * * *, * *, and * represent significance at the 1%, 5%, and 10% levels, respectively.

Table 5
Regression results of the heterogeneity test.

Variables	(7)	(8)	(9)
	Economic development level	Geographical location conditions	Industrial structure level
VFI	0.6182*** (5.76)	0.5716*** (5.52)	0.6703*** (5.66)
dum × VFI^1	−0.4818** (−2.46)	−0.5398** (−2.25)	−0.5201*** (−2.80)
VFI^2	−1.4170*** (−5.63)	−1.3535*** (−5.88)	−1.3665*** (−4.74)
dum × VFI^2	0.9143** (2.07)	1.7764** (2.44)	0.7223* (1.71)
VFI^3	0.8772*** (5.14)	0.7851*** (5.19)	0.6856*** (3.45)
dum × VFI^3	−0.7042** (−2.40)	−1.1352* (−1.91)	−0.2332 (−0.83)
_cons	−0.2085** (−2.01)	−0.2195** (−2.11)	−0.1982* (−1.91)
Control variables	Yes	Yes	Yes
City- fixed effect	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes
R^2	0.1737	0.1676	0.1697
N	3780	3780	3780

Note: The values in parentheses are t values, and * * *, * *, and * represent significance at the 1%, 5%, and 10% levels, respectively.

The results of the three heterogeneity tests are presented in the three columns in Table 5. The hypotheses regarding the nonlinear effect of vertical fiscal imbalance on green development efficiency still hold, but the inflection points of the curves differ for different types of regions (Table 6).

This difference is obvious for two reasons. First, underdeveloped regions are more likely to adopt immediate development strategies, such as lowering tax rates, raising debt financing and relaxing budget constraints, which leads to a loss of revenue and an increase in risk and can easily form a Matthew effect that is not conducive to local fiscal sustainability and green development efficiency. On the other hand, developed regions have less fiscal imbalance and sufficient tax sources, and their farsighted development strategies and action plans combined with their strong economic power enable them to effectively play their incentive role.

Second, China's openness to the outside world decreases from the eastern region (especially the southeastern coast) to the western region. Due to limited exposure to the global community, inland areas not only have fewer opportunities to learn from solutions to undesirable fiscal phenomena and advanced experiences but also show low receptivity to green development. This means that the incentive effect of the vertical fiscal imbalance is not fully exercised, and the negative effects are difficult to overcome owing to the inefficient operation of local governments.

Under similar conditions, regions with high industrial structure show a higher VFI level at the inflection point of the GDE curve than do those with low industrial structure. Moreover, their efficiency exceeds that of the latter when the VFT falls below 0.7200. These regions possess a robust industrial foundation, favorable market conditions, and superior capabilities for managing the ecological landscape, all of which contribute to counteracting the adverse impact of VFI on GDE to some extent. However, the limited positive effect is offset by the negative impact of continuing increases in the VFI on industrial development. The promotion of high-tax enterprises within the industrial sector results in the gradual relocation and unhindered expansion of polluting industries, which increases pressure on environmental quality. The N-shaped curve shows an increased level of intervention by local governments in areas with lower levels of industrial structure, with a particular emphasis on accelerating the conversion of production to capital-driven and technology-driven high-end industrial structures. These endeavors produce significant spillover and industrial linkage effects, leading to markedly improved social outcomes that contribute to the overall growth of GDE. This highlights the importance of industrial in regions with initially low levels of industrial structure.

5.5. Further discussion

Based on the above analysis of how the of scientific and technological human resources affects GDE, this resource will be a key part of improving green development efficiency in the strategic context of using innovation to break through green development bottlenecks [62]. This article further establishes an econometric model to empirically quantify the scale of the transmission effect, and the specific results are shown in Table 7.

Based on the empirical results of the impact of vertical fiscal imbalance on the level of human resources in science and technology reported in column (12), the positive primary term coefficient of *VFI* is accompanied by a negative quadratic term coefficient and a positive cubic term coefficient, all of which are significant at a level above 10%. The findings suggest an N-shaped nonlinear

Table 6
Sample curve inflection points for each type of area.

Inflection points	Developed regions	Developing regions	Coastal areas	Inland areas	Higher industrial level areas	Lower industrial level areas
Inflection point 1	0.3039	0.1468	−0.0360	0.2787	0.3245	0.1550
Inflection point 2	0.7731	1.7913	0.8412	0.8706	1.0043	0.4714
Curve shape	N type	Inverted U-shape	Inverted U-shape	N type	Inverted U-shape	N type

Note: The shape of the curve in the third row only indicates the trajectory of GDE when VFI is in the (0, 1) interval.

relationship between *VFI* and *S&TL*. Further data analysis shows that inflection point 1 is approximately 0.2710, and inflection point 2 is above 1 (approximately 1.0460). Consequently, an inverted U-shaped relationship exists between the variables within the range of (0, 1). These discoveries strongly support Hypothesis 2.

The introduction, absorption, digestion, imitation, and improvement of foreign advanced technologies require specific human capital threshold conditions [63]. When the degree of vertical fiscal imbalance is lower than 0.2786, local governments have relatively abundant funds to support the policy of talent introduction, attract outstanding talents to their jurisdictions, and improve the level of industry-academia research and labor productivity. Second, local governments develop an expenditure structure that can sustain long-term quality development, including all levels of education as the "cornerstone" and "ladder" of human resource development and reinforcing the growth potential of scientific and technological manpower. Finally, the contradiction between the supply and demand of science and technology human resources and other factors with development potential under a high level of healthy competition is highlighted, further stimulating local governments to improve the intensity of talent introduction and training, supporting innovation, and promoting the transformation of regional green development. However, when the imbalance crosses the inflection point, local governments tend to devote most of their financial resources to achieving immediate and significant "economic growth" projects while strategically reducing the financial expenditures on talent training and introduction, which have weak short-term economic benefits, thus leading to the loss of scientific and technological manpower in the short term and the insufficient cultivation of talent reserves in the long term. Moreover, there is slow progress in green scientific and technological innovation and even R&D in the broader sense due to the lack of innovative resources and innovative talent, ultimately inhibiting the improvement in green development efficiency.

6. Research conclusions and discussion

6.1. Research conclusions

Based on theoretical and empirical analysis, it becomes apparent that the impact of vertical fiscal imbalance on green development efficiency follows an N-shaped nonlinear pattern. This indicates that there exists an optimal level of vertical fiscal imbalance that can effectively incentivize green development efficiency, with the estimated peak level being 0.2801, and many cities have already exceeded this threshold. This paper discusses the impact of the fiscal game played by the central and local governments on the relationship between economic production and the ecological environment. The conclusion supports the theories of fiscal decentralization, green development, and the EKC hypothesis. Additionally, it highlights the current excessive deviation of fiscal revenues and expenditures in many cities, which poses a barrier to regional environmental progress. Implementing measures to reduce and regulate the level of VFI is essential and crucial in fostering sustainable and environmentally-conscious economic growth.

Further research suggests that the institutional advantage of vertical fiscal imbalances on green development is more pronounced in economically developed regions, eastern coastal areas, and regions with a higher level of industrial structure, as indicated by the results of the heterogeneity tests. Additionally, the level of scientific and technological human resources plays a crucial role in promoting green development efficiency, serving as a significant transmission channel in the nonlinear relationship between vertical fiscal imbalance and green development efficiency, this issue deserves careful consideration in the upcoming reforms of modernized fiscal system.

6.2. Discussion

This study argues that there are significant, nonlinear differences, which contrasts with the results of Chu Deyin's (2020) work. Chu's results showed that the institutional dividend of VFI would experience a sharp decline upon exceeding a certain threshold but still maintain an overall upward trend [52]. This paper identifies the optimal degree of imbalance that sustains GDE by examining the phase changes in the impact of VFI. Compared to the previous study, this research offers a more thorough understanding of the impact mechanism of VFI and presents a clearer illustration of the nonlinear changes.

The test demonstrates the significant impact of VFI on the level of scientific and technological human resources and reveals a nonlinear relationship between the two factors. The findings indicate that VFI can affect efficient green development through the transmission channel of the level of scientific and technological human resources, expanding the research scope of fiscal

Table 7
Regression results for the effect of vertical financial imbalance on the level of science and technological human resources.

Variable	(10)	(11)	(12)
VFI	−0.0080*** (−2.77)	0.0112** (2.52)	0.0329** (2.08)
VFI^2		−0.0201*** (−4.79)	−0.0764** (−2.37)
VFI^3			0.0386* (1.90)
_cons	0.0419* (1.93)	0.0392*** (3.86)	0.0364* (1.77)
Control variable	Yes	Yes	Yes
City- fixed effect	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes
R^2	0.0786	0.0846	0.0867
N	3780	3780	3780

Note: The values in parentheses are t values, and * * *, * *, and * represent significance at the 1%, 5%, and 10% levels, respectively.

decentralization theory to regional factor markets. However, much of the literature tends to focus on local government behaviors, such as transfer payments, expenditure structure, and environmental regulations [21,22,64]. Additionally, the heterogeneity tests further confirm the influence of economic development [8], geographic location [59], and industrial structure on green development [61], as previously advanced in other studies.

By synthesizing the findings and discussions, our paper contends that local municipalities should strive to effectively control and maintain vertical fiscal balance. This approach not only fosters healthy competition among regions but also encourages innovation and growth in local enterprises, ultimately unleashing the development potential of the jurisdiction.

6.3. Policy implications and recommendations

6.3.1. Policy implications

The findings of this paper present a new benchmark for research and a fresh perspective for evaluating the reform of China's decentralized system in the modern era. While vertical fiscal imbalance is typical in federal systems, importantly, China's decentralized reform began within the framework of a politically unified system. As a result, China has experienced a relatively high degree of vertical fiscal imbalance. According to the present study, it appears that the majority of cities in China are currently at the second stage of the impact of VFI on GDE. This means that an increase in vertical fiscal imbalance will impede the efficiency of green development. Additionally, the study reveals that a moderate vertical fiscal imbalance between the central and local governments provides decentralized incentives and development power for local governments under China's decentralized system. These findings serve as a practical foundation for a scientific evaluation and a comprehensive investigation of this system.

The green transformation of industries has been viewed as a crucial method for advancing environmental sustainability. Notably, however, many local governments in China currently present vertical fiscal imbalance to a significant degree. The relaxation of financial budget constraints and market entry regulations has led to an influx of highly polluting enterprises. This may alleviate financial pressure but simultaneously hinder the progress of transformation toward a more environmentally friendly model. It is crucial to find a balance between economic growth and environmental protection and to incentivize sustainable practices in the business sector. Additionally, the GDP-focused promotion system for officials encourages malicious competition, further hindering regional green development. In light of these challenges, it is imperative for China's fiscal system reform to address and eliminate the deepening of vertical imbalance, promote healthy competition and foster a more collaborative and cooperative approach among local governments.

Scientific and technological talent is indispensable in driving green innovation and plays a key role in enhancing the green development of the national economy. The migration of these experts has a significant impact on the level of green development in both the places of outflow and the places of inflow due to scale effects in knowledge production. However, the current lack of effort by local governments to attract them, coupled with disparities in salaries and working conditions between regions, has led to an uneven distribution of scientific and technological talent. Many skilled individuals seek opportunities overseas and therefore cannot contribute to green development. Therefore, attracting and retaining scientific and technological human resources and providing them with the support they need to promote regional green development are urgently needed.

6.3.2. Policy recommendations

1. It is imperative to effectively manage and gradually reduce the excessive level of vertical fiscal imbalance. This can be achieved by enhancing the financial autonomy of local governments, fostering healthy competition among regions, and maintaining long-term innovative development momentum, thereby ensuring the sustainability of green development at its peak. Governments at all levels should carefully define their functions and delineate their rights and expenditure responsibilities, and the central government's ability to regulate the finances of local governments should be strengthened. By doing so, the financial pressure on local governments can be alleviated, and a more efficient and effective financial relationship between the central government and local governments can be established. This new model is characterized by clear rights and responsibilities, appropriate powers and duties, coordinated financial resources and regional balance. This can provide a new systemic dividend and source of motivation for the realization of green development in the new era. To further improve China's financial transfer payment system, it is necessary to clearly define the scope of use of transfer payment funds and establish and improve the system of apportionment of transfer payments. Furthermore, a dedicated fund for green development must be established at the central level to provide effective financial support for improving regional green development efficiency [65]. Moreover, it is imperative to steadily increase the allocation of resources to underdeveloped regions while considering variations in regional and economic development. These measures will facilitate the greening progress of industrial institutions and maximize the potential for sustainable development in these areas, which will contribute to bolstering the overall growth and prosperity of China's economy.
2. The government must fully implement the four key tasks of nurturing, attracting, utilizing and retaining talent to address the shortage of scientific and technological talent in the country. The primary focus should be on optimizing talent training around key industries and areas. This can be achieved through promoting industry-education integration, fostering school-enterprise cooperation, and increasing investment in science and education. Emphasis should be placed on cultivating innovative ability in green science and technology [66]. In addition, policy propaganda activities should be widely carried out to attract individuals with scientific and technological expertise to enterprises and public institutions. It is essential to establish a comprehensive system for talent recruitment and to enhance the implementation of related measures. Efforts should also be made to attract talent back to the region [67]. Furthermore, the establishment of a supportive platform for the integration of green technology into the local

industrial economy is essential. Such a platform would effectively overcome bottlenecks in green innovation and facilitate the development and transformation of green innovation-driven initiatives. It is crucial to enhance the welfare benefits of enterprises based on the needs of talented individuals, strengthen the fundamental rights and interests of talent services, and effectively address the concerns of most researchers.

3. A "multitask" performance appraisal index system for local officials should be developed to replace the traditional "economic growth" appraisal and promotion mechanism. To guide local governments in adjusting their financial revenue and expenditure structure, the assessment system must integrate green indicators, such as pollution control, energy consumption, and green innovation. This will correct the current imbalance in which a high proportion of expenditures are devoted to economic growth, while insufficient funds are allocated to environmental protection. By doing so, the weak environmental governance and low efficiency of environmental development can be addressed. It is important to acknowledge the multiple perspectives and show respect for differing opinions while emphasizing the common ground and shared goals to foster a cooperative atmosphere. The local government must confidently restructure the current industrial landscape, which is dominated by the secondary sector, and gradually withdraw industries that prioritize quick gains over sustainable investment. This will encourage regions to capitalize on their local strengths to form a diverse industrial structure, promoting collaboration and sustainable growth. To achieve high-quality and sustainable economic development, we must facilitate the wider dissemination and expansion of advanced skills and technological innovations. We should also promote intra- and interindustry structural upgrading and foster the emergence of new industries and business models.

6.4. Limitations and future recommendations

This paper acknowledges the limitations of the study and proposes the potential for further exploration in future research. Nevertheless, the findings are valid and provide valuable insights into the topic.

One notable limitation is the wide range of indicators used to measure green development, which has resulted in some missing data for certain prefecture-level cities and challenges in collecting data for entire county and townships. Future research can expand the dataset to increase sample capacity and focus on county- and township-level regions. This expansion will produce more comprehensive and accurate research results.

Furthermore, this study utilized appropriate regression methodology. In addition, future research could potentially benefit from implementing more advanced econometric techniques, such as spatial econometric models that integrate geographic regions and their economic factors. These advanced methodologies can provide more spatially-informed conclusions.

Finally, it will be worthwhile to explore potential additional variables or transmission mechanisms that could enhance the overall understanding of the topic. By taking these factors into account, a more nuanced and comprehensive perspective on the relationship between vertical fiscal imbalances and green development can be provided. Subsequent work should focus on exploring the substantive implications of the empirical practices in this study. This contribution will lead to a deeper understanding of the actual impacts and outcomes, thereby advancing the field.

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Institutional review board statement

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Informed consent statement

Not applicable.

Data availability statement

The authors of this study are not authorized to share the data without prior permission. However, the data supporting the findings of this study can be obtained from the corresponding author upon request. We apologize for any inconvenience this may cause and appreciate your understanding.

Ethics declarations

Review and/or approval by an ethics committee was not needed for this study because it did not involve any animal or human subjects.

CRediT authorship contribution statement

Ruichao Liu: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Conceptualization.

Kenong Sun: Writing – original draft, Validation, Software, Investigation, Formal analysis. **Hongjie Cao:** Writing – review & editing, Visualization, Software, Methodology.

Declaration of competing interest

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

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