Policy Effects of Carbon Emissions Trading on the Quality and Efficiency of Regional Quality Green Development

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Abstract This study investigates the role of carbon emissions trading (CET) in advancing regional high-quality and green development (QGD) from quality and efficiency perspectives. Firstly, theoretical analysis via an evolutionary game model formulates hypotheses. Secondly, a multi-period DID model, based on panel data from 30 Chinese provinces (2007–2020), evaluates the impact of CET pilot policies on provincial QGD. Robustness and heterogeneity analyses assess variations by region, industrial structure, and economic development. Additionally, the moderating effects of government regulation and market conditions on the CET-QGD relationship are examined. Key findings include: 1) CET significantly improves both the quality and efficiency of QGD, with a stronger impact on efficiency. 2) Geographical heterogeneity reveals CET impacts peak in eastern provinces, moderate in central regions, and diminish in the west, amplified by industrialization and economic development. 3) Indirect governmental regulations, such as environmental spending and resource taxes, strengthen CET's effectiveness, whereas direct interventions like pollution control investments may hinder green transformation, adversely impacting QGD. 4) Increased carbon trading volumes improve QGD quality, while elevated prices enhance quality but reduce efficiency by favoring short-term emissions cuts over long-term green transitions. Therefore, this study recommends addressing regional disparities, balancing regulation with market mechanisms, and ensuring a competitive, transparent national CET market.

1 Introduction

According to data published in Earth System Science Data, global CO_2 emissions stabilized between 2014 and 2023, with projections indicating a total of 41.6 gigatons ($GtCO_2$) by 2024. This stabilization contrasts sharply with the rapid annual growth rate of 2% observed between 2004 and 2013, signaling preliminary progress in mitigating emissions [1]. However, current mitigation efforts remain insufficient to place global emissions on a sustained downward trajectory, underscoring the gravity of the challenge [2]. Recognizing the critical importance of this issue, governments worldwide have intensified their commitments. Leading developed economies, including the United States, Canada, South Korea, Japan, and the European Union, have pledged to achieve carbon neutrality by 2050. Similarly, in 2020, China announced its "dual-carbon" targets, aiming for peak emissions by 2030 and carbon neutrality by 2060, accompanied by action plans to optimize its industrial and energy structures. Hence, advancing Quality Green Development (QGD) under these targets is pivotal for China to achieve a balance between environmental sustainability and economic growth [3].

The QGD represents a transformative paradigm that emphasizes efficient resource utilization and sustained ecological enhancement [4]. At its core, QGD seeks to balance the dual imperatives of improving economic development quality and safeguarding environmental integrity, striving for a harmonious coexistence between socioeconomic systems and natural ecosystems. Achieving QGD necessitates the establishment of an integrated framework that combines technological innovation, institutional reform, and structural optimization to drive systemic changes in production and consumption patterns while accelerating the adoption of green and low-carbon technologies [5]. However, a critical challenge lies in effectively incentivizing and regulating the emission reduction behaviors of market participants [6].

Carbon Emission Trading (CET) has emerged as a market-based environmental policy tool offering robust economic incentives for QGD through the allocation and trading of carbon quotas. Its efficacy has been widely acknowledged in academic research. Internationally, successful CET systems in regions such as the European Union, the United States, and South Korea have significantly advanced industrial transitions toward low-carbon development [7]. Since 2011, China has initiated CET pilot programs in cities like Beijing, Tianjin, and Shanghai, culminating in the establishment of a national CET market in 2021. However, compared to mature international systems, Chinese CET framework remains in a developmental stage, with notable limitations in areas such as market mechanism sophistication, functional performance, and operational efficiency [8]. For instance, enhancing market activity and fully realizing its economic and environmental potential require further intervention through government regulation and market-driven adjustments [9]. In light of this, exploring the impact mechanisms of CET on QGD is therefore imperative. Such inquiry not only elucidates CET's potential to optimize in-

dustrial structures, stimulate technological innovation, and redirect capital flows toward green and low-carbon sectors but also offers a theoretical foundation and practical insights for refining CET system design and enhancing policy implementation effectiveness.

Existing research has predominantly focused on examining the relationship between CET and QGD, with particular emphasis on the effects of CET on carbon emissions, green technological innovation, and economic performance[10–12]. Empirical findings suggest that CET fosters greater alignment between green economic growth and environmental equity[4]. Studies adopting firm-level[13] and prefecture-city-level[14] perspectives on green total factor productivity (GTFP) further highlight the significant role of CET in enhancing GTFP, which is widely recognized as a key indicator for evaluating the efficiency of QGD. Additionally, some theoretical analyses have explored the roles of government[15,16] and market mechanisms[17] in advancing QGD through CET, although these studies often lack robust empirical support. Despite the growing body of literature on CET's contributions to green development in China, limited research has undertaken a comprehensive investigation of CET's impact on QGD from both quality and efficiency dimensions. Moreover, insufficient attention has been devoted to the moderating effects of governmental regulatory factors — such as environmental quality, pollution control measures, and tax penalties — and market environmental variables, including carbon allowance allocation mechanisms, market liquidity, and carbon market size, in shaping the efficacy of CET in promoting QGD.

Consequently, this paper systematically investigates the theoretical and empirical relationship between CET pilot policy and QGD. First, it explores the theoretical nexus between CET and QGD by constructing an evolutionary game model, which serves as the basis for a hypothesis framework to guide empirical analysis. Utilizing panel data from 30 Chinese provinces from 2007 to 2020, the study employs a multi-period Difference-in-Differences (DID) model to empirically evaluate the specific impacts of CET on the quality and efficiency dimensions of QGD. Building on this foundation, it further examines the moderating effects of government regulation and market conditions on CET policy outcomes. The research aims to address four core objectives: 1) To quantify the quality (proxied by GTFP) and efficiency (measured by the Green High-Quality Index, GHQI) of QGD and to investigate the mechanisms through which CET influences these dimensions. 2) To analyze the heterogeneity of CET's policy effects on QGD quality and efficiency across provinces with varying regional, economic structural, and developmental characteristics. 3) To assess the moderating effects of government regulatory instruments, such as environmental protection expenditures, resource taxation, and industrial pollution control measures, in CET implementation. 4) To explore the moderating roles of market factors, including carbon allowance allocation mechanisms, market liquidity, transaction volumes, and transaction prices, in shaping the effectiveness of CET policies.

This study aims to achieve marginal contributions in the following aspects.

i) Integration of research methodologies. This study employs an evolutionary game model to analyze the strategic decisions and evolutionary trajectories of local governments in advancing

QGD before and after the implementation of the CET pilot policy. This approach deepens the investigation into the relationship between the CET and QGD. Based on the analysis of the evolutionarily stable strategies, the paper develops empirical research hypotheses, which are then subsequently testing them using the multi-period DID model. By integrating theoretical coherence with the empirical validation of data, this paper distinguishing itself from prior studies[18,19] that derived empirical model hypotheses solely from literature or theoretical analysis.

ii) Measurement of QGD across quality and efficiency dimensions. This study evaluates provincial QGD by examining both its quality and efficiency dimensions, with a focus on the effects of CET policies. For the quality dimension, we use the GHQI, constructed using the DP-SIR framework, which integrates 11 indicators across driving forces (D), pressure (P), state (S), impact (I), and response (R), providing a comprehensive measure of provincial green development. For the efficiency dimension, we adopt an enhanced GTFP metric that incorporates labor, capital, and energy inputs alongside GDP as the desired output. This metric also accounts for undesirable outputs, including industrial smoke (dust) emissions, wastewater discharges, sulfur dioxide, and solid waste, offering a more precise and comprehensive assessment. By incorporating smoke (dust) emissions and GHQI, this approach surpasses traditional methods that primarily focus on "three industrial wastes"[20–22]. Moreover, to ensure robustness, we conduct a sensitivity analysis by replacing GDP with industrial added value as the desired output in GTFP calculations. This substitution tests the stability and reliability of QGD efficiency measurements across different output metrics, thereby enhancing the scientific rigor and broad applicability of the findings.

iii) This study investigates the moderating roles of government oversight and market conditions in advancing provincial QGD, offering a departure from the traditional focus on direct environmental regulation[3,23]. In the context of CET markets, we propose that strategic regulatory measures — such as increasing environmental budget allocations and raising resource tax rates — should be employed by governments to indirectly incentivize pollution reduction. This approach alleviates the potential crowding-out effect of direct pollution control investments on corporate green innovation, thereby more effectively fostering provincial QGD. Building on the findings of Liu et al.[24], our analysis corroborates the positive impact of increased carbon trading volume on provincial QGD. However, it reveals deviations from existing literature[11,12], as the moderating effects of market liquidity and carbon allocation mechanisms do not appear significant within our analytical framework. Additionally, while higher carbon price initially enhance the contribution of CET to provincial QGD, our findings indicate that long-term market rigidity may constrain these benefits. This contrasts with optimistic projections positing that carbon pricing universally supports green and high-quality development[4,13]. These findings offer a nuanced perspective, providing policymakers with a more comprehensive and cautious framework for decision-making in the design and implementation of CET policies.

The article follows a structured approach: Section 2 reviews of the existing literature on CET and QGD. Section 3 examines the theoretical link between CET and QGD through an

evolutionary game model, forming the basis for research hypotheses. Section 4 empirically investigates the impact of the pilot policy for CET on QGD utilizing provincial data from China and the multi-period DID method. Section 5 presents empirical findings, robustness tests, and heterogeneity analysis. Section 6 examines the influence of government oversight and market conditions on the pilot policy for CET's impact on QGD. Finally, Part VII summarizes the findings and offers policy recommendations.

2 Literature Review

2.1 Carbon Emissions Trading (CET)

Research on CET is critical to advancing environmental, energy, and socio-economic development[25]. Despite its high construction costs, CET has proven more effective in reducing emissions compared to carbon tax policies[26]. It efficiently lowers carbon emissions[27] and driving an eco-friendly economic transitions[28]. Existing studies mainly focuses on quota allocation, carbon emission reduction, and economic development. For instance, Carl and Fedor[20] analyzed global carbon tax and allowance trading revenues, revealing that 70% of allowance trading revenues subsidized "green" initiatives in energy efficiency or renewable energy. Zhou et al.[29] used the Data Envelopment Analysis (DEA) method to explore carbon quota allocation in 71 Chinese cities (2005–2012), concluding that a comprehensive index method incentivizes carbon emission reductions through CET. Shen and Huang[30] using quasi-natural experimental scenarios, showed that CET enhances short-term enterprise value in China but has no significant impact on long-term value.

This study investigates the impact of the pilot CET policy on QGD, offering a comparative analysis with existing literature. Wang and He[12] assessed the impact of CET on GTFP from efficiency and fairness. While Yu et al.[31] focused on GTFP in the agricultural sector using Chinese interprovincial data and a DID approach. Extending beyond sectoral analyses, this study provides a comprehensive examination of the pilot policy for CET effects on GTFP across all sector, not limited solely to the agricultural sector. Similarly, Li et al.[22] used the DID to confirm the short-term impact of the pilot CET policy on GTFP, noting limited improvements. Building on these foundation, our study investigates Chinese pilot CET policy's broader effects on GTFP as a measure of efficiency within QGD. Furthermore, it incorporates the quality dimension of QGD, offering a more comprehensive assessment of the policy's impact on provincial-level green development.

2.2 Quality Green Development (QCD)

Given the absence of a consensus on the measurement of QGD, this study integrates available literature from two perspectives: GTFP and GHQI.

2.2.1 Green Total Factor Productivity (GTFP)

GTFP, an advanced measure derived from Total Factor Productivity (TFP), serves as a critical indicator of national energy efficiency, integrating resource consumption and environmental

degradation as undesirable outputs to enhance the accuracy of QGD assessment[32]. Using the SVAR model, Pan et al.[33] demonstrated that environmental regulatory actions can temporarily boost GTFP, but this effect diminishes over time. Wu et al.[34], employing a dynamic threshold panel model with data from 30 provinces, revealed that the effectiveness of environmental regulation on GTFP depends on exceeding a specific intensity threshold. Zhou and Qi[35] analyzed data from 280 Chinese cities (2006–2017) using the DID method to evaluate the impact of the pilot CET policy on GTFP but overlooked variations in policy implementation timeline across cities. This study employs a multi-period DID methodology to address this gap, examining the influence of the staggered implementation of the pilot CET policy on GTFP across regions.

2.2.2 Green High-Quality Indicators (GHQI)

The GHQI captures the green dimensions of high-quality economic development. Existing research on GHQI predominantly revolves around developing a comprehensive index for QGD. Wei and Li[36] employed the entropy-weight TOPSIS method, incorporating ecological civilization indicators as a foundation for GHQI. Li et al.[37] emphasized that GHQI in the Chinese context should include five positive indicators: The percentage of high-quality arable land, air quality index, sewage treatment rate, harmless treatment rate of domestic garbage, and surface water quality. Additionally, Xu and Wang[5], focusing on Shandong Province, highlighted the significance of resource utilization, environmental governance, green living, and agricultural land protection within GHQI framework. In contrast to previous studies, this paper employs the DP-SIR framework to construct GHQI across five dimensions: Driving force (D), Pressure (P), State (S), Impact (I), and Response (R), offering a more comprehensive assessment of provincial-level QGD.

2.3 Carbon Emissions Trading and Quality Green Development

Since China established its QGD goal in 2017, research on the role of the pilot policy for CET in the green development aspect of QGD has gained traction. In theoretical exploration, Fang et al.[17] developed a carbon trading-driven government-enterprise carbon emission reduction evolution game model, incorporating variables such as public willingness. They emphasized the government's capacity to shift corporate strategic from non-emission to emission reduction by managing carbon emissions and regulating carbon prices. Wu et al.[16] delved into the impact of carbon price and quotas on corporate energy consumption through a behavioral evolution game model, emphasizing the need for relaxed carbon quotas during the early stages of the carbon market to encourage corporate energy investments. Additionally, Wu et al.[15] constructed a low-carbon strategy evolution model in a complex network environment, exploring the diffusion of low-carbon policies among enterprises under governmental influence. They found that corporate expectations of incentives, such as subsidies and regulations, significantly influence the adoption and diffusion speed of low-carbon strategies.

In terms of empirical investigations, Wang et al.[38] employed the TOPSIS method to construct high-quality development indicators and applied PSM-DID analysis on data from 30

Chinese provinces (2011–2016), revealing a policy lag in the CET pilot despite an improvement in the level of economic development. Lin et al.[18], utilizing data from 2008 to 2018 for Chinese A-share listed companies, found that the carbon market pilot regions significantly boosted green innovation output. Lin[39], through scenario analysis considering Chinese actual national conditions, affirmed the feasibility of a market-based approach to achieve QGD.

While previous research has examined the CET's role in promoting high-quality development but have insufficiently clarified its specific impact on the efficiency and quality of provincial-level QGD. To address this, our study systematically evaluates CET's effects on both QGD efficiency and quality at the provincial scale. We also investigate how regional heterogeneity, economic structure, and development disparities influence outcomes. By analyzing both governmental and market factors, we provide theoretical and practical insights to optimize CET's contribution to provincial QGD, offering valuable guidance for policymakers.

3 Theoretical Basis and Research Hypothesis

3.1 Theoretical Basis

The complex relationship between the CET pilot policy and QGD is characterized by a dynamic interactions among diverse participants, variables, and temporal dimensions. Evolutionary game theory provides a robust framework for modeling and analyzing this complexity. By examining the long-term strategic behaviors of game participants while accounting for bounded rationality, this approach uncovers key mechanisms and evolutionary trajectories, evaluates the adaptability and competitive advantages of various strategies, and predicts as well as explains real-world behavioral patterns and market phenomena.

Within this framework, we developed an evolutionary game model involving local governments and enterprises to explore the linkage between CET and QGD. The model generates research hypotheses, establishing a solid theoretical foundation for subsequent empirical analysis.

3.1.1 Game Model Construction

The proposed model involves two primary participants: The central government and local governments, both operating under conditions of bounded rationality. The central government's strategic decisions focus on the extent of support for CET implementation, represented as {*strong support*, *limited support*} or $\{x, 1-x\}$ where $x \in [0, 1]$. A higher value of x reflects greater support for CET. Simultaneously, the local government's strategy relate to the level of commitment to QGD, represented as {*high, low*} or $\{y, 1-y\}$ where $y \in [0, 1]$. A higher y indicates a stronger dedication to advancing QGD. The model classifies different strategy combinations into four distinct scenarios based on the interactions between these two decision-makers.

Scenario 1   The central government adopts a strategy of "*strong support*" for CET construction, and the local government achieves a "high" level of QGD. The central government's robust efforts in CET development have substantially enhanced market liquidity (m), established a more scientific pricing mechanism (p), and optimized quota allocation optimization (Q_0),

Table 1 Payoff matrix of evolutionary games

Strategic choice		The local government	
		y	$1-y$
The central government	x	$R_{\text{Cet}}(m, Q_0, p) + \Delta r,$ $R_{\text{EG}} - C_{\text{EG}} + R_{\text{Tax}} - C_{\text{PR}} + \Delta r$	$R_{\text{Cet}}(m, Q_0, p),$ $R_y - l$
	$1-x$	$R_x + r_{\text{Cet}}(m, Q_0, p) - l,$ $R_{\text{EG}} - C_{\text{EG}} + R_{\text{Tax}} - C_{\text{PR}} - C_{\text{Cet}}$	$R_x,$ R_y

thereby expanding the scale of carbon trading $R_{\text{Cet}}(m, p, Q_0)$. This reflects the dual achievements of the central government: Generating fiscal revenue and meeting emissions reduction targets. In response, local governments have responded with a "high" QGD, increasing environmental budgets (C_{EG}), rationalizing resource taxes (R_{Tax}), and creating dedicated pollution control funds (C_{PR}), which directly enhancing environmental performance (R_{EG}). Moreover, the integration of the CET and high QGD objectives drives green transformation, fostering high-quality socio-economic development. This alignment strengthens central-local collaboration, yielding additional synergies benefits (Δr) that significantly boosting carbon emission reduction efficiency and advancing economic restructuring, technological innovation, and societal well-being.

Scenario 2 The central government implements a strategy of "*strong support*" for CET construction, and the local government attains a "low" level of QGD. In this scenario, the central government achieves similar gains to Scenario 1. However, the local government places a higher priority on economic growth (R_y) at the expense of aligning with sustainability goals. This imbalance weakens environmental resilience, leading to negative societal impacts (l) and reducing the overall effectiveness of the green transition. In the context of global efforts to achieve environmental benefits, the net benefits from green development — represented by $R_{\text{EG}} - C_{\text{EG}} + R_{\text{Tax}} - C_{\text{PR}} + \Delta r + l$ — are far more significant than the economic returns derived from conventional growth R_y.

Scenario 3 The central government implements a strategy of "*limited support*" for CET construction, and the local government achieves a "high" level of QGD. In this scenario, the local government opposes direct support for CET, incurring no costs. The central government's focus on R_x driven economic growth may lead to the neglect of a unified CET framework, resulting in fragmented market standards across local governments. This fragmentation undermines market efficiency and integration (l). Given the prevailing global emphasis on green development, the construction of CET is assessed based on its direct and potential benefits ($R_{\text{Cet}} - r_{\text{Cet}} + \Delta r + l$), which surpass the benefits derived from conventional economic development (R_x). In their pursuit of high-quality development, local governments have increased environmental budgets (C_{EG}), introduced resource taxes (R_{Tax}), and invested in industrial pollution control (C_{PR}) to enhance environmental governance (R_{EG}). Simultaneously, they have incurred CET infrastructure costs (C_{Cet}) to compensate for the lack of centralized planning. Despite adding

fiscal and administrative complexity, these efforts result in CET with revenues $r_{\text{Cet}}(m, Q_0, p)$, which remain suboptimal compared to the potential of a fully integrated system $R_{\text{Cet}}(m, Q_0, p)$.

Scenario 4 The central government implements a strategy of "*limited support*" for CET construction, and the local government achieves a "low" level of QGD. In this scenario, both central and local governments shift their focus towards prioritizing economic gains, denoted as R_x and R_y, respectively.

3.1.2 Game Model Solving and Analysis

1) The Expected Utility Functions of the Central Government and Local Governments.

The expected utility for the central government with respect to CET construction under conditions of "*strong support*" and "*limited support*" is denoted as U_{x1} and U_{x2}, as expressed by Equations (1) and (2), respectively. The average expected utility for the central government is given by Equation (3).

$$U_{x1} = y[R_{\text{Cet}}(m, Q_0, p) + \Delta r] + (1-y)R_{\text{Cet}}(m, Q_0, p), \tag{1}$$

$$U_{x2} = y[R_x + r_{\text{Cet}}(m, Q_0, p) - l] + (1-y)R_x, \tag{2}$$

$$\overline{U_x} = xU_{x1} + (1-x)U_{x2}. \tag{3}$$

The expected utility for the local government at the "high" and "low" levels of QGD is denoted as U_{y1} and U_{y2}, as formulated in Equations (4) and (5), respectively. The average expected return for the local government is expressed in Equation (6).

$$U_{y1} = x(R_{\text{EG}} - C_{\text{EG}} + R_{\text{Tax}} - C_{\text{PR}} + \Delta r)$$
$$+ (1-x)(R_{\text{EG}} - C_{\text{EG}} + R_{\text{Tax}} - C_{\text{PR}} - C_{\text{Cet}}),$$

$$U_{y2} = x(R_y - l) + (1-x)R_y, \tag{4}$$

$$\overline{U_y} = yU_{y1} + (1-y)U_{y2}. \tag{5}$$

2) The Analysis of Local Stability for the Central Government and Local Governments.

A. Central government. The replicated dynamic equation for central government and its first order derivatives as follow.

$$f(x) = \frac{\mathrm{d}x}{\mathrm{d}t} = x(1-x)R_{\text{Cet}}(m, Q_0, p) - R_x + y[\Delta r + l - r_{\text{Cet}}(m, Q_0, p)], \tag{6}$$

$$f'(x) = \frac{\mathrm{d}f(x)}{\mathrm{d}x} = (1-2x)R_{\text{Cet}}(m, Q_0, p) - R_x + y[\Delta r + l - r_{\text{Cet}}(m, Q_0, p)]. \tag{7}$$

In summary, where $f(x)$ represents the rate of change in the central government's support for CET construction over time. According to the stability theorem of differential equations asserts that the evolution of x reaches a stable state when $f(x) = 0$ and $f'(x) < 0$. When the evolutionary rate $f(x)$ is stable ($f(x) = 0$), solutions for $x = 0$, $x = 1$, and $y = \frac{[R_x - R_{\text{Cet}}(m, Q_0, p)]}{[\Delta r + l - r_{\text{Cet}}(m, Q_0, p)]}$ can be determined. Let $y_0 = \frac{[R_x - R_{\text{Cet}}(m, Q_0, p)]}{[\Delta r + l - r_{\text{Cet}}(m, Q_0, p)]}$ and consider the following two cases:

- When $y = y_0$, $f(x) \equiv 0$. In this case, the probability of the central government's support for CET, x, reaches a stable state, and time will not affect the central government's strategy.

- When $y \neq y_0$, setting $f(x) = 0$ yields two solutions, $x = 0$ and $x = 1$. Specifically, when $y > y_0$, the evolutionary stability point satisfying $f'(x) < 0$ is $x = 1$, indicating the central government's strategy as "*strong support*", when $y < y_0$, the evolutionary stability point with $f'(x) < 0$ is $x = 0$, signifying the central government's strategy of "*limited suppor*".

B. Local government. The replication dynamic equation and its derivatives are as follows.

$$f(y) = \frac{\mathrm{d}y}{\mathrm{d}t} = y(1-y)[R_{\mathrm{EG}} - C_{\mathrm{EG}} + R_{\mathrm{Tax}} - C_{\mathrm{PR}} - C_{\mathrm{Cet}} - R_y + x(l + \Delta r + C_{\mathrm{Cet}})], \qquad (8)$$

$$f'(y) = \frac{\mathrm{d}f(y)}{\mathrm{d}y} = (1-2y)[R_{\mathrm{EG}} - C_{\mathrm{EG}} + R_{\mathrm{Tax}} - C_{\mathrm{PR}} - C_{\mathrm{Cet}} - R_y + x(l + \Delta r + C_{\mathrm{Cet}})]. \quad (9)$$

The function $f(y)$ represents the temporal evolution rate of the strategy regarding whether the local government attains a "high" level of QGD. Similarly, under the condition of a stable evolution rate $f(y) = 0$, solutions for $y = 0$, $y = 1$, and $x = \frac{[C_{\mathrm{Cet}} + C_{\mathrm{PR}} - (R_{\mathrm{EG}} - C_{\mathrm{EG}}) - R_{\mathrm{Tax}}]}{(l + \Delta r + C_{\mathrm{Cet}})}$ can be determined. Let $x_0 = \frac{[C_{\mathrm{Cet}} + C_{\mathrm{PR}} - (R_{\mathrm{EG}} - C_{\mathrm{EG}}) - R_{\mathrm{Tax}}]}{(l + \Delta r + C_{\mathrm{Cet}})}$ and consider the following two cases:

- When $x = x_0$, $f(y) \equiv 0$, the probability y, indicating whether the local government's development is at a "high" level of QGD, reaches a stable state, and time will not alter the local government's strategy.

- When $x \neq x_0$, setting $f(y) = 0$ yields two solutions: $y = 0$ and $y = 1$. Specifically, when $x > x_0$, the evolutionary stable point satisfying $f'(y) < 0$ is $y = 1$, indicating that the local government's QGD is "high". Conversely, when $x < x_0$, the evolutionary stability point satisfying $f'(x) < 0$ is $y = 0$, signifying that the local government 's QGD as "low".

3) The Analysis of Evolutionary Stabilization Strategies.

The dynamic equations $f(x)$ and $f(y)$ describe the evolutionary dynamics of the strategic decisions made by the central and local governments. By setting $f(x) = 0$ and $f(y) = 0$, five locally stable equilibrium points are identified: $E_1 = (0,0)$, $E_2 = (1,0)$, $E_3 = (0,1)$, $E_4 = (1,1)$, and $E_5 = (x_0, y_0)$. To ensure that $x_0, y_0 \in [0,1]$, the conditions $C_{\mathrm{Cet}} - R_{\mathrm{EG}} + C_{\mathrm{EG}} - R_{\mathrm{Tax}} + C_{\mathrm{PR}} > 0$ and $R_x - R_{\mathrm{Cet}}(m, p, Q_0) > 0$ must be satisfied[1]. Using equation (11) and the Jacobian matrix, as outlined in Friedman's research[31], the five locally stable equilibrium points are analyzed, with the results summarized in Table 2.

$$\boldsymbol{J} = \begin{bmatrix} (1-2x)[R_{\mathrm{Cet}}(m, Q_0, p) - R_x \\ + y(\Delta r + l - r_{\mathrm{Cet}}(m, Q_0, p))] & x(1-x)[\Delta r + l - r_{\mathrm{Cet}}(m, Q_0, p)] \\ \\ y(1-y)(l + \Delta r + C_{\mathrm{Cet}}) & (1-2y)[R_{\mathrm{EG}} - C_{\mathrm{EG}} + R_{\mathrm{Tax}} - C_{\mathrm{PR}} \\ - C_{\mathrm{Cet}} - R_y + x(l + \Delta r + C_{\mathrm{Cet}})] \end{bmatrix}. \qquad (10)$$

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[1]The inequality $R_x - R_{\mathrm{Cet}}(m, p, Q_0) > 0$ carries profound economic implications, signifying that while the current economic landscape is characterized by a relatively stable trajectory, the CET market remains in its nascent phase of exploration. Consequently, the economic benefits accrued from non-CET related activities, denoted as R_x, outweigh those derived from the CET market, $R_{\mathrm{Cet}}(m, p, Q_0)$. The expression $C_{\mathrm{Cet}} - R_{\mathrm{EG}} + C_{\mathrm{EG}} - R_{\mathrm{Tax}} + C_{\mathrm{PR}} > 0$ underscores that for local governments, the costs associated with establishing and maintaining a CET system, $C_{\mathrm{C}}et$, significantly exceed the net costs incurred in environmental governance over the same period, $R_{\mathrm{EG}} - C_{\mathrm{EG}} + R_{\mathrm{Tax}} - C_{\mathrm{PR}}$.

Table 2 Stability analysis of evolutionary stabilization strategies

Equilibrium Point	det $\boldsymbol{J}$	Tr $\boldsymbol{J}$	Sign	Stability
$(0,0)$	$A_1 A_2$	$-A_1 - A_2$	$(+,-)$	Stable
$(1,0)$	$A_1 A_3$	$A_1 + A_3$	$(+,+)$	Unstable
$(0,1)$	$A_2 A_4$	$A_2 + A_4$	$(+,+)$	Unstable
$(1,1)$	$A_3 A_4$	$-A_3 - A_4$	$(+,-)$	Stable
(x_0, y_0)	$-\dfrac{A_2 A_3 (A_1 + A_4)}{(l + \Delta r - r_{\mathrm{Cet}})(l + \Delta r + C_{\mathrm{Cet}})}$	0	$(-,0)$	Saddle Point

Note: For ease of representation in tables, let $A_1 = R_x - R_{\mathrm{Cet}}$, $A_2 = R_y + C_{\mathrm{Cet}} - (R_{\mathrm{EG}} - C_{\mathrm{EG}}) - R_{\mathrm{Tax}} + C_{\mathrm{PR}}$, $A_3 = R_{\mathrm{EG}} - C_{\mathrm{EG}} + R_{\mathrm{Tax}} - C_{\mathrm{PR}} - R_y + \Delta r + l$, and $A_4 = R_{\mathrm{Cet}} - R_x - r_{\mathrm{Cet}} + \Delta r + l$.

Table 2 illustrates two combinations of Evolutionarily Stabilizing Strategies (ESS) for central governments and local government, denoted as $E_1 = (0,0)$ and $E_4 = (1,1)$. In E_1, the central government's backing for CET construction is characterized as "*limited*", and the local government's QGD is categorized as "low". Conversely, in E_4, the central government's support for CET construction is described as "*strong*", while the local government's QGD remains at a "low" level.

3.2   Research Hypothesis

3.2.1 The Relationship Between CET and QGD

The aforementioned theoretical model indicates that E_1 and E_4 are the evolutionarily stable points for the central government's support of CET construction and the local government's QGD. The economic significance of E_1 and E_4 lies in the inverse relationship between local government support for CET and the level of enterprise QGD. The central government's robust promotion of the CET market serves as a catalyze for green development, aiding local governments in their pursuit of high-quality growth[40]. By providing clear economic signals and incentives, the CET market enables local authorities to better reconcile economic expansion with environmental sustainability[41]. Furthermore, it stimulates investment and innovation in green and low-carbon technologies[10], thereby fostering a transformative development model that transcends conventional growth trajectories, granting regions a competitive edge in high-quality development. Under a unified carbon trading framework, local governments are compelled to enhance coordination in tackling shared carbon challenges, optimizing resource allocation, and leveraging regional strengths[42]. This market-driven approach fosters nationwide progress in high-quality green development. Therefore, we posit Hypothesis 1.

Hypothesis 1   The implementation of the CET can promote QGD at the local government level.

3.2.2 The Moderating Role of Government Regulation

Figure 1 illustrates the phase diagram depicting the evolutionary strategies employed by central and local governments. The figure reveals two stable state strategies in the dynamic interaction: One in which the central government provides "limited support" for CET, result-

ing in the local government achieving "low" levels of QGD, and another in which the central government offering "*strong support*" for CET, leading to the local government attaining "high" levels of QGD. The latter strategy more closely aligns with the national objectives for QGD. As depicted in Figure 1, achieving the stable combination of the second strategy requires reducing the areas labeled A and B while expanding the areas of C and D. This adjustment can be achieved by optimizing parameters such as $R_{Cet}(m, Q_0, p)$, $R_{EG} - C_{EG}$, R_{Tax}, and C_{PR} to minimize x_0 and y_0 at saddle point E_5.
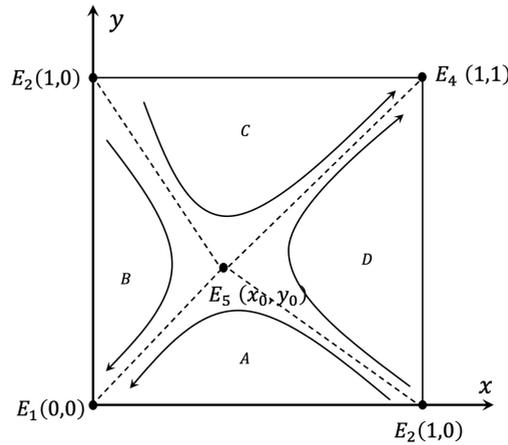

Figure 1   Phase diagram of strategic evolution of x and y

Building on the theoretical model, from the perspective of government oversight, strategies that increase environmental protection budgets (R_{EG}) to enhance treatment efficiency ($R_{EG} - C_{EG}$), raise resource taxes (R_{Tax}) to optimize resource utilization, and reduced direct abatement expenditures (C_{PR}) to shift governance towards market-based mechanisms collectively serve to optimize the cost-benefit ratio of environmental management. This approach approaches a critical threshold, denoted as x_0 near zero, where $x_0 = \left[\frac{C_{Cet} + C_{PR} - (R_{EG} - C_{EG}) - R_{Tax}}{(l + \Delta r + C_{Cet})}\right]$. Consistent with prior research findings[43], government regulation plays a key role in addressing market inefficiencies.

1) Increased allocations to environmental protection (R_{EG}) enhance management efficiency through investments in digital low-carbon technology, infrastructure, and pollution control, while simultaneously accelerating industrial restructuring towards greener development pathways[44]. These measures bolster carbon market liquidity, drives economic transitions towards low-carbon growth, and fosters sustainable development.

2) Raising resource taxes (R_{Tax}) augment government revenues and utilize price signals to incentivize resource efficiency, thereby reducing negative externalities and stabilizing the carbon market[45]. This approach strengthens market confidence in green transitions and establishes a robust foundation for localized green development strategies.

3) Reducing direct pollution abatement expenditures (C_{PR}) reflects a strategic shift from government-led intervention to market-driven environmental responsibility[46]. This shift moti-

vates firms to innovate and optimize operations for emission reductions, alleviating fiscal pressures on governments. Simultaneously, it stimulates carbon market dynamics by promoting cost-effective emissions reductions and driving sustainable governance models at the local level.

Given the aforementioned findings, we hereby formulate Hypothesis 2.

Hypothesis 2   Government oversight moderates the influence of CET on the level of QGD at the local government level. Notably, environmental protection expenditure and resource taxes exert a positive effect, whereas direct pollution control expenditures has a negative impact.

3.2.3 The Moderating Role of Market Conditions

Building on the theoretical model, enhancing the CET market's transaction volume $R_{\text{Cet}}(m, Q_0, p)$ to align with other commodity markets is essential for reducing the economic decarbonization index (y_0) toward zero, where $y_0 = \frac{[R_x - R_{\text{Cet}}(m, Q_0, p)]}{[\Delta r + l - r_{\text{Cet}}(m, Q_0, p)]}$. This adjustment depends on carbon allowance allocation (Q_0), market liquidity (m), and carbon pricing (p).

1) Regarding initial carbon quotas (Q_0), while Wang et al.[28] suggested that diverse allocation methods can incentivize low-carbon production, their efficacy is constrained by policy orientation, historical emissions, and regional disparities. As a result, in the early stages of the CET market, allocation mechanisms have a limited direct impact on transaction volumes.

2) Market liquidity (m), a key measure of CET market efficiency, is influenced by factors including market transparency, trading mechanisms, and participant diversity. Despite its role in fostering green innovation[11], early-stage CET market faces challenges such as information asymmetry, incomplete trading rules, and limited participants. These issues collectively hinder market liquidity, restricting the growth of transaction volumes.

3) Carbon pricing (p), the core of market driver, must balance abatement costs with policy goals and supply-demand. Optimal pricing incentivizes corporate decarbonization and facilitates green transitions[14]. For firms with green technology, higher pricing enhances profits from
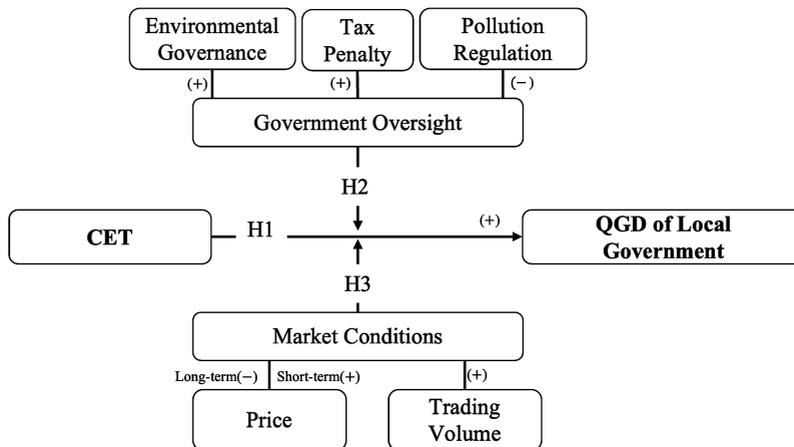

Figure 2   Variable relationships and empirical research hypotheses

surplus allowances, encouraging reinvestment. Conversely, *f* elevated pricing increases costs for high-emitting firms, delaying upgrades and challenging regional QGD. While well-calibrated pricing promotes short-term green development, sustained increases may diminish incentives for low-carbon firms and strain high-emission enterprises, impeding long-term QGD growth.

In summary, as demonstrated by Hypothesis 3.

Hypothesis 3 Market conditions moderate the influence of CET on QGD at the local government level. Specifically, trading scale exert positive effects, while price exerts a short-term positive influence but may have a suppressive effect in the long term.

The relationships among the research hypotheses are shown in Figure 2.

4 Methodology

4.1 Research Data Sources

This study draws on data from 30 provinces in Chinese provinces (excluding Xizang)[2] covering 2007–2020, sourced from the China Stock Market & Accounting Research (CSMAR) database, the Chinese Research Data Services Platform (CNRDS), and provincial statistical yearbooks. The specific variables are outlined below.

4.2 Variable Description

4.2.1 Dependent Variable

To evaluate the impact of CET pilot policy on QGD level from diverse angles, this study employs GTFP and the GHQI as dependent variables to examine its effects on efficiency and quality at the provincial level, representing energy efficiency and environmental development quality, respectively.

1) GTFP. Based on established methodologies in existing literature[19,22,31], GTFP is calculated using the non-oriented SBM-GML index with labor, capital, and energy as inputs. Labor is measured by the number of employed individuals at the end of the province's fiscal year. Capital is represented by provincial fixed assets adjusted for price indices. Energy input is quantified as energy consumption (in ten thousand tons of standard coal) at the fiscal year's end. Outputs are classified as desired or undesired. Desired output is real GDP of each province, adjusted for price indices. While undesired outputs include industrial smoke (dust) emissions, industrial wastewater discharge, sulfur dioxide emissions, and solid waste generation.

2) GHQI. To evaluate the GHQI, we adapt a refined DPSIR model encompassing five dimensions: Driving force (D), Pressure (P), State (S), Impact (I), and Response (R). Specifically, Driving force (D) represents factors promoting provincial green high-quality development. Pres-

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[2]China encompasses a grand total of 34 provinces and administrative regions. However, owing to the inherent limitations in data accessibility from Hong Kong, Taiwan, Macao, and Xizang, our research adopts a sample comprising 30 provinces. This deliberate sample selection is in congruence with a plethora of preceding scholarly endeavors[47,48], thereby ensuring the comparability and methodological rigor of our analysis. (There is no carbon emission data in Xizang).

sure (P) reflects the environmental strain from human activities. State (S) describes the current condition of green development under these driving forces and pressures. Impact (I) assesses how environmental changes affect socio-economic systems. Response (R) reflects government policies aimed at enhancing green development. Based on Table 3 indicators, GHQI values were quantified using the entropy method to determine indicator weights, enabling a comprehensive assessment of provincial green development.

Table 3 Detailed description of GHQI

Primary indicators	Secondary indicators	Tertiary indicators	Indicator direction	Unit
Driving force (D)	Economic drive	Environmental protection expenditure	+	Ten thousand yuan
	Social drive	Total number of civilian vehicles	−	Ten thousand vehicles
Pressure (P)	Energy pressure	Total energy consumption	−	Ten thousand tons of standard coal
	Environmental pressure	Industrial smoke and dust emissions	−	Ten thousand tons
		Industrial wastewater discharge	−	Ten thousand tons
		Sulfur dioxide emissions	−	Ten thousand tons
State (S)	Environmental state	Forest coverage rate	+	Percentage (%)
		Domestic waste harmless treatment rate	+	Percentage (%)
Impact (I)	Social impact	Fuel retail price index	−	Base year = 100
Response (R)	Infrastructure investment	Investment in urban environmental infrastructure construction	+	Ten thousand yuan
	Pollution control	Investment completed in industrial pollution control	+	Ten thousand yuan

4.2.2 Independent Variable

The primary explanatory variable in this study, the pilot policy for CET (PCET_{it}). As a critical policy tool for achieving carbon peaking and neutrality, CET was initiated in October 2011 through the "Notice on Pilot Policy for CET Work" issued by Chinese National Development and Reform Commission. Seven pilot regions — Beijing, Shanghai, Tianjin, Guangdong, Shenzhen, Chongqing, and Hubei — were selected, followed by the inclusion of Fujian Province

in 2016. The pilot programs launched online in these regions starting in 2013. By November 2020, the pilot areas encompassed over 20 industries and nearly 3,000 enterprises, with a cumulative turnover exceeding 430 million tons and nearly 10 billion yuan.

The China National CET Market Construction Program, initiated in late 2017, aimed to establish a unified national carbon market. From 2018 onward, the Ministry of Ecology and Environment issued administrative measures, management systems, and technical specifications, forming an institutional framework for a nationwide CET, which officially launched on July 16, 2021.

The variable PCET_{it} is operationalized as the product of two binary indicators: Pilot province (pcet_i) and the implementation year (time_t).

4.2.3 Control Variables

Per capita GDP, population density, industrial structure, marketization level, R&D intensity, and FDI influence regional energy consumption and pollution emissions[34,49]. To account for these effects, the paper incorporates corresponding control variables.

1) GDP per capita (lnpgdp) is the natural logarithm of provincial GDP divided by the total population.

2) Population density (lnpeople) is the logarithm of provincial population divided by the provincial area.

3) Industrial structure (lnindustr) refers to the proportion of tertiary industry in the provincial economy.

4) Marketization level (marklevel) is a composite index based on Fan Gang's marketization index[50], encompassing five dimensions such as the government-market relationship and the development of the non-state sector.

5) Research and Development Intensity (RDI) is the ratio of R&D expenditure to GDP.

6) Foreign Direct Investment (FDI) captures the positive impact of technology transfer, industry structure adjustment, and income growth on carbon emissions.

4.3　Research Methods

Given the varying launch times of CET across pilot regions, this study employs a Multi-Period DID model to investigate the effects of the pilot policy for CET on QGD. This approach controls for endogeneity, holding variables constant, and assesses the differences in the impact of pilot and non-pilot regions on QGD pre- and post-launch of CET. The empirical model is expressed as follows:

$$Y_{it} = \alpha_0 + \alpha_1 \text{PCET}_{it} + \beta \text{control}_{it} + \mu_i + \gamma_t + \epsilon_{it}. \tag{11}$$

In the model, subscript i denotes the CET pilot province, and t denotes the year. The dependent variable Y_{it} measures the QGD level of province i in year t. PCET_{it} is the independent variable, serving as a dummy variable indicating whether province i initiates CET in year t. The control_{it} represents a location-dependent and time-dependent control variable affecting QGD.

The μ_i is the region-specific fixed effect, capturing time-invariant factors influencing development. The γ_t is the year-specific fixed effect, accounting for time-related factors independent of the region. The ϵ_{it} denotes the error term.

Moreover, $\text{PCET}_{it} = \text{pcet}_i \times \text{time}_t$. Here, pcet_i is a binary dummy variable indicating CET pilot regions, where $\text{pcet}_i = 1$ for pilot provinces (Beijing, Shanghai, Tianjin, Chongqing, Guangdong, Hubei, and Fujian)[3] and $\text{pcet}_i = 0$ for non-pilot provinces. Subsequently, considering the varying initiation times of the pilot policy for CET in each province, time_t is defined as follows: $\text{time}_t = 1$ when i is Beijing, Shanghai, Tianjin, or Guangdong and $t \geq 2013$; or when i is Chongqing or Hubei province and $t \geq 2014$; or when i is Fujian province and $t \geq 2016$; otherwise, $\text{time}_t = 0$. If the CET pilot policy significantly impacts QGD, the coefficient α_1 will be statistically significant.

5 Results and Analysis

5.1 Benchmark Regression Model

Table 4 presents the regression results from the multi-period DID model equation (12), including district fixed effects and year fixed effects, with standard errors clustered at the provincial level. Specifically, columns (1) and (3) in Table 4 exclude control variables, while columns (2) and (4) include them. The dependent variable in columns (1) and (2) is GTFP, and in columns (3) and (4), it is GHQI.

Table 4 Benchmark Regression Results

Variables	Dependent Variables			
	(1) GTFP	(2) GTFP	(3) GHQI	(4) GHQI
$\text{pcet}_i \times \text{time}_t$	0.266***	0.234***	0.058***	0.064***
	(2.92)	(2.83)	(2.99)	(3.35)
Control Variables	No	Yes	No	Yes
Constant term	0.962***	−7.761***	0.296***	0.137
	(86.87)	(−3.16)	(125.10)	(0.28)
Year Fixed Effects	Yes	Yes	Yes	Yes
Area Fixed Effects	Yes	Yes	Yes	Yes
Observations	420	420	420	420
R-squared	0.233	0.262	0.616	0.632

Note: Standard errors in parentheses, clustered at the province level.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. This note applies to all subsequent tables.

Table 4 reveals that, without control variables, the impact coefficients on GTFP and GHQI are 0.266 and 0.058, respectively. With control variables, these coefficients adjust to 0.234 and 0.064, both significant at the 1% level. This indicates that the effect of the CET pilot

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[3]In this paper, the data for Shenzhen are combined and presented in Guangdong Province.

policy remains stable and significant despite control variables. Further, when comparing GTFP (efficiency) and GHQI (quality), the policy shows a stronger impact on efficiency, as evidenced by the higher coefficient for GTFP. This underscores the critical role of the CET market in optimizing resource allocation and increasing the efficiency of transforming labor, capital, and energy into desired outputs. While the policy's direct effect on GHQI is more modest, its statistical significance confirms a positive contribution to QGD, though with a smaller effect size. In conclusion, the CET pilot policy is a key driver of green economic efficiency and an effective tool for promoting QGD, supporting Hypothesis 1.

5.2 Robustness Check

Although the baseline regression outcomes support hypotheses 1, potential endogeneity, particularly omitted variable bias, may undermine the estimates' integrity. To ensure the robustness, we conducted additional tests, including parallel trend analysis, placebo tests, alternative dependent variable measures, and the exclusion of confounding policy impacts.

5.2.1 Parallel Trend Test

Following Wu et al. [34] and McGavock [51], we conduct a parallel trend test to analyze the dynamic effects of the CET pilot policy. Interaction terms between time and policy dummy variables are constructed for the six years before, during, and after the implementation of the pilot policy, with the year prior to initiation serving as the reference point. The model is specified as follows.

$$Y_{it} = \beta_0 + \sum_{t=1}^{6} \beta_{\mathrm{pre}_t}\mathrm{DID}_{\mathrm{pre}_t} + \beta_{\mathrm{current}}\mathrm{DID}_{\mathrm{current}} + \sum_{t=1}^{6} \beta_{\mathrm{post}_t}\mathrm{DID}_{\mathrm{post}_t} +$$
$$\beta_2\mathrm{control}_{it} + \mu_i + \gamma_t + \epsilon_{it}, \tag{12}$$

where, $\mathrm{DID}_{\mathrm{pre}_t}$, $\mathrm{DID}_{\mathrm{current}}$, and $\mathrm{DID}_{\mathrm{post}_t}$ represent the interactions between year and policy dummy variables for the six years before, during, and after the CET pilot policy implementation. β_{pre_t}, β_{current}, and β_{post_t} denote the coefficients of the these interaction terms. The dynamic effects of the CET pilot policy are scrutinized by comparing the significance of β_{pre_t}, β_{current}, and β_{post_t}. Figure 3 demonstrates that the β_{pre_t} coefficients for both GTFP and GHQI are insignificant, indicating that, prior to the implementation of the CET pilot policy, QGD efficiency (GTFP) and development level (GHQI) differences between pilot and non-pilot provinces were similar, supporting the parallel trend assumption.

At the QGD efficiency level (GTFP), the coefficients β_{post_1}, β_{post_2}, β_{post_4}, β_{post_5}, and β_{post_6} for PCET are significant at the 5% level, indicating a distinct post-baseline divergence in efficiency between pilot and non-pilot provinces, with a marked increase in GTFP. However, the insignificance of the β_{current} coefficient suggests that during the initial implementation period, the efficiency gap did not significantly differ from the baseline, likely due to a "lagged effect" of the CET pilot policy on provincial GTFP.

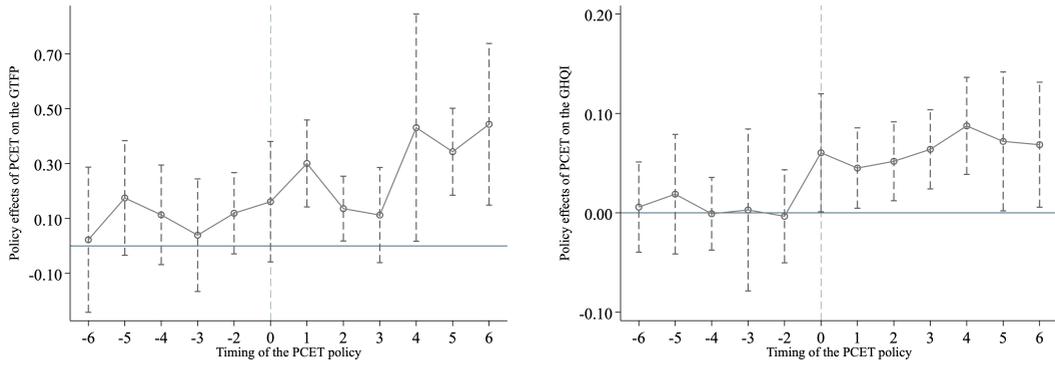At the QGD quality level (GHQI), PCET shows statistically significant immediate (β_{current})

Figure 3 Plot of parallel trend tests for the CET pilot policy

and lagged $(\beta_{\mathrm{post}_t})$ effects on GHQI ($p < 0.05$), indicating that the CET pilot policy significantly widened the GHQI gap between pilot and non-pilot provinces, both immediately and over time. While the benchmark model suggests a weaker effect of CET on GHQI compared to GTFP, the GHQI effect remains stable and significant across periods, underscoring the effectiveness and lasting impact of the CET policy in enhancing provincial-level QGD.

5.2.2 Placebo Test

To address the standard error bias from serial correlation in the multi-period DID analysis, a placebo test using the non-replacement method is conducted[34]. Ten provinces are randomly selected from the 30-province sample to form a "pseudo-treatment group", with the remaining provinces serving as the control group. The interaction term of the "pseudo-policy dummy variable" is generated and regressed on the "pseudo-policy dummy", and the process is repeated 1000 times to acquire regression results. Finally, the distribution of estimated coefficients for the 1000 "pseudo-policy dummy" and corresponding P-test values are shown in Figure 4.
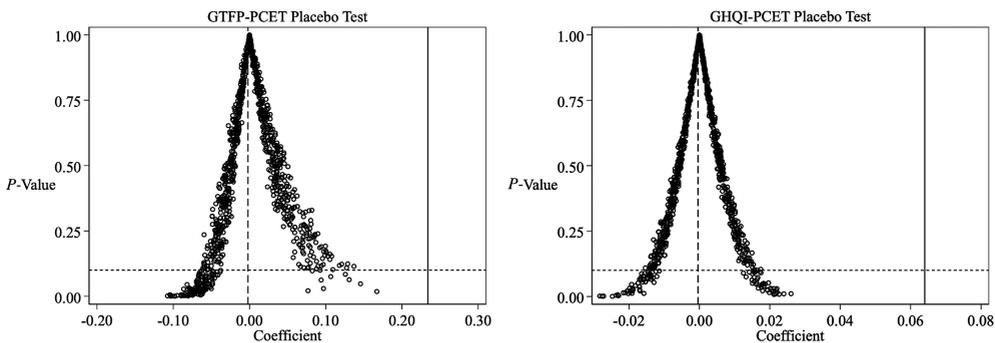

Figure 4 Placebo test plot of the CET pilot policy

In the baseline model, the impact coefficient of the CET pilot policy on GTFP is 0.234, and on GHQI is 0.064, as shown by the vertical dotted line in Figure 4. After 1000 randomization, P-values for most coefficients remained above 0.1, with no overlap with the original coefficient of 0.057, indicating lack of significance at the 10% level. This suggests that the effects of PCET on

GTFP and GHQI are not confounded by unobserved factors, confirming the model's robustness in the placebo test.

5.2.3 Diagnosis and Testing of Heterogeneous Treatment Effects

In analyzing the heterogeneous treatment effects using a multi-period DID model with two-way fixed effects, it is essential to account for potential differential biases across individuals receiving the same intervention. This study first diagnoses such biases and then conducts a robustness test to adjust and validate the estimators, enhancing their accuracy in capturing treatment heterogeneity.

The bias diagnosis employs the decomposition strategy proposed by Goodman-Bacon[52], which splits the 2×2 DID estimator into three distinct configurations: 1) A pre-period comparison between treated and untreated units; 2) A post-period comparison between treated and untreated units; 3) A comparison between early-treated and later-treated units, with the latter potentially affected by treatment carryover effects. Using this decomposition to balanced panel data with GTFP as the dependent variable, we estimate that the "never treated" control group contributes 85.95% (GHQI is 84.95%), with a two-way fixed effects DID estimate of 0.233 (GHQI is 0.064), and intergroup variation contributing only 10.12% (GHQI is 11.17%). This suggests minimal bias, despite some heterogeneity in treatment effects.

Further analysis using De Chaisemartin and d'Haultfoeuille's[53] decomposition reveals a total of 51 positive weights, accounting for 100% of the total (applicable to both GTFP and GHQI). These findings confirm that the two-way fixed effects estimators exhibit no significant bias, reinforcing the robustness of our conclusions.

5.2.4 Alternative Measures for the Dependent Variable

Measurement errors from different variable metrics may affect research reliability. To test the hypotheses from multiple perspectives, we replaced the original GTFP indicator with industrial value-added, while keeping input factors and undesirable outputs constant, creating a new provincial-level GTFP indicator, GTFP_IO. Additionally, we replaced the existing GHQI framework with Sun et al.'s indicator system[54], renaming it GHQI_ [4], offering an alternative perspective on the research topic.

The regression results in Table 5 (1) and (2), indicate that PCET significantly improves both GTFP_IO and GHQI_, with coefficients of 0.095 and 0.035, respectively, significant at the 5%

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[4]This indicator system evaluates green development in Chinese high-quality growth, focusing on four key metrics: GDP energy intensity, energy consumption elasticity, wastewater discharge per unit of output, and exhaust gas emissions per unit of output. Specifically, GDP energy intensity is the ratio of standard coal consumption to regional GDP; energy consumption elasticity is the ratio of the growth rate of energy consumption to GDP growth rate; wastewater discharge per unit of output is total wastewater discharge relative to regional GDP; and exhaust gas emissions per unit of output are sulfur dioxide emissions relative to regional GDP. All indicators are treated as negative, with weights calculated using the entropy method to provide a comprehensive assessment of green development achievements.

level. These results support the baseline model's findings, confirming the robustness of CET in enhancing green development efficiency (GTFP) and quality (GHQI).

Table 5 Alternative Dependent Variables and Exclusion of Other Policy Effects

Variables	Dependent variables					
	(1) GTFP_IO	(2) GHQI_	(3) GTFP	(4) GHQI	(5) GTFP	(6) GHQI
$\text{pcet}_i \times \text{time}_t$	0.095**	0.035**	0.262***	0.077***		
	(2.52)	(2.65)	(4.29)	(4.46)		
Other			−0.053	−0.024	0.129	0.029
			(−0.72)	(−1.53)	(1.38)	(1.38)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Constant term	0.591	1.861***	−7.874***	0.085	−8.821***	−0.193
	(0.94)	(3.40)	(−3.20)	(0.18)	(−3.20)	(−0.40)
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Area Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	420	420	420	420	420	420
R-squared	0.274	0.193	0.262	0.634	0.245	0.608

5.2.5 Excluding Other Policies

During the sample period, parallel policies aimed at improving provincial QGD efficiency and quality may impact the assessment of CET pilot policy effects. To address this, we incorporated the 2011 "*Ten Thousand Enterprises Energy-Saving and Low-Carbon Action Implementation Plan*" (FGHZ [2011] No. 2873) (Hereafter referred to as the "Plan") into our analysis. By setting 2011 as the intervention year ("other") and including it in the regression alongside the CET pilot policy, we conducted robustness checks.

Regression results (Table 5, columns (3) and (4)) show that the CET pilot policy(PCET_{it}) coefficient remains significant after accounting for the "Plan", while the coefficient of "other" is insignificant. This suggests that the CET policy's impact on provincial QGD efficiency and quality is independent of the "Plan". Additional regression focusing solely on the "Plan" (Table 5, columns (5) and (6)) also shows an insignificant "other" coefficient, reinforcing the robustness of the CET pilot policy's effects and validating the baseline results.

5.3 Heterogeneity Analysis

To explore the heterogeneous impact of the CET pilot policy across provinces, this study conducts heterogeneity tests based on three factors: Regional location, employment structure, and economic development level.

5.3.1 Heterogeneity in Regional

Given regional disparities in economic foundations, resource endowments, and technological innovation among different regions in China, this study classifies the 30 provinces into Eastern, Western, and Central regions to assess regional heterogeneity of the CET pilot policy's effects.

As shown in Columns (1) to (6) of Table 6, the CET policy significantly improves both the efficiency (GTFP) and quality (GHQI) of QGD. However, the specific degree and direction of these effects vary regionally.

- The Eastern region, characterized by a robust economic foundation, optimized industrial structure, and strong market adaptability and innovation capacity, gains the most from the CET policy, significantly boosting both GTFP and GHQI. Comparisons with non-Eastern regions highlight its superior ability to capitalize on policy dividends for green transformation and high-quality development.
- In contrast, the Western region shows more limited gains in GTFP and GHQI. The direct effects are weaker than those in the Eastern and Central regions, with interaction analysis indicating a dampened impact of the CET policy on QGD efficiency. This is due to a weaker economic base, a more rigid industrial structure, and deficiencies in resource utilization, innovation, and talent, which hinder its adaptability to CET.
- The Central region shows no significant deviation from the national average in CET policy effects, with no notable difference from non-Central regions. This neutrality likely reflects its developmental stage, lacking both the Eastern region's market maturity and the Western region's need for industrial restructuring.

These findings highlight regional disparities in the effects of the CET pilot policy, emphasizing the need for region-specific measures to foster green transformation and QGD nationwide.

Table 6 Regression results of regional heterogeneity

Variables	Dependent Variables					
	(1) GTFP	(2) GHQI	(3) GTFP	(4) GHQI	(5) GTFP	(6) GHQI
$\text{pcet}_i \times \text{time}_t$	0.154***	0.048***	0.174***	0.049***	0.222***	0.063***
	(2.90)	(5.695)	(2.95)	(3.31)	(3.09)	(3.63)
$\text{pcet}_i \times \text{time}_t \times \text{East}$	0.257**	0.052**				
	(2.09)	(2.07)				
$\text{pcet}_i \times \text{time}_t \times \text{West}$			−0.274**	−0.070***		
			(−2.51)	(−4.57)		
$\text{pcet}_i \times \text{time}_t \times \text{Middle}$					−0.127	−0.012
					(−1.21)	(−0.56)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Constant term	−8.059***	0.078	−8.169***	0.033	−7.691***	0.148
	(−3.19)	(0.16)	(−3.23)	(0.07)	(−3.14)	(0.31)
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Area Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	420	420	420	420	420	420
R-squared	0.269	0.636	0.263	0.637	0.267	0.632

5.3.2 Heterogeneity in Economic Structure

The secondary industry, a key driver of industrialization, significantly impacts regional green development. Variations in the proportion of secondary industry employment across provinces reflect differing economic trajectories and industrialization stages, affecting the effectiveness of CET pilot policies. This study classifies provinces into "industrially dominant" or "non-industrially dominant" based on whether secondary industry employment exceeds 30% of total employment, to explore differential CET policies effects.

As shown in Table 7 (1) and (2), in industrially dominant provinces, the CET pilot policy significantly improves provincial GTFP, indicating that intensive industrial activities, under effective policy guidance, enhance resource allocation and pollution reduction. However, the CET policy's impact on GHQI is not significant, likely due to GHQI's focus on the static level and comprehensive quality of green development, while CET effects — such as industrial structural optimization, innovation, and environmental governance — tend to materialize over a longer period, lagging behind the immediate efficiency gains.

Table 7   Regression results of heterogeneity in employment structure and economic level

Variables	Dependent variables			
	(1) GTFP	(2) GHQI	(3) GTFP	(4) GHQI
$pcet_i \times time_t$	0.172***	0.064**	0.145***	0.046***
	(3.42)	(2.71)	(2.77)	(3.31)
$pcet_i \times time_t \times PESI$	0.267**	0.000		
	(2.07)	(0.00)		
$pcet_i \times time_t \times PGDP$			0.257**	0.052**
			(2.09)	(2.07)
Control Variable	Yes	Yes	Yes	Yes
Constant term	−8.040***	0.144	−8.060***	0.078
	(−3.14)	(0.29)	(−3.19)	(0.16)
Year Fixed Effects	Yes	Yes	Yes	Yes
Area Fixed Effects	Yes	Yes	Yes	Yes
Sample Size	420	420	420	420
R-squared	0.271	0.632	0.269	0.636

5.3.3 Heterogeneity in Economic Level

In evaluating the effects of CET policies, it is crucial to consider how regional economic development affects policy adaptability and green transformation. Regions with high per capita GDP, advanced resources, and technology can more effectively implement CET policies and drive green transformation. Conversely, regions with low per capita GDP face challenges such as resource scarcity, technological limitations, and the need for economic restructuring. This study classifies provinces into "higher economic development level" (above the national average per capita GDP) and "lower economic development level" groups to explore the varying impacts

of CET policies on provincial QGD.

Table 7 (3) and (4) show that provinces with higher per capita GDP experienced greater improvements in both efficiency (GTFP) and quality (GHQI) under CET policies. This indicates that higher economic development levels facilitate policy effectiveness, accelerating resource allocation, technological innovation, and environmental governance. Policy recommendations should be differentiated: Developed provinces should lead in green technologies and low-carbon transformation, while less developed provinces require enhanced support to overcome initial challenges, ensuring equitable CET implementation and advancing China's sustainable development.

6 Moderating Effects of Government Oversight and Market Conditions

In effectiveness of CET in driving provincial QGD hinges on both external regulatory factors and internal market conditions.

Externally, government oversight plays a critical role by shaping the regulatory environment through environmental governance, stringent pollution controls, and targeted tax penalties, which alter firms' cost structures and market entry. These external measures indirectly enhance CET's effectiveness in promoting QGD.

Internally, market conditions critically influence CET efficiency. Equitable carbon quota allocation ensures balanced participation, while high liquidity and trading volumes reflect market maturity, enhancing price discovery and resource allocation. Carbon price fluctuations directly incentivize firms to adopt emission reduction strategies,

6.1   Moderating Effects of Government Oversight

This study examines how key facets of government oversight — Environmental Governance (EG), Pollution Regulation intensity (PR), and Tax Penalty measures (TaxPen) — moderate CET policy effects, elucidating the role of external regulatory factors in shape policy outcomes. The moderation effect model is presented in Equation (14).

1)Environmental Governance (EG): Defined as the ratio of environmental protection expenditure to general public budget expenditure, reflecting the government's commitment to environmental sustainability.

2) Pollution Regulation intensity (PR): Following Zhang et al.[55], ER is measured as the completed investment in industrial pollution control relative to the proportion of the secondary industry.

3) Tax Penalty (TaxPen): To assess the impact of resource taxation on firms, we use the proportion of resource tax to industrial value-added, capturing regional variations in resource endowments and economic development that affect taxation efficacy.

$$Y_{it} = \alpha_0 + \alpha_1 \text{PCET}_{it} + \theta \text{PCET}_{it} \times \text{gov}_{it} + \alpha_2 \text{gov}_{it} + \beta_2 \text{control}_{it} + \mu_i + \gamma_t + \epsilon_{it}. \qquad (13)$$

Among these, PCET_{it} represents the interaction between policy and time, and gov_{it} captures

government oversight, including EG, PR, and TaxPen. After incorporating the interaction term of PCET_{it} and gov_{it}, α_1 is the coefficient of CET policy's impact when controlling for government oversight variables, and θ quantifies the moderating effect of government oversight, serving as the key coefficient for evaluating government regulation. Other terms follow the definitions in Equation (12).

Regression results in Table 8 confirm the positive effects of the CET pilot policy has a positive impact on both GTFP and GHQI indices, with government oversight (EG, PR, and TaxPen) exhibiting differential moderating impacts.

- Firstly, environmental governance (EG) shows no significantly moderating effect on the CET policy's impact on provincial GTFP, indicating that independent environmental governance efforts may not directly improve green economic efficiency. However, EG significantly and positively moderates the policy's influence on provincial GHQI, suggesting that increased EG expenditure amplifies the CET pilot's benefits in improving green and high-quality development. This underscores the critical role of EG in supporting green transformation, not through efficiency gains but by enhancing environmental quality and

Table 8 Regression results under the moderating effects of Government Oversight

Variables	Dependent Variables					
	GTFP			GHQI		
	EG	PR	TaxPen	EG	PR	TaxPen
PCET_{it}	0.219***	0.151**	0.220***	0.047***	0.049**	0.072***
	(2.83)	(2.40)	(2.85)	(3.28)	(2.29)	(4.42)
$\text{PCET}_{it} \times \text{EG}_{it}$	−0.018			0.015**		
	(−0.60)			(2.64)		
$\text{PCET}_{it} \times \text{PR}_{it}$		−0.504**			−0.106	
		(−2.15)			(−1.45)	
$\text{PCET}_{it} \times \text{TaxPen}_{it}$			−0.960			0.480***
			(−0.67)			(3.34)
EG_{it}	0.016			0.020***		
	(0.87)			(5.30)		
PR_{it}		−0.027			0.052***	
		(−0.57)			(3.12)	
TaxPen_{it}			−0.135			0.056***
			(−0.77)			(3.14)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes
Constant term	−7.864***	−7.508***	−7.648***	0.042	0.288	0.091
	(−3.13)	(−3.15)	(−3.15)	(0.10)	(0.59)	(0.19)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Area fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Sample size	420	420	420	420	420	420
R-squared	0.263	0.266	0.266	0.667	0.654	0.642

fostering sustainable development.

- Secondly, pollution regulation (PR) significantly negatively moderating the CET policy's effect of GTFP, while showing no significant impact on GHQI. This indicates that excessive investments in industrial pollution control may reduce firms' incentives to optimizing resource allocation through innovation and market mechanisms, thus inhibiting green economic efficiency. Striking a balance between pollution control investments and market-driven incentives for autonomous green transformation is essential to sustain efficiency while achieving environmental improvements.

- Furthermore, tax penalties (TaxPen), as a moderating variable, do not significantly moderate the CET policy's impact on provincial GTFP but play a significant and positive role in enhancing provincial GHQI. Higher resource taxes reflect the internalization of environmental costs while effectively incentivizes firms to adopt environmentally friendly production methods, thereby elevating green and high-quality development. This underscores the crucial role of economic instruments in green transformation, leveraging tax mechanisms to align corporate behavior with both environmental and economic objectives.

The above conclusion supports Hypothesis 2. In summary, short-term improvement in green development quality can be achieved by increasing environmental governance investments and resource tax collections. For long-term efficiency, pollution regulation should transition from direct industrial control to market-based mechanisms like CET, promoting green innovation and sustainable economic growth.

6.2 Moderating Effects of Market Conditions

This study explores the moderating effects of market conditions on the CET scheme's impact on provincial QGD, focusing on key market factors: Carbon Quota Allocation Mode (CQAM), Market Mobility, Relative Carbon Trading Volume (TransVol), and Trading Price (Price). The regression model incorporating these market factors is presented in Equation (15), with the metrics described as follows.

1. Relative Carbon Trading Volume (TransVol): Inspired by Wu et al.[56], TransVol is constructed as the ratio of a region's annual carbon trading volume to its CO_2 emissions: $\text{TransVol} = \frac{\text{Regional Carbon Trading Volume}}{\text{Regional } CO_2 \text{ Emissions}}$. A higher TransVol reflects a larger relative trading scale, indicating more active market participation in emissions trading.

2. Carbon Quota Allocation Mode (CQAM): The allocation of carbon quotas is central to carbon trading, with pilot provinces adopting either free allocation or a combined free-and-auction mode. The CQAM variable is 1 for free allocation and 0 for the hybrid approach.

3. Market Mobility (Mobility): Following Zhong et al.[57] and Song et al.[58], Mobility is calculated as the ratio of trading days to total open days in the carbon market annually, reflecting the market's liquidity and trading activity.

4. Trading Price (Price): The role of carbon prices is analyzed from two perspectives. For emission-reduction leaders, higher prices boost carbon sales revenue, facilitating green transformation and QGD. For laggards, rising prices increase purchasing quotas costs, potentially

diverting resources from green development. The annual carbon price for each pilot region is derived from daily trading data, adjusted for inflation using the Producer Price Index for Purchased Industrial Products.

$$Y_{it} = \alpha_0 + \alpha_1 \text{PCET}_{it} + \theta \text{PCET}_{it} \times \text{markfac}_{it} + \alpha_2 \text{markfac}_{it} + \beta_2 \text{control}_{it} + \mu_i + \gamma_t + \epsilon_{it}.$$

(14)

In this context, PCET_{it} represents the interaction term between policy and time ($\text{pcet}_i \times \text{time}_t$); meanwhile, markfac_{it} reflects market conditions, including TransVol, CQAM, Mobility and Price of the carbon market. The coefficient θ captures the moderating impact induced by the market conditions. Other terms follow the definitions in Equation (12).

As shown in Table 9, TransVol, CQAM, Mobility, and Price, all factors influencing carbon trading volume, are further analyzed in detail.

- For TransVol, the interaction terms is statistically significant for GHQI but not GTFP. This indicates that higher TransVol amplifies the impact of CET pilots on provincial QGD quality but not efficiency. The discrepancy may be due to the longer time and

Table 9   Regression Results Under the Moderating Effects of Market Conditions

Variables	Dependent Variables							
	GTFP				GHQI			
	TransVol	CQAM	Mobility	Price	TransVol	CQAM	Mobility	Price
PCET_{it}	0.082	0.289**	0.137	0.255***	0.057***	0.061***	0.085***	0.050***
	(0.67)	(2.30)	(0.79)	(2.77)	(2.81)	(2.99)	(3.34)	(2.79)
$\text{PCET}_{it} \times$ TransVol$_i$	0.003***				0.0001*			
	(2.96)				(1.93)			
$\text{PCET}_{it} \times$ Mobility$_{it}$		−0.167				0.008		
		(−1.11)				(0.25)		
$\text{PCET}_{it} \times$ CQAM$_{it}$			0.193				−0.042	
			(0.76)				(−1.26)	
$\text{PCET}_{it} \times$ Price$_{it}$				−0.058**				0.037***
				(−2.67)				(15.47)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant term	−8.093***	−7.780***	−7.896***	−7.559***	0.128	0.147	0.180	0.032
	(−3.68)	(−3.10)	(−3.32)	(−3.13)	(0.27)	(0.30)	(0.36)	(0.07)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Area fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sample size	420	420	420	420	420	420	420	420
R-squared	0.300	0.266	0.265	0.264	0.633	0.632	0.634	0.647

greater investment required for efficiency gains, which demand structural and technological changes, whereas quality enhancements, such as the use of eco-friendly materials or designs innovations, can be achieved more quickly. Consequently, firms may prioritize short-term quality improvements in response to higher carbon trading volumes, deferring longer-term efficiency gains.

• For CQAM and Mobility, the study found that neither CQAM nor Mobility significantly mediated the effects of CET pilots on provincial GTFP or GHQI. This may result from two factors: first, the current CQAM design may lack sufficient incentives to drive market engagement and innovation, limiting its influence on policy outcomes; second, while Mobility is essential for efficiency, its underdevelopment during the pilot phase, combined with participants' incomplete alignment with market mechanisms, may have constrained its moderating effect.

• Regarding carbon trading price (Price), as an influential factor in carbon trading volume (TransVol), it significantly moderated both GTFP and GHQI. For GTFP, rising prices reduced the positive effect of CET pilots on efficiency, likely due to increased compliance costs, which may crowd out investments in innovation and process optimization. However, for GHQI, higher prices strengthened CET's contribution to green quality, likely by incentivizing firms to prioritize green technology development and environmentally friendly production methods, thereby improving overall environmental quality.

This section of the study confirms Hypothesis 3, elucidating how market conditions shape the effectiveness of CET policies in provincial QGD. In the short term, CET accelerates green transformation by raising carbon trading prices, strengthening market incentives, and driving provincial GHQI growth. However, sustaining long-term GTFP within provincial QGD necessitates keeping carbon prices within an optimal range, balancing emission reduction costs with economic growth to avoid potential slowdowns. Additionally, increasing carbon market liquidity and transaction volumes further enhances the quality of provincial QGD, as reflected in GHQI.

7 Conclude

7.1 Discussion

This study employs an evolutionary game-theoretic model to explore the strategic inter-

actions between central and local governments, providing a theoretical basis for the research hypotheses. Empirical validation is conducted using a multi-period DID model with panel data from 30 Chinese provinces from 2007 to 2020. Robustness is ensured through parallel trend verification, placebo tests, and alternative specifications of both dependent and policy variables. Heterogeneity analyses investigate the moderating effects of geographical distribution, regional economic structure, and development levels. Furthermore, the study examines the moderating role of government oversight — including environmental protection expenditures, resource taxes, and pollution control investments — and market conditions including carbon trading volume, market liquidity, quota allocation, and carbon prices, in shaping the quality (GHQI) and efficiency (GTFP) dimensions of CET's impact on provincial QGD.

7.2 Conclusion

The key findings are presented below.

First, the effectiveness of CET in promoting provincial QGD is substantiated from both quality and efficiency dimensions, particularly through the enhancement of GTFP, which reflects the quality aspect of QGD. These results align with the research of Wu et al.[34] at the enterprise level and extend the theoretical predictions of CET to a broader provincial context, reinforcing the rationale for further expansion and optimization of CET reforms.

Second, the impacts of CET exhibit significant variation across regions, economic structures, and development levels. Cai and Ye[10] identified insufficient low-carbon innovation as a key barrier to QGD. In this context, our analysis yields the following insights: Eastern regions, benefiting from robust economic foundations and innovation capacities, achieve notable improvements in both GTFP and the GHQI. In contrast, western regions, constrained by weaker economies and resource-dependent industries, exhibit limited or even adverse effects, while central regions display a neutral response. This regional heterogeneity contrasts with the findings of Wang and He[12], who argued that CET impacts are more pronounced in western regions than in central or eastern regions. Additionally, Industrialized provinces demonstrate efficiency gains but lag in quality improvements, reflecting the influence of economic structure on policy outcomes. Provinces with higher per capita GDP utilize CET more effectively, achieving simultaneous advancements in GTFP and GHQI, highlighting the critical role of economic development. These findings provide valuable insights for formulating differentiated regional policies and optimizing economic structures.

Third, the moderating role of government oversight mechanisms — environmental protection expenditures, resource taxes, and industrial pollution controls — on CET outcomes. Increased environmental protection budgets significantly boost GHQI but have limited impact on in GTFP, highlighting the focus of environmental governance on quality over efficiency. Resource taxes promote GHQI but exert minimal influence on GTFP, consistent with findings by Peng et al.[23]. that highlighted the positive regulatory role of government in encouraging green behavior and innovation. Conversely, industrial pollution controls negatively moderate GTFP, potentially diverting resources from innovation, while having negligible effects on GHQI, indicating limited

contributions to direct quality improvements. This aligns with the conclusion proposed by Yang et al. [4], advocating for a balanced approach to government environmental regulation. The above conclusions provide clear directional guidance for the government in formulating supporting policies during the construction of the CET.

Lastly, the moderating role of market dynamics — carbon allowance allocation, liquidity, transaction volumes, and pricing — on CET impacts reveals mixed outcome. Contrary to some studies [11,12], we find that allowance allocation and liquidity have non-significant effects, revealing limitations in market design and development. While transaction volumes modestly boost GHQI, their impact on GTFP is limited, indicating that market activity supports quality improvements without significantly driving efficiency. Carbon pricing presents a dual challenge: on one hand, high prices increase compliance costs and exert pressure on GTFP; on the other hand, as noted by Wu and Wang [14], a significant positive correlation exists between carbon prices and firms' total factor productivity, thereby fostering improvements in the GHQI. These findings highlight the complexity of market-based resource allocation and underscore the need for nuanced CET policy design that accounts for multifaceted market forces.

7.3   Managerial Implication

In the context of Chinese carbon market liberalization, all levels of government must leverage this opportunity to advance green and high-quality development (QGD). Based on our findings, we offer the following policy recommendations for guiding managerial action.

7.3.1 Differentiated Support Policies for CET and QGD

Given the significant regional, economic structural, and developmental disparities in the impact of CET on QGD, governments must leverage these differences to implement targeted policies.

- First, to address regional disparities, governments should provide targeted support to areas with suboptimal CET outcomes. This includes offering policy incentives and financial backing to enhance environmental infrastructure, strengthen governance capabilities, and promote the adoption of green technologies. For regions with more successful CET implementation, governments should further consolidate gains by recognizing achievements, disseminating best practices, and incentivizing continued innovation in green development.
- Second, in regions with a higher concentration of secondary industries, governments should focus on promoting industrial upgrading. By implementing policies that encourage investment in technological innovation and R&D, governments can drive the transition of traditional industries toward high-end, intelligent, and green sectors. Conversely, in regions with a lower share of secondary industries, governments should prioritize the introduction and cultivation of emerging sectors, fostering a diversified, high-value-added industrial base to support green and high-quality development.
- Lastly, for provinces with varying levels of economic development, differentiated strategies should be adopted. In economically advanced provinces, governments should refine the

carbon trading market to incentivize energy conservation, emission reduction, and green development through market mechanisms. In less developed provinces, governments should increase investment in green technologies, supporting the growth and innovation of green and low-carbon industries. This can be achieved through the establishment of dedicated funds, tax incentives, and measures to attract private capital, thereby fostering green growth and advancing regional green and high-quality development.

7.3.2 Balancing the Role of Government Regulation and Market Adjustment in CET

- Appropriate regulatory measures and market adjustment strategies are essential to fostering QGD. Research indicates that increased government investment and adjustments to resource taxes have significantly enhanced QGD quality. However, these measures have had a relatively limited impact on improving QGD efficiency, suggesting that regions focused on enhancing quality can achieve further progress by scaling up government investment or optimizing the structure of resource taxes.

- Governments can directly improve QGD quality by increasing investment in green technology R&D, environmental infrastructure, and supporting green industries. Additionally, by adjusting resource tax structures — such as raising taxes on high-pollution and high-energy-consuming industries while reducing taxes for clean energy and environmental protection sectors — resources can be redirected towards green industries, thereby indirectly boosting QGD quality.

- However, it is important to note that environmental regulations may have adverse effects on QGD, particularly in regions dependent on traditional industries. In such cases, governments should not rely solely on environmental regulations to drive QGD. Instead, market mechanisms, particularly carbon trading markets, should play a central role. Governments can establish and refine carbon trading mechanisms, set appropriate emission quotas and trading prices, and guide enterprises towards self-regulated carbon reductions. Simultaneously, these policies should incentivize the adoption of low-carbon technologies and advanced production methods to improve QGD efficiency. Moreover, providing carbon trading-related policy support and information services can help mitigate participation costs and risks for enterprises, further accelerating QGD development.

7.4 Practical Implications

7.4.1 Synergistic Effects Between Environmental Governance and CET Policy

Environmental governance, aimed at improving environmental quality by reducing pollution and enhancing resource efficiency, shares common objectives with CET policy, which incentivizes emissions reductions through market mechanisms to promote green, low-carbon development. While environmental governance is primarily government-driven, CET relies more on market-based adjustments. These policies can complement each other or produce unintended effects if not properly implemented.

To strengthen the synergy between environmental governance and CET, several strategies are essential. Firstly, targeted investment in environmental infrastructure, green technology R&D, and clean energy projects in high-pollution and ecologically sensitive areas is necessary to improve environmental quality. Additionally, a robust evaluation mechanism should be established to monitor and adjust the implementation of both policies to ensure desired outcomes.

In economically underdeveloped regions facing significant environmental pressures, increased investment in environmental protection is crucial. This investment not only improves local environmental quality but also supports the development of green industries, facilitating economic transformation. Moreover, an improved environmental tax policy should be implemented to internalize environmental costs, encouraging businesses to adopt environmentally friendly practices.

However, caution is needed regarding over-reliance on pollution treatment. While such investment can yield short-term environmental improvements, it may lead to rising costs and limited long-term benefits without fostering industrial transformation. Thus, alongside increased environmental investment, emphasis must be placed on the development and application of green and low-carbon technologies to achieve both environmental and economic objectives through innovation.

7.4.2 Creating a "competition-neutral" Carbon Emissions Trading Market

A "competition-neutral" framework for the carbon market is crucial for ensuring effective contributions to green transitions. This framework should minimize market distortions in liquidity and allowance allocation, facilitating efficient market dynamics. Governments should offer financial support, such as low-interest loans and innovation funds, to mitigate the compliance costs of carbon pricing and encourage investment in efficiency-enhancing technologies. Continued emphasis on carbon pricing will incentivize green innovation, driving progress in both GTFP and GHQI, ultimately supporting comprehensive advancements in provincial QGD.

7.5 Limitations and Future Prospects

First, the CET pilot policy is currently limited to seven economically advanced provinces out of Chinese 34 administrative regions, which are characterized by relatively strong economic foundations and educational resources. As a result, the data's representativeness is constrained. Second, the rapid development and widespread application of digital technologies increasingly influence provincial QGD. Furthermore, while evolutionary game theory provides a robust framework for analyzing strategic interactions and dynamics in complex systems, it does not fully capture factors such as participants' psychological expectations, information asymmetry, and bounded rationality.

Therefore, future research should expand the CET pilot scope, collect more comprehensive data, and consider the impact of digital technologies. Additionally, employing methods such as multi-attribute decision-making[59] and other advanced approaches will facilitate more nuanced analyses of CET policies and their interactions with digital technologies and provincial indica-

tors, providing a scientific basis for policy development and contributing to the creation of a smart, equitable, and sustainable society.

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