



Economic green transformation and environmental quality: does financial market development matter?

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Abstract

Achieving an economic green transformation is a crucial strategy for addressing climate change and environmental pollution. Therefore, an in-depth study of this transformation holds significant practical importance. This paper constructs a theoretical analysis framework for economic green transformation from a full-chain perspective encompassing upstream, midstream, and downstream sectors. It utilizes panel data from 30 Chinese provinces (2008–2020) and employs a two-way fixed effects model to empirically examine the impact of economic green transformation on environmental quality, as well as the moderating role of financial market development in this process. The findings show that the economic green transformation significantly improves environmental quality. Specifically, 1% increase in green energy production, green innovation, green investment, and green consumption respectively enhances environmental quality by 0.104%, 0.101%, 0.476%, and 0.058%. Under the moderation of financial market development, the effects of green energy production (upstream), green innovation and green investment (as supporting sectors in the midstream), and green consumption (downstream) on environmental quality are notably more pronounced. Furthermore, the moderating effect of financial market development on economic green transformation exhibits heterogeneity, particularly evident in the eastern regions, non-resource-based areas, and regions experiencing population inflow. Thus, further promoting economic green transformation, accelerating financial market development, and formulating tailored policies based on regional characteristics are crucial for China's response to global climate change.

Keywords Economic green transformation · Financial market development · Environmental quality · Moderating effect · China

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1 Introduction

In recent years, the growing imbalance between global economic development and the environment has become increasingly pronounced (Bakhsh et al., 2024). Environmental disasters such as Air pollution, water contamination, and soil salinization have emerged with alarming frequency, presenting significant challenges for China and nations worldwide. According to a 2021 report from the National Bureau of Statistics of China, the rapid expansion of the Chinese economy has been accompanied by substantial discharges of wastewater, exhaust emissions, and industrial solid waste, posing a serious threat to high-quality economic development (Ghosh et al., 2023; Jiang et al., 2020; Zheng & Kahn, 2013). Environmental pollution and rising temperatures have emerged as two of the foremost global issues over the past few decades, and the main driving force for both is the emission of various pollutants and greenhouse gases (Ibrahim & Vo, 2021). Scientific projections indicate that by 2050, global temperatures could rise by as much as 3 °C compared to the 20th century, placing immense pressure on the foundations of natural resources and heightening the risk of environmental disasters (Zoundi, 2017). The Intergovernmental Panel on Climate Change (IPCC) underscores that in order to protect natural resources, all economies must achieve “net-zero” greenhouse gas emissions by 2050 (Meadowcroft & Rosenbloom, 2023). During the 28th United Nations Climate Change Conference (COP-28) in 2023, governments from around the globe pledged to accelerate their efforts to meet the 1.5 °C climate target alongside sustainable development goals. China presented effective measures it has undertaken to combat climate change and environmental pollution, thereby offering a Chinese solution to these pressing global challenges (Wang et al., 2019).

The urgent need to harmonize economic development with the Sustainable Development Goals (SDGs), particularly SDG 7 (affordable and clean energy), SDG 9 (industry, innovation, and infrastructure), SDG 13 (climate action), and SDG 17 (partnerships for the goals), has emerged as a core issue in addressing climate-energy nexus challenges. As the world’s largest carbon emitter, China’s green economic transformation represents both a crucial challenge in fulfilling global commitments and a unique opportunity to implement the SDGs. This study, employing an upstream-midstream-downstream analytical framework, is the first to empirically reveal the amplifying effect of financial market development on the environmental benefits of China’s provincial green economic transformation, offering a novel theoretical paradigm for sustainable development science. Through this research, we aim to provide new insights and approaches for addressing global environmental issues, as well as theoretical support and practical guidance for achieving the environmental protection (SDG 13) and economic growth (SDG 8) goals within the SDGs.

Currently, governments around the world are seriously considering how to address the pressing issues of environmental pollution and rising global temperatures. Research indicates that the key to tackling climate change and environmental degradation lies in promoting a green transformation of the economy to achieve sustainable development (Kuriqi et al., 2021; Zhai & An, 2020). In this context, carbon accounting analysis has emerged as a widely adopted framework among global researchers (Yang & Chen, 2014), providing an in-depth examination of greenhouse gas emissions from various sectors involved in carbon emissions. Meanwhile, the energy, technology, and finance sectors are frequently highlighted in discussions about this economic green transformation. The energy production sector, as an upstream contributor to pollution emissions, has caused significant ecologi-

cal issues through the extensive extraction of fossil fuels, with thermal power generation serving as the backbone of China's electricity supply. This reliance has resulted in serious environmental problems that adversely affect sustainable economic development. Therefore, it is imperative to establish green production methods within the energy sector (Aziz & Bakoben, 2024). Industrial activities are closely linked to pollution emissions through the technologies employed; traditional industrial processes can generate substantial pollution, while green technologies are increasingly recognized for their potential to reduce emissions (Nikzad & Sedigh, 2017; Weina et al., 2016). This consensus underscores the importance of transformation and innovation within the technology sector for achieving sustainable development (Li et al., 2025; Roepke, 2013; Usman et al., 2024; Xing et al., 2019). Finance plays a critical role in resource allocation, monetary circulation, and macroeconomic regulation. In light of the increasingly severe environmental challenges, China proposed as early as 2014 the establishment of a comprehensive green finance system, emphasizing that achieving a green transformation cannot be separated from the support of the financial sector. Furthermore, as downstream contributors to carbon emissions, consumption patterns—specifically whether the resources consumed by households and businesses are green and clean—are closely tied to overall carbon emission levels. Therefore, the assessment of economic green transformation should be conducted from a holistic perspective that encompasses the upstream, midstream, and downstream sectors. Specifically, green energy production (GEP) (upstream), green innovation (GIN) and green investment (GIV) (as supporting sectors in the midstream), and green consumption (GC) (downstream) are all critical for improving environmental quality (EQ). Only when all three sectors—upstream, midstream, and downstream—achieve greenness can it be accurately termed a true economic green transformation.

Recent studies have gradually developed a green transformation analytical paradigm based on the perspective of industrial linkages (Bak & Cheba, 2022; Feng et al., 2025; Kanan et al., 2022; Lu et al., 2023). This paper selects the “upstream-midstream-downstream” full-chain framework, mainly based on the following three theoretical considerations: Firstly, from the perspective of supply chain theory (Porter & Kramer, 2011), economic green transformation needs to break through the limitations of traditional linear analysis. Energy production in the upstream constitutes the material basis of the transformation (Chen et al., 2022), innovation and investment in the midstream provide technological support (Horbach, 2008), and consumption patterns in the downstream determine the sustainability of the transformation (Sovacool et al., 2021). Together, they form a complete value chain. Secondly, in terms of policy transmission mechanisms, this framework accurately corresponds to the policy action path of “supply side-moderating mechanism-demand side.” Financial market development (FD) directly affects the upstream production capacity structure through capital allocation, promotes midstream technological transformation through risk-sharing, and guides downstream preferences through consumer credit, forming differentiated moderating paths. Thirdly, compared with existing mainstream frameworks, this framework has unique advantages: Life Cycle Analysis (LCA) focuses on environmental impact assessment but neglects economic transmission (Pomponi & Lenzen, 2018; Suh & Huppes, 2005; Treloar et al., 2000); Industrial linkage models emphasize the technological connections between sectors but tend to downplay the moderating function of FD (Schmoch et al., 2003; Wang & Dong, 2021). In contrast, the full-chain framework, through its three-

stage division, not only maintains the integrity of the supply chain but also highlights the pivotal moderating role of FD.

Over the past few decades, global energy demand has continued to rise, with many countries relying on unsustainable production methods, primarily the combustion of fossil fuels. This approach has led to a steady increase in greenhouse gas emissions (Quadrelli & Peterson, 2007). According to estimates from the World Bank, the energy sector accounts for 73.2% of global greenhouse gas emissions. Among non-renewable energy sources, fossil fuels are a major contributor to global warming (Hoel & Kverndokk, 1996), with China's largest carbon emissions stemming from fossil fuel consumption. Transitioning to clean energy not only has the potential to improve EQ but also to reduce public health risks (Sattler et al., 2020; Shankar et al., 2020). In the long run, the consumption of renewable energy and globalization are actively contributing to environmental improvements (Inglesi-Lotz, 2016; Wang et al., 2024b). Consequently, the low-carbon transformation of the energy sector has become an inevitable trend. In this context, the utilization of Renewable energy can provide 39% of the emission reductions needed by the energy sector, making it a key focus area for low-carbon transformation. By producing energy from cleaner sources such as solar, wind, and hydropower, we can not only address existing environmental issues but also decouple negative externalities from economic activities, thereby achieving sustainable production (Sohag et al., 2024; Song et al., 2024). As a supporting sector in the midstream of the economic green transformation, technological innovation is one of the core points. Technological innovation plays a pivotal role in enhancing EQ. Efficient innovations, such as energy-saving technologies and renewable energy solutions, significantly contribute to reducing emissions of pollutants and greenhouse gases, thereby mitigating negative impacts on natural resources (Qing et al., 2024; Shan et al., 2021; Xie et al., 2023). In the fight against climate change and global warming, innovation—especially GIN—becomes essential. GIN encompasses production activities that not only achieve resource conservation and environmental enhancement but also embody originality, innovation, and value. The key to addressing global climate and environmental challenges lies in transitioning the economy toward a green, low-carbon future, with green technological innovation recognized as a crucial driver of this transformation (Hossain et al., 2024). By fostering GIN, we can effectively combat climate change and advance sustainable development.

Furthermore, effective environmental governance inherently relies on the support of the financial sector. Over the next thirty years, China requires between 100 trillion to 500 trillion RMB in green low-carbon investments during its transformation. Given such a substantial funding demand, GIV, as the second core supporting sector in the midstream of the economic green transformation, plays a pivotal role in addressing climate change (Ran & Zhang, 2023). The “G20 Green Finance Synthesis Report,” published in 2016, defines green finance as investment and financing activities that contribute to environmental improvement and sustainable development. This encompasses financial services for projects related to environmental protection, energy conservation, clean energy, green transportation, and green buildings, including project financing, operations, and risk management. GIV becomes a crucial channel for achieving the “dual carbon” goals (Su & Lee, 2023). At the micro level, financial institutions serve as custodians of social capital and can rapidly mobilize large-scale funding. GIV adheres to the principle of “differentiated treatment,” imposing stricter financing constraints on high-pollution enterprises while directing funds toward industries characterized by low energy consumption, low emissions, and low pollution (He

et al., 2023). Simultaneously, it encourages greater investment in green industries, compelling high-pollution enterprises to undergo transformation and upgrade, thereby positively impacting carbon reduction (Qing et al., 2024). Compared to traditional finance, GIV places greater emphasis on environmental governance and sustainable development (Managi et al., 2022; Wang & Fan, 2023). Within the framework of green finance, green credit is its most significant component, while GIV, green insurance, and green securities are also essential elements (Lee & Lee, 2022; Zhang et al., 2024). Currently, research on green finance predominantly focuses on GIV. Therefore, this study considers GIV as a critical factor in addressing environmental issues.

Energy consumption is consistently one of the primary driving forces behind socio-economic development. From a global perspective, as the world's population continues to grow and industrialization accelerates, the demand for energy steadily increases, primarily focusing on traditional energy sources such as coal and oil (Jakob et al., 2012; Li et al., 2017; Ouedraogo, 2013; Wang et al., 2019). In 2015, the International Energy Agency (IEA) highlights three main sources of carbon pollution: electricity, industry, and transportation, with electricity generation accounting for the largest share at 42% (Khan et al., 2019). According to data from the China Energy News in 2022, carbon dioxide emissions in China mainly concentrate in three areas: energy activities, industrial production processes, and waste management. Among these, emissions from energy activities account for approximately 87% of total societal emissions, with about 55% of these emissions originating from the consumption side. Clearly, China is one of the largest energy consumers in the world (Crompton & Wu, 2005; Sadiq et al., 2023). Thus, it is evident that energy consumption serves as a major source of carbon emissions. In light of increasingly severe ecological and environmental issues, as well as the imperative for a green and low-carbon economy, promoting the greening of energy use gradually becomes an important means of reducing carbon emissions and fostering a green economy. Therefore, from a consumer perspective, achieving green and low-carbon development necessitates a focus on more efficient energy utilization while prioritizing the use of "low-carbon" and "zero-carbon" energy sources to significantly reduce one's own carbon emissions.

The discussion above highlights that the economic green transformation of various sectors is a crucial lever for addressing environmental changes. It is undeniable that achieving economic green transformation necessitates the support of a robust financial market, a notion that is substantiated by numerous examples. Higher levels of FD are more likely to increase investment in environmental governance and energy-saving technologies, which in turn reduces per capita energy consumption and pollutant emissions, leading to improved EQ (Ozturk & Acaravci, 2013). Additionally, FD enhances the efficiency of corporate financing (Naeem & Li, 2019; Tsai et al., 2021), inter-industry capital allocation, and regional GIV efficiency (Dima et al., 2014) by expanding the coverage of financial services and improving the completeness of financial market information, thereby facilitating economic green transformation. With the maturation of financial markets, ample R&D funding can provide financial support for the research of clean technologies, guiding high-energy-consuming enterprises to transform their energy consumption structures, thereby reducing carbon emissions (Shahbaz et al., 2013). These findings indicate that the FD has a significant influence on economic green transformation. However, the specific manifestations of this mechanism warrant further investigation. In particular, it remains unclear to what extent FD can play a role throughout all stages of the economic green transformation process (upstream, mid-

stream, downstream). Therefore, a comprehensive examination of the mechanisms through which FD impacts economic green transformation is a primary focus of this paper.

This study focuses on the core issue of environmental governance and sustainable development, namely the impact of economic green transformation on ecological improvement and its underlying mechanisms. In the face of the increasingly stringent global environmental constraints, constructing a green economic system has become an essential pathway to achieving high-quality development. As the central hub of the modern economic system, FD play a pivotal role in driving economic green transformation through multiple functions, including optimizing capital allocation efficiency, transmitting price signals, and Managing risks. Based on this understanding, this study systematically explores two core issues. First, utilizing panel data from 30 provinces in China over the period of 2008–2020, this study empirically examines the impact of provincial economic green transformation on regional EQ. By constructing a theoretical framework of transformation across GEP (upstream), GIN and GIV (as supporting sectors in the midstream), and GC (downstream), this study reveals the necessity of a systemic transformation across multiple sectors for sustainable development. Second, this study investigates the role of FD in the interplay between economic green transformation and EQ, providing theoretical support for optimizing green finance and economic policies and advancing a low-carbon transformation across the entire industrial chain.

The novelty of this study is primarily reflected in three aspects. First, this study transcends the limitations of traditional research by adopting a comprehensive upstream-midstream-downstream perspective to construct a theoretical analytical framework for economic green transformation. It provides an in-depth analysis of the impacts of GEP (upstream), GIN and GIV (as supporting sectors in the midstream), and GC (downstream) on EQ. This approach offers a novel theoretical foundation for a holistic understanding of the underlying mechanisms of economic green transformation. Second, by examining the moderating role of FD, it offers new insights into the interplay between economic green transformation and EQ. This also guides future long-term research on the role of FD in economic green transformation and elucidates the mechanisms through which various types of financial instruments contribute to this process. Finally, this study not only investigates the impact of FD on economic green transformation at the national level but also conducts a heterogeneity analysis. The findings reveal that the moderating effect of FD is particularly pronounced in the eastern regions, non-resource-based areas, and regions experiencing population inflow. This provides valuable references for China to formulate region-specific policies in the future.

The subsequent sections of this paper are organized as follows: Sect. 2 presents the theoretical foundation and research hypotheses, while Sect. 3 outlines the methodology and data. Furthermore, Sect. 4 encompasses the empirical analysis and discussion. Finally, Sect. 5 summarizes the conclusions and explores their policy implications.

2 Theoretical analysis and research hypotheses

2.1 Green energy production and environmental quality

In recent years, there has been a burgeoning interest in exploring the relationship between renewable energy and the reduction of carbon emissions and other pollutants on a global

scale. In the context of striving for an economic green transformation, the optimization of industrial structures within the energy sector and the transformation towards clean, low-carbon production methods have emerged as a prevailing trend. This optimization not only facilitates the green transformation of production processes but also enables the implementation of environmentally sustainable and clean practices that significantly mitigate greenhouse gas and pollutant emissions, thereby enhancing overall EQ (Liddle & Sadorsky, 2017; Zheng et al., 2021). This process can be conceptualized as an environmentally conscious upgrade of production systems.

More specifically, production that harnesses clean energy generates virtually no CO₂ other greenhouse gases and pollutants, serving as a stark contrast to traditional energy-dependent production modes. The latter represents one of the principal sources of global greenhouse gas emissions and is frequently accompanied by pollutant outputs. Additionally, compared to traditional energy generation, clean energy production requires significantly less water, contributing to the conservation of water resources and the improvement of EQ.

As the upstream segment of the energy supply chain, energy production sectors must ensure that the energy they generate is both green and clean to enable downstream users to access low-pollution products, thereby effectively enhancing EQ. With the increase in clean energy generation, societal demand for such resources has experienced a sustained upward trend. This shift has prompted various industries and sectors to elevate the proportion of clean energy within their consumption frameworks. For instance, in the industrial sector, companies are increasingly inclined to utilize green electricity, while in the transportation sector, the adoption of clean energy technologies such as electrification and hydrogen fuel is progressing rapidly. These transformations not only advance the green transformation of diverse industries but also optimize energy consumption structures, effectively alleviating negative environmental impacts.

Nonetheless, prior research has primarily concentrated on the correlation between energy consumption and carbon emissions, leaving the potential role of green energy in improving EQ underexplored. Therefore, this paper posits the need for a comprehensive examination of the influence of energy production on EQ. In this regard, the paper introduces the hypothesis:

H1. GEP has the potential to significantly enhance EQ.

2.2 Green innovation and environmental quality

Currently, research into the relationship between GIN and EQ is flourishing on a global scale (Wang & Juo, 2021). Numerous studies demonstrate that green technological innovation provides effective solutions for the simultaneous advancement of economic development and EQ (Chen et al., 2022; D'Attoma & Ieva, 2020; Ganda, 2019). GIN mitigates pollutant emissions directly by introducing energy-efficient and emission-reducing technologies (Hao et al., 2023). For instance, the optimization of end-of-pipe pollution control methods and the development of advanced techniques such as carbon capture and storage significantly diminish pollutant outputs (Vijay et al., 2010). Furthermore, a substantial body of research highlights the positive impact of enhanced technological innovation levels on EQ, particularly through the adjustment of energy consumption structures and the promo-

tion of regional industrial upgrades, which collectively contribute to reduced carbon emissions (Ofori et al., 2023).

More specifically, GIN related to clean energy technologies can produce a substitution effect, wherein clean energy sources supplant non-renewable ones (van der Ploeg & Withagen, 2012). Renewable energies, such as solar and wind power, serve as alternatives to conventional fossil fuels, thereby reducing pollutant emissions at their source and subsequently improving EQ. Additionally, GIN enhances EQ by optimizing industrial structures and minimizing resource consumption (Du et al., 2021; Sun et al., 2019). Innovations facilitate improvements in production processes and technological skills, leading to greater energy efficiency and productivity. With total energy consumption remaining constant, these enhancements can indirectly lower carbon emissions and, over the long term, exert a suppressive effect on pollutant emissions.

While existing research has examined the relationship between green technological innovation and environmental outcomes, studies specifically addressing the connection between green industrial innovation and EQ remain relatively limited, resulting in an incomplete understanding of green industrial innovation. To investigate further the impact of green industrial innovation on EQ, this paper posits the hypothesis:

H2. GIN can effectively enhance EQ.

2.3 Green investment and environmental quality

The role of finance in resource allocation has a direct and profound influence on EQ (Thampanya et al., 2021). At the micro level, financial mechanisms optimize corporate stock trading behavior, enhancing operational efficiency and profitability, which subsequently affects the long-term value of businesses. Building upon this mechanism, green finance channels financial resources toward environmentally sustainable industries, thereby facilitating the optimization of industrial structures (Wang & Wang, 2021).

Specifically, green finance reallocates capital from high-pollution enterprises to those committed to environmental protection, fostering a transformation in industrial structures toward sustainability, rationality, and higher value. This shift encourages the phasing out of obsolete production capacities (Fan & Zhang, 2024), effectively curbing debt financing for heavily polluting firms, and enhancing the efficiency of financial resource allocation, ultimately leading to improvements in EQ (Baloch et al., 2021).

At the macro level, green finance performs a crucial role in disseminating green signals, guiding publicly listed companies and entire sectors toward a green transformation. It facilitates the reallocation of resources across various industries (Acemoglu & Guerrieri, 2008), accelerates the overall societal shift toward a greener economy, and incentivizes new capital investments in green industries, thereby contributing to EQ enhancement (Zhang et al., 2021). This highlights green finance as a pivotal mechanism for advancing industrial green transformation.

Clearly, green finance and green investments, as innovative financial instruments that amalgamate policy guidance with strategic direction, play an essential role in effectively reducing pollutant emissions and enhancing EQ. Consequently, this paper posits the hypothesis:

H3. GIV contributes significantly to the improvement of EQ.

2.4 Green consumption and environmental quality

The energy sector is pivotal in achieving the objectives of carbon reduction and pollution control, and transitioning energy consumption toward greener practices is essential for enhancing EQ (Ahmad et al., 2023; Bakhsh et al., 2024; Inglesi-Lotz & Dogan, 2018; Wang et al., 2024a). Existing research indicates that renewable energy consumption plays a significant role in reducing carbon emissions and is a critical factor in improving EQ. With the emergence of GC, regional energy efficiency has progressively increased, leading to a shift in economic production models from energy-dependent frameworks to innovation-driven approaches, effectively mitigating negative externalities on the environment (Cheng et al., 2023; Ye & Rasoulinezhad, 2023).

However, some scholars have noted that China's current traditional energy structure, dominated by coal and oil, limits the efficiency of carbon dioxide and other pollutant emissions. In contrast, renewable energy, due to its environmentally friendly characteristics, generates virtually no CO₂ emissions during consumption. As the proportion of renewable energy in total energy consumption continues to rise, the mobility of green factors increases, facilitating the development of green enterprises and industries, which ultimately contributes to the improvement of EQ.

Additionally, the growing propensity among consumers and businesses to embrace renewable energy will stimulate the active circulation of green factors in the marketplace, such as carbon emission rights and energy usage rights. This dynamic will further advance the societal and economic transformation toward greener practices, resulting in reduced pollutant emissions (Adams & Klobodu, 2018). Moreover, the Chinese government's policy incentives and guidance for renewable energy have promoted the flow of resources and factors towards individuals and enterprises that utilize renewable energy, allowing them to reap benefits from this process and generating a consumption effect that further enhances EQ.

Therefore, to thoroughly investigate the impact of GC on EQ in China, this paper posits the hypothesis:

H4. GC can significantly enhance EQ.

2.5 Financial market development and economic green transformation

Current research has established that the development of financial markets plays a vital role in enhancing EQ and facilitating a green economic transformation (Adams & Klobodu, 2018). Firstly, the advancement of financial markets undoubtedly provides essential funding support for research in clean technologies research, guiding high-energy-consuming enterprises in transitioning and upgrading their energy consumption structures toward greener and low-carbon alternatives. As green energy technologies continue to evolve and mature, the green energy sector is poised to achieve scalability and industrialization, thereby reducing production costs, increasing output, and enhancing market competitiveness. This, in turn, encourages a growing number of enterprises and individuals to adopt green energy consumption, ultimately contributing to improved EQ. Consequently, the FD functions as

a moderating factor in the mechanisms through which energy production and consumption influence EQ.

Secondly, at the microeconomic level, the development of capital markets incentivizes enterprises to implement energy-saving and emissions-reduction measures to cultivate a favorable corporate image, thus securing more advantageous financing conditions (Shahbaz et al., 2013). The evolution of financial markets facilitates risk diversification and lowers financing costs, promoting technological innovation among firms and reducing pollutant emissions in the energy production sector. At the macroeconomic level, a higher level of FD increases investments in environmental management and energy-saving technologies, thereby influencing the relationship between GIN and EQ through the strategic allocation of resources and factors.

Furthermore, within an economic framework that prioritizes environmental protection, a well-developed financial sector can secure funding at lower costs, enabling both enterprises and governments to invest in environmental protection initiatives, or green investments (Claessens & Schmukler, 2007). The more advanced the financial market, the greater its capacity to create a diverse array of green financial products. Additionally, developed financial capital markets are more inclined to establish comprehensive green market mechanisms and policy frameworks, thus facilitating systematic GIV strategies that enhance EQ.

In light of these considerations, we are justified in asserting that FD serves as a moderating factor in the complex interrelationships among GEP, GIN, GIV, GC, and EQ. Currently, no research has specifically examined FD as a moderating variable within these relationships at the provincial, municipal, and regional levels in China. This paper seeks to address this gap and proposes the following hypotheses:

H5a. FD moderates the relationship between GEP and EQ.

H5b. FD moderates the relationship between GIN and EQ.

H5c. FD moderates the relationship between GIV and EQ.

H5d. FD moderates the relationship between GC and EQ.

The theoretical framework illustrating the impact of FD on the green economic transformation is shown in Fig. 1.

3 Methodology and data

3.1 Model specification

This paper constructs a theoretical analytical framework for the economic green transformation from the perspective of the whole upstream-midstream-downstream chain, and in-depth analyzes the impacts of GEP (upstream), GIN and GIV (as supporting sectors in the midstream), as well as GC (downstream) on EQ. Considering the nature and length of the data, this paper employs a two-way fixed-effects model to estimate the empirical results. It also includes appropriate control variables, and the model is presented below:

$$\ln EQ_{it} = \alpha_{10it} + \beta_{11it} \ln GEP_{it} + \beta_{12it} \ln GIN_{it} + \beta_{13it} \ln GIV_{it} + \beta_{14it} \ln GC_{it} + \tau_{15it} \sum X_{it} + \mu_{16it} + \sigma_{17it} + \varepsilon_{18it} \quad (1)$$

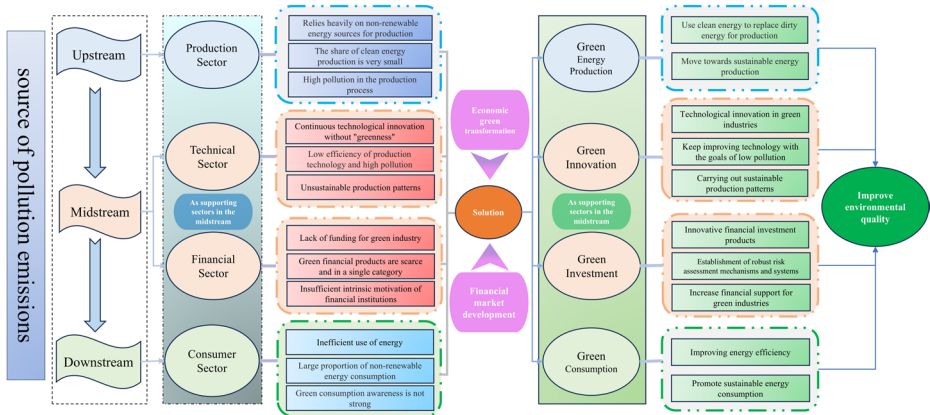


Fig. 1 The theoretical framework of the impact of FD on the green economic transformation

Moderation is a mechanism that can strengthen, weaken, or alter the relationship between independent and dependent variables (Jaworski & Czerwonka, 2024; Saddique et al., 2024). To investigate the moderating role of FD level between independent variables and the dependent variable, this paper employs the following econometric model to ascertain:

$$\ln EQ_{it} = \partial_{20it} + \gamma_{21it} \ln GEP_{it} + \gamma_{22it} \ln GIN_{it} + \gamma_{23it} \ln GIV_{it} + \gamma_{24it} \ln GC_{it} + \theta_{25it} \ln FD_{it} + \rho_{26it} \sum X_{it} + \omega_{27it} (\ln FD_{it} * \ln GEP_{it}) + \mu_{28it} + \sigma_{29it} + \varepsilon_{210it} \quad (2)$$

$$\ln EQ_{it} = \partial_{30it} + \gamma_{31it} \ln GEP_{it} + \gamma_{32it} \ln GIN_{it} + \gamma_{33it} \ln GIV_{it} + \gamma_{34it} \ln GC_{it} + \theta_{35it} \ln FD_{it} + \rho_{36it} \sum X_{it} + \omega_{37it} (\ln FD_{it} * \ln GIN_{it}) + \mu_{38it} + \sigma_{39it} + \varepsilon_{310it} \quad (3)$$

$$\ln EQ_{it} = \partial_{40it} + \gamma_{41it} \ln GEP_{it} + \gamma_{42it} \ln GIN_{it} + \gamma_{43it} \ln GIV_{it} + \gamma_{44it} \ln GC_{it} + \theta_{45it} \ln FD_{it} + \rho_{46it} \sum X_{it} + \omega_{47it} (\ln FD_{it} * \ln GIV_{it}) + \mu_{48it} + \sigma_{49it} + \varepsilon_{410it} \quad (4)$$

$$\ln EQ_{it} = \partial_{50it} + \gamma_{51it} \ln GEP_{it} + \gamma_{52it} \ln GIN_{it} + \gamma_{53it} \ln GIV_{it} + \gamma_{54it} \ln GC_{it} + \theta_{55it} \ln FD_{it} + \rho_{56it} \sum X_{it} + \omega_{57it} (\ln FD_{it} * \ln GC_{it}) + \mu_{58it} + \sigma_{59it} + \varepsilon_{510it} \quad (5)$$

In the aforementioned model, EQ is indicative of environment. GEP signifies the generation of green energy. GIN encapsulates the concept of green innovation. GIV embodies green finance, emphasizing green investment. FD is a measure of financial market development. $\sum X_{it}$ serves as the control variable, encompassing UR, GDP, and FDI. GDP denotes the gross regional product on a per year. UR indicates the urbanization rate. FDI stands for foreign direct investment. The interaction between the level of FD and each core explanatory variable reflects the comprehensive moderating effect of each variable. $\alpha_{ij}, \partial_{ij}, \beta_{ij}, \gamma_{ij}, \delta_{ij}, \theta_{ij}, \rho_{ij}, \omega_{ij}, \mu_{ij}, \sigma_{it}, \varepsilon_{it}$ are all parameters to be estimated.

The methodology framework is shown in Fig. 2.

The moderating effect model developed in this study carries threefold implications for advancing socially sustainable development:

First, by integrating an upstream-midstream-downstream systemic analytical framework, the model overcomes the fragmented approaches of conventional studies that focus on isolated stages, thereby providing a structured tool for evaluating synergistic effects in

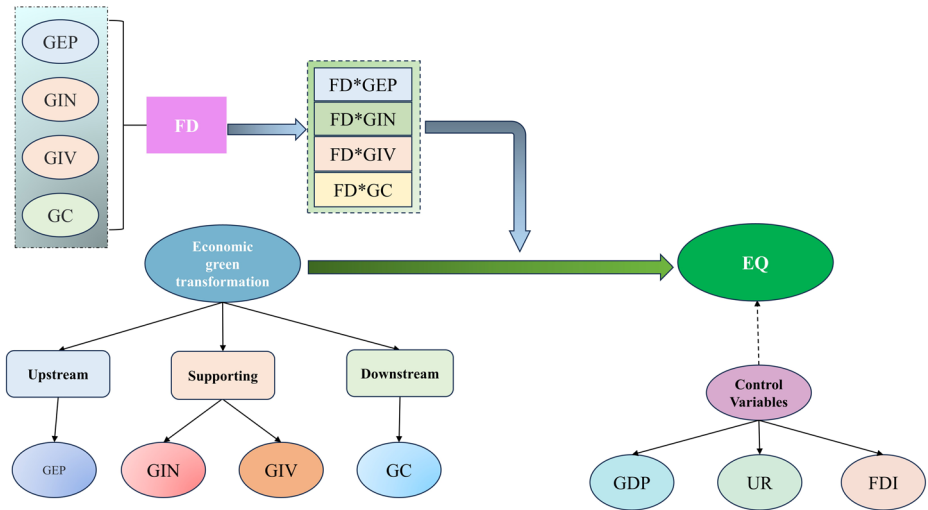


Fig. 2 Methodology framework

economic green transformation. Second, through elucidating the heterogeneous moderating pathways through which FD influence green economic elements, it offers policymakers precision-targeted strategies for optimizing resource allocation. Third, the model empirically validated heterogeneous moderating effects provide quantitative foundations for regional collaborative development policies, effectively addressing challenges posed by the “green transformation divide.” This aligns closely with the inclusive growth principles emphasized in the United Nations Sustainable Development Goal 10 (SDG10) and establishes an empirical basis for designing differentiated climate financing mechanisms (Ai et al., 2025).

Beyond its theoretical contributions to refining the cognitive framework of economic green transformations, the model advances the development of a multi-scale, multidimensional climate policy toolkit. It enables policymakers to calibrate interventions across institutional hierarchies—from national regulatory regimes to local governance structures—while ensuring alignment with sector-specific technological trajectories and socio-institutional contexts. Such granularity not only enhances the operational feasibility of decarbonization strategies but also bridges critical gaps between macro-level climate commitments and micro-level implementation efficacy, fostering resilient pathways toward net-zero economies.

3.2 Variables

3.2.1 Dependent variable

This paper uses EQ as the explanatory variable. There are various ways to measure EQ, and this paper utilizes the Environmental Pollution Index (EPI), calculated using the entropy value method, as a measurement index. This indicator is derived by summing up the wastewater emissions, sulfur dioxide emissions from environmental outputs, and general industrial solids generation data for the region for the year, assigning certain weights (Atici, 2009;

Lisciandra & Migliardo, 2017; Ren et al., 2023; Shan et al., 2021; Yang et al., 2024). The lower the EPI, the higher the EQ is deemed to be.

3.2.2 Key independent variables

GEP: this paper employs the ratio of electricity generation from clean energy sources to total electricity generation as a metric of green energy production (Naqvi et al., 2023). Additionally, the clean energy generation in the selected data primarily comprises nuclear, wind, solar, and hydro energy generation. Data for other forms of clean energy generation are excluded due to their relative scarcity and substantial data gaps.

GIN: this study utilizes the number of green invention patents obtained as an indicator of GIN. The number of green patents granted is not selected as an indicator due to the considerable time it takes and its pronounced lag effect (Brunel, 2019; Xiang et al., 2022). Green patents are specifically categorized into green invention patents and green utility model patents. Furthermore, utility model patents have a narrower scope than invention patents, and the patent protection period for invention patents is substantially longer than that for utility model patents. Consequently, this paper opts to select the number of green invention patents applied by the region in the year as an indicator.

GIV: this study employs the ratio of investment in environmental pollution control to GDP as a metric of GIV. Theoretical research on GIV has been interpreted in various ways and has not yet reached a unified statement. Most scholars view GIV as environmental protection investment. Consequently, investment in environmental pollution control serves as a suitable indicator.

GC: this paper assesses GC by the amount of renewable energy consumed (Gyamfi et al., 2023; Lin et al., 2016). That is, the consumption of wind, solar, and hydroelectric power in each region of China for that year is considered green energy consumption. Numerous studies have employed the consumption of clean energy consumer goods, such as renewable energy, as a metric of GC. Thus, this variable is assessed in a reasonable manner.

3.2.3 Moderating variable

FD: FD refers to the process through which the expansion of the scale of financial transactions and the increased sophistication of the financial industry contribute to a sustained increase in financial efficiency. There are numerous indicators to assess the FD level of a country or region, and the indicator measuring the ratio of the year-end balance of deposits and loans of financial institutions to GDP more effectively captures the level of FD from a macroeconomic perspective and the value added by the financial industry (Thampanya et al., 2021; Xu et al., 2021), which serves as the measurement indicator in this study.

3.2.4 Control variables

This paper controls for the influence of other factors on EQ by selecting GDP, UR, and FDI as control variables, drawing on economic theories and existing literature.

GDP: the development of the Gross Regional Product (GDP) inevitably impacts carbon emissions and EQ improvements. To account for price effects, this paper adopts 2000 as the base year for price deflation (Lin & Wu, 2021; Muller, 2014).

UR: the UR is calculated based on the proportion of the urban population to the total population in each region. Urbanization can significantly impact EQ (Adebayo et al., 2023; Khan et al., 2021). On the one hand, increased urbanization can promote industrial agglomeration, enhance public access to facilities and technology, boost productivity, and expand the use of clean energy, thereby reducing carbon emissions. On the other hand, higher urbanization rates can amplify energy and industrial consumption, elevating carbon emissions. Both aspects jointly contribute to carbon emissions. Thus, this indicator is included as a control variable.

FDI: this indicator, measured by the ratio of regional foreign direct investment to GDP (Lessmann, 2013), exerts an impact on carbon emissions. On the one hand, the “pollution paradise” effect arises from the transfer of high-energy-consuming and high-emission industries to China by foreign direct investment. On the other hand, the “pollution halo” effect stems from the introduction of green technologies and technology spillovers from foreign direct investment (FDI). The net effect of foreign dependence on carbon emissions hinges on the cumulative impact of these two effects.

3.3 Data source and descriptive statistics

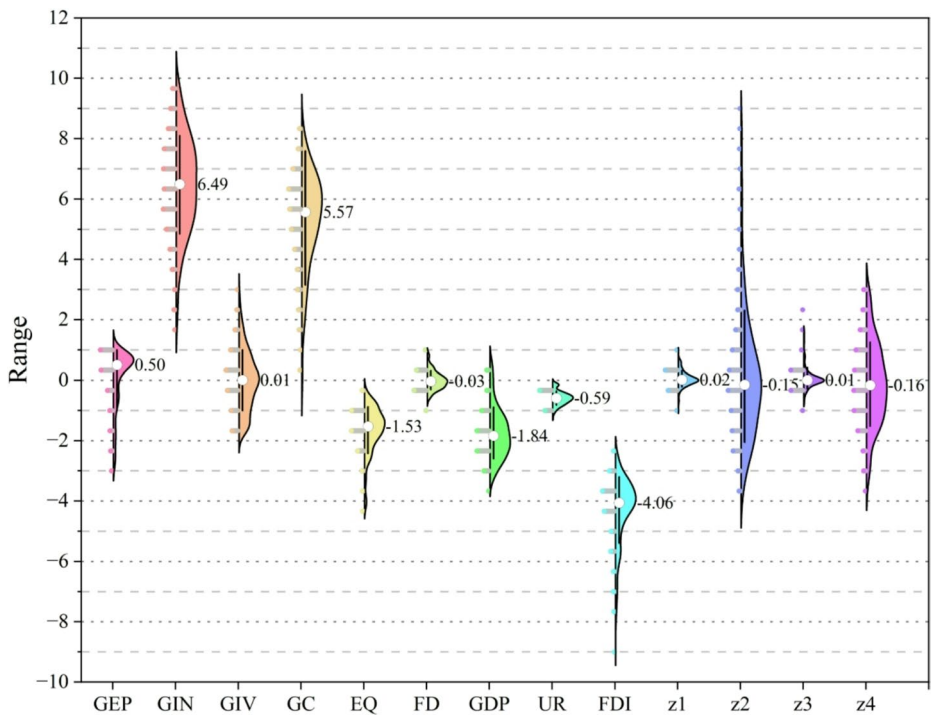
In this paper, we analyze data from 30 provincial-level autonomous regions and municipalities in China (excluding Hong Kong, Macao, Taiwan, and the Tibet Autonomous Region) for the period 2008–2020. The time span is limited due to incomplete data and unaccounted factors. The primary data sources include the China Statistical Yearbook, China Energy Statistical Yearbook, the official website of the National Bureau of Statistics, the CNRDS database, and regional statistical yearbooks. Among these, EQ data originate from the China Urban Statistical Yearbook, regional statistical yearbooks, and statistical bulletins. Data on GEP, GIN, and FD are sourced from the CNRDS. Data on GC primarily stem from the China Energy Statistical Yearbook and China Electricity Statistical Yearbook, while GIV data derive from the China Energy Statistical Yearbook and China Financial Yearbook. Data on GDP and UR by region are obtained from the National Bureau of Statistics. FDI data are compiled from China’s National Bureau of Statistics and regional bureaus of commerce.

In this paper, the data are treated as follows. First, the indicators relating to GDP are adjusted to constant 2000-based amounts, and then the logarithm is taken and divided by the total regional population as the measurement indicator. Second, considering the discrete nature of the data and the economic implications of the variables, we apply natural logarithm transformation and centering to all the data. Third, to address multicollinearity among the variables in the original model and to prevent biased estimation results, we employ logarithmic transformation for EQ, GC, and all control and moderating variables. Additionally, we lag GIN by one period and then apply logarithmic transformation, and standardize the data for GEP and GIV. Fourth, we utilize interpolation to impute a small number of missing values of observations.

This paper conducts descriptive statistical analysis on the processed data, and the results are shown in Table 1. The half violin plot in Fig. 3 illustrates the probability density distribution of the variables, with the vertical axis representing the variable values range. The hollow circle represents the median, and the enclosed area within the plot depicts the kernel density estimate of the variables. Notably, the medians of the individual data congregate

Table 1 Descriptive statistics of variables

Variables	Definition	Obs	Mean	Std Dev.	Min	Max
GEP	The ratio of electricity generated from clean energy to total electricity generated	390	8.941	1	-2.809	0.956
GIN	The number of green invention patents obtained	390	6.469	1.623	1.609	9.963
GIV	The ratio of investment in environmental pollution control to GDP	390	1.5715	1	-1.714	3.193
GC	Consumption of renewable energy	390	5.293	1.588	0	8.204
FD	The ratio of the balance of deposits and loans of financial institutions to GDP at the end of the year	390	-2.931	0.306	-0.749	0.908
EQ	The comprehensive index of environmental pollution calculated by the entropy method	390	-1.648	0.773	-4.168	-0.397
GDP	GDP in the current year	390	-1.744	0.85	-3.372	0.655
UR	Proportion of urban population to total population	390	-0.587	0.225	-1.234	-0.11
FDI	Ratio of foreign direct investment to GDP	390	-4.298	1.097	-9.21	-2.502

**Fig. 3** Half violin plot of the variables

around a central value, indicating that the data distribution is reasonably uniform and appropriate for analysis.

4 Empirical analysis and discussion

4.1 Multicollinearity test

In assessing the robustness of regression models, multicollinearity testing is a crucial step, as it can reveal the presence of bias within the model. This study conducts a multicollinearity test on model (1) to ensure the accuracy of the model estimates. The Variance Inflation Factor (VIF) is utilized as the diagnostic tool in this study. Empirical guidelines suggest that a VIF value of 10 or higher for an explanatory variable signifies significant multicollinearity with other variables, potentially adversely affecting the model's estimation results (Peng & Lai, 2012). Consequently, the VIF test is crucial for identifying and addressing potential multicollinearity issues, ensuring the reliability and validity of the model estimates.

The results of the multicollinearity test are shown in Table 2, which shows that all the VIF values are much less than 10, so there is no problem of multicollinearity between the variables.

4.2 Baseline regression and moderating effect analysis

Data are being substituted into models (1)–(5), and baseline regression analyses are conducted using Stata, resulting in the regression outcomes as shown in Table 3. Herein, z1, z2, z3, and z4 correspond to the interaction terms between the variable FD and the key explanatory variables GEP, GIN, GIV and GC respectively.

4.2.1 Baseline regression results and discussion

In this study, we perform a baseline regression analysis on model (1) to evaluate the impact of the economic green transformation on EQ. Specifically, we assess the influence of the impact of GEP, GIN, GIV and GC on EQ. The following findings from the regression analysis demonstrate that they have passed statistical tests at various significance levels, thereby affirming support for the corresponding hypotheses.

At the 5% significance level, the coefficient for GEP (-0.104) is statistically significant, indicating that an increase in GEP has a positively significant impact on EQ. This result corroborates Hypothesis H1, which asserts that an increase in GEP can enhance the

Table 2 Results of multicollinearity test

Variable	VIF	1/VIF
UR	4.45	0.22
GIN	3.99	0.25
GIV	3.28	0.31
GDP	3.05	0.33
GC	2.70	0.37
FDI	2.20	0.46
GEP	2.16	0.46
Mean VIF	3.12	

Table 3 Baseline regression and moderated effects regression results

	(1)	(2)	(3)	(4)	(5)
	EQ	EQ	EQ	EQ	EQ
GEP	-0.104** (0.0524)	-0.129** (0.0552)	-0.150*** (0.0511)	-0.166*** (0.0519)	-0.120** (0.0538)
GIN	-0.101*** (0.0381)	-0.101*** (0.0379)	-0.0618* (0.0354)	-0.0983*** (0.0355)	-0.0915** (0.0370)
GIV	-0.476*** (0.0616)	-0.493*** (0.0628)	-0.299*** (0.0629)	-0.141* (0.0754)	-0.421*** (0.0629)
GC	-0.0578** (0.0256)	-0.0246 (0.0315)	-0.0250 (0.0253)	-0.0599** (0.0251)	-0.0965*** (0.0266)
GDP	0.504*** (0.120)	0.462*** (0.123)	0.444*** (0.112)	0.494*** (0.113)	0.500*** (0.118)
UR	-0.990*** (0.289)	-1.153*** (0.304)	-1.804*** (0.292)	-1.674*** (0.293)	-1.133*** (0.295)
FDI	-0.0340 (0.0225)	0.174 (0.133)	-0.0564*** (0.0208)	-0.0451** (0.0209)	-0.0643*** (0.0224)
FD		-0.0242 (0.0226)	1.793*** (0.231)	0.0137 (0.126)	1.381*** (0.264)
z1		-0.265*** (0.0978)			
z2			-0.302*** (0.0367)		
z3				-0.584*** (0.0773)	
z4					-0.248*** (0.0477)
_cons	-0.535 (0.434)	-0.827* (0.449)	-1.603*** (0.421)	-0.972** (0.409)	-0.645 (0.420)
N	390	390	390	390	390
R ²	0.444	0.458	0.536	0.524	0.486
adj. R ²	0.387	0.399	0.486	0.473	0.430

***, ** and * are significant at the levels of 1%, 5%, and 10%, respectively. Standard errors are in parentheses. The following tables are all the same

improvement of EQ. The underlying reasons for these results are as follows: First, the substitution effect of clean energy directly reduces the carbon emission intensity at the production end. Second, the production processes of clean energies such as hydropower and wind power have significant water resource conservation effects. Finally, the scale effect of the clean energy industry chain promotes the systematic optimization of the energy structure. Through the synergistic effects of new infrastructure such as the energy Internet, a full-chain emission reduction path of “production-transmission-consumption” is formed.

Similarly, at the 1% significance level, the coefficient for GIN (−0.101) is statistically significant, demonstrating a negative correlation between GIN and the dependent variable. This suggests that with the advancement of GIN, environmental pollution is efficiently mitigated, thereby substantiating Hypothesis H2, which claims that the development of GIN can curtail environmental pollution. On the one hand, breakthrough innovations such as energy-saving technologies and carbon capture directly reduce the pollution intensity per unit of output. On the other hand, innovation-driven industrial upgrading prompts the flow of factors towards environmentally friendly sectors, thereby improving EQ.

Consistent with the previous conclusions, at the 1% significance level, the coefficient for GIV is -0.476 and is statistically significant, indicating that an increase in GIV can substantially enhance the improvement of EQ. It is anticipated that increased investment in green industries can markedly improve EQ. Therefore, Hypothesis H3 is endorsed, which asserts that an increase in GIV has a beneficial impact on the improvement of EQ. The increase in GC directly alleviates environmental pressure, spurring firms to produce more green products and stimulating technological innovation and the transformation of production models towards greener alternatives. Concurrently, it steers societal resources towards green industries through market signals, propelling the green transformation of the economy.

As hypothesized earlier, the coefficient for GC is -0.0578 and is statistically significant at the 5% significance level, meaning that for each unit increase in GC, environmental pollution decreases by 0.0578 units. Its prominent role is derived from the leverage effect of capital allocation, which forms a virtuous cycle of “investment-technology-emission reduction” by supporting the industrialization of clean technologies and the renewal of pollution control facilities. The result corroborates Hypothesis H4, which proposes that an increase in GC can mitigate environmental pollution.

4.2.2 Moderating mechanisms for financial market development

This paper constructs a moderating effect model to investigate the role of FD, thereby uncovering new perspectives in understanding the interrelationship between economic green transformation and EQ. In the study examining the moderating role of FD on the relationship between green economic activities and EQ, we performed regression analyses on models (2)–(5).

In model (2), at the 10% significance level, all variables pass the significance test, and the coefficients of $z1$ and GEP are negative. This indicates the presence of a moderating effect. The moderating effect exists. Specifically, we find that FD has the capacity to significantly enhance the efficacy of GEP in improving EQ. In other words, FD can amplify the positive impact of GEP on mitigating environmental pollution. As a result, the null hypothesis H5a stands accepted. This stems from the financial system’s role in guiding capital allocation through green credit policies, effectively alleviating the financing constraints of environmental protection projects (Wang et al., 2023). As the maturity of FD increases, financial innovations such as green bonds and environmental rights pledges reduce the capital costs for green projects. This enables a unit of green investment to leverage a larger scale of environmental governance expenditure, creating a capital leverage effect.

In model (3), both GIN and the interaction term $z2$ are statistically significant at the 10% significance level, with negative coefficients. This result indicates the presence of a moderating effect. Specifically, the impact of GIN on EQ improvement is significantly enhanced by FD. Therefore, it is confirmed that the null hypothesis H5b is accepted. This phenomenon may stem from the capacity of advanced FD to steer households toward green product consumption—such as energy-efficient appliances and new energy vehicles—through structural optimization of consumer credit portfolios (Sadorsky, 2010). Concurrently, financial innovations at the consumer end, including credit allocation adjustments and carbon credit mechanisms, facilitate the internalization of GC externalities by aligning individual purchasing behaviors with broader environmental objectives (Zhang, 2023). Specifically, tailored green financing instruments (e.g., preferential loan rates for eco-labeled goods) and

carbon point reward systems lower the effective cost of sustainable consumption, thereby accelerating market penetration of low-carbon technologies. Such institutional synergies not only amplify the price elasticity of green demand but also establish self-reinforcing feedback loops between financial system efficiency and environmental governance efficacy.

At the 10% significance level, the coefficients of GIV and interaction term $z3$ in model (4) are negative and statistically significant. This result indicates the presence of a moderating effect of FD on the relationship between GIV and EQ. Specifically, FD exerts a pronounced catalytic effect on the role of GIV in bolstering EQ. Consequently, the null hypothesis H5c has been accepted. This phenomenon may stem from FD establishing institutional support mechanisms for renewable energy projects, which bolster investor confidence and mobilize social capital toward photovoltaic, wind power, and other green energy sectors. Such capital reallocation accelerates low-carbon transitions in energy infrastructure by displacing fossil fuel dependencies and enhancing technological scalability.

The regression results of model (5) demonstrate that GC and the $z4$ are statistically significant, with negative coefficients. This suggests the presence of a moderating effect of FD on the relationship between GC and EQ. Specifically, FD significantly enhances the negative impact of GC on EQ, implying that FD amplifies the effect of GC in improving EQ. Consequently, the null hypothesis H5d is accepted. This outcome likely arises as multi-tiered capital markets provide risk capital for green technology R&D (Horbach, 2008), while financial innovations like intellectual property securitization accelerate marketization of eco-innovations. Such synergies amplify the environmental returns of R&D investments by bridging technological scalability gaps and aligning innovation trajectories with decarbonization imperatives. The underlying mechanisms can be attributed to two synergistic effects. First, the development of multi-tiered capital markets provides essential risk capital financing for green technology innovation (Horbach, 2008). Concurrently, financial innovations such as intellectual property securitization significantly accelerate the commercialization of research outcomes (Xia et al., 2024). These institutional arrangements collectively enhance the efficiency of translating R&D investments into measurable emission reductions, thereby optimizing the environmental returns on innovation expenditure. This dual-channel mechanism demonstrates how financial market sophistication complements technological advancement in achieving climate mitigation objectives.

4.3 Robustness tests

To ensure the reliability of the empirical research findings, this study employs a shortened sample period, performs data winsorizing on the sample dataset, and implements lagged treatment to the explanatory variables to test the robustness of both the baseline regression model and the moderating models.

4.3.1 Shorten the sample

Firstly, the high-quality development of intellectual property rights (IPR) influences the quality of patents, which in turn affects the outcomes of carbon reduction and pollution control, and subsequently, EQ (Nie, 2024). To mitigate the impact of policy changes on the empirical results, this study sets the sample period to conclude in 2018, yielding the results as shown in Table 4.

Based on the regression analysis provided, at the 10% significance level, all variables in column (1) of Table 4 significantly pass the statistical tests, with the core explanatory variable exerting a negative impact on EQ consistent with the baseline model. Upon further analysis of columns (2)–(5) in Table 4, which exhibit the moderating effect models under different treatment approaches, it is observed that the interaction terms and their corresponding coefficients for the core explanatory variables are significantly negative at the 10% significance level, aligning with the original model, thereby validating the robustness of the model.

4.3.2 Data winsorizing

In this study, to mitigate the impact of extreme values on the regression outcomes, employs a data winsorization technique specifically on the variables GEP, GIN, GIV, and GC. This method involves adjusting values that exceed the 99th percentile and fall below the 1st percentile by replacing them with their respective percentile values. Consequently, data points

Table 4 Robustness test results for shortened sample period

	(1)	(2)	(3)	(4)	(5)
	EQ	EQ	EQ	EQ	EQ
GEP	−0.0975* (0.0552)	−0.146** (0.0577)	−0.165*** (0.0539)	−0.163*** (0.0537)	−0.138** (0.0560)
GIN	−0.153*** (0.0409)	−0.153*** (0.0405)	−0.113*** (0.0383)	−0.144*** (0.0376)	−0.158*** (0.0392)
GIV	−0.377*** (0.0756)	−0.413*** (0.0756)	−0.257*** (0.0742)	−0.112 (0.0823)	−0.372*** (0.0740)
GC	−0.167* (0.0907)	−0.154 (0.103)	−0.0655 (0.0908)	−0.179** (0.0873)	−0.178* (0.0916)
GDP	0.583*** (0.128)	0.586*** (0.131)	0.530*** (0.120)	0.558*** (0.120)	0.649*** (0.124)
UR	−0.823** (0.362)	−1.199*** (0.388)	−1.833*** (0.372)	−1.611*** (0.365)	−1.360*** (0.377)
FDI	−0.0523** (0.0262)	0.391*** (0.146)	−0.0758*** (0.0244)	−0.0499** (0.0240)	−0.0738*** (0.0256)
FD		−0.0367 (0.0266)	1.966*** (0.266)	0.137 (0.141)	1.573*** (0.288)
z1		−0.201** (0.101)			
z2			−0.307*** (0.0444)		
z3				−0.625*** (0.0886)	
z4					−0.809*** (0.172)
_cons	−0.0632 (0.459)	−0.225 (0.461)	−1.241*** (0.456)	−0.566 (0.427)	−0.341 (0.443)
N	330	330	330	330	330
R ²	0.322	0.348	0.432	0.436	0.386
adj. R ²	0.239	0.262	0.358	0.362	0.305

that are below the 1st percentile and above the 99th percentile are substituted with the values corresponding to these percentiles. The results of this approach are presented in Table 5.

At the 10% significance level, model (1) in Table 5 shows that all variables meet the statistical criteria. The impact of these core variables on EQ is in line with the baseline regression model, exhibiting a significantly negative correlation. Furthermore, models (2)–(5) in Table 5 depict the regression results of the moderating effect models under various treatment approaches. The analysis reveals that, at the 5% significance level, the interaction term coefficients and their corresponding core explanatory variable coefficients in these models are all statistically significant and negative, aligning with the relationships observed in the original model. These findings substantiate the robustness of the model.

4.3.3 Lag explanatory variables

In empirical research, it is widely recognized that the green economy transformation is not a process that can be achieved in one step, and its impact on EQ may exhibit time lags. Consequently, this paper undertakes robustness checks by incorporating a one-period lag to

Table 5 Robustness test results of 1% data winsorizing processing

	(1)	(2)	(3)	(4)	(5)
	EQ	EQ	EQ	EQ	EQ
GEP	-0.0913* (0.0528)	-0.115** (0.0557)	-0.140*** (0.0515)	-0.157*** (0.0521)	-0.106* (0.0540)
GIN	-0.124*** (0.0391)	-0.120*** (0.0389)	-0.0756** (0.0363)	-0.112*** (0.0361)	-0.113*** (0.0377)
GIV	-0.464*** (0.0636)	-0.479*** (0.0649)	-0.293*** (0.0640)	-0.161** (0.0729)	-0.413*** (0.0642)
GC	-0.0598** (0.0254)	-0.0276 (0.0314)	-0.0256 (0.0253)	-0.0585** (0.0250)	-0.0973*** (0.0264)
GDP	0.499*** (0.120)	0.448*** (0.123)	0.437*** (0.111)	0.507*** (0.112)	0.498*** (0.117)
UR	-0.797*** (0.287)	-0.947*** (0.301)	-1.667*** (0.292)	-1.579*** (0.293)	-0.951*** (0.292)
FDI	-0.0320 (0.0225)	0.154 (0.133)	-0.0551*** (0.0207)	-0.0431** (0.0208)	-0.0632*** (0.0224)
FD		-0.0226 (0.0226)	1.783*** (0.230)	0.0178 (0.125)	1.400*** (0.263)
z1		-0.257*** (0.0980)			
z2			-0.302*** (0.0363)		
z3				-0.570*** (0.0726)	
z4					-0.254*** (0.0472)
_cons	-0.266 (0.443)	-0.586 (0.460)	-1.437*** (0.431)	-0.803* (0.416)	-0.396 (0.428)
N	390	390	390	390	390
R ²	0.443	0.456	0.536	0.528	0.487
adj. R ²	0.386	0.396	0.486	0.477	0.432

all explanatory, moderating, and control variables. The results of these analyses are reported in Table 6.

The regression analysis results indicate that, at the 5% significance level, all variables in model (1) of Table 6 are significant, and the explanatory variables have a consistent negative impact on EQ as observed in the baseline regression model. Furthermore, models (2)–(5) in Table 6 present the regression outcomes of the moderating effect models. The coefficients of interaction terms and their corresponding core explanatory variable in these models are all significant at the 5% significance level and are negative, aligning with the relationships in the original model, thereby confirming the robustness of the model.

In summary, after employing robustness tests through three different methods, at the 10% significance level, the impact of the core explanatory variables on the dependent variable remains consistent and statistically significant, corresponding to the results of the original baseline regression model. Additionally, the interaction effects among variables in the moderating effect models are also consistent with the original models. This demonstrates that the models developed in this paper possess strong robustness.

Table 6 Robustness test results for core explanatory variables lagged by one period

	(1)	(2)	(3)	(4)	(5)
	EQ	EQ	EQ	EQ	EQ
GEP	−0.109** (0.0487)	−0.115** (0.0496)	−0.150*** (0.0454)	−0.166*** (0.0453)	−0.114** (0.0491)
GIN	−0.176*** (0.0347)	−0.170*** (0.0340)	−0.101*** (0.0322)	−0.145*** (0.0311)	−0.164*** (0.0338)
GIV	−0.412*** (0.0612)	−0.419*** (0.0612)	−0.229*** (0.0600)	−0.0198 (0.0704)	−0.403*** (0.0608)
GC	−0.152** (0.0713)	−0.0482 (0.0804)	−0.0323 (0.0686)	−0.156** (0.0664)	−0.148** (0.0724)
GDP	0.579*** (0.104)	0.530*** (0.103)	0.433*** (0.0946)	0.464*** (0.0935)	0.567*** (0.101)
UR	−0.983*** (0.291)	−1.130*** (0.301)	−1.753*** (0.284)	−1.620*** (0.279)	−1.161*** (0.298)
FDI	−0.0566** (0.0222)	0.183 (0.122)	−0.0734*** (0.0201)	−0.0548*** (0.0199)	−0.0714*** (0.0219)
FD		−0.0341 (0.0225)	1.802*** (0.211)	−0.0534 (0.113)	1.033*** (0.223)
z1		−0.316*** (0.0826)			
z2			−0.320*** (0.0348)		
z3				−0.654*** (0.0691)	
z4					−0.620*** (0.133)
_cons	−0.0850 (0.388)	−0.355 (0.386)	−1.505*** (0.381)	−0.826** (0.355)	−0.386 (0.382)
N	390	390	390	390	390
R ²	0.476	0.499	0.580	0.585	0.509
adj. R ²	0.423	0.445	0.534	0.540	0.456

4.4 Heterogeneity analysis

To delve into the impact of GEP, GIN, GIV and GC on EQ, as well as the Heterogeneity of the moderating mechanisms of FD, this study employs three methods to analyze the sample in grouped segments. Firstly, given the differences in geographical location, economic environment, and policy frameworks across regions, which may lead to varying effects of FD on regional economic green transformation, it is necessary to categorize different areas to analyze their Heterogeneity. Regional positions are divided according to the economic regional division standards set by the National Development and Reform Commission in 2000, into eastern and central-western groups. As shown in Fig. 4.

Secondly, an area's resource endowment influences its energy transformation process (Bu et al., 2024), and technological innovation development is resource-based, with changes in the aforementioned factors affecting the scale of GIV, thereby leading to Heterogeneity in the moderating mechanisms of FD. Consequently, this paper groups resource-rich and non-resource-rich areas to explore their Heterogeneity. Based on the distribution of resource-based cities in China in 2022, regions with more than three resource-based cities are categorized as resource-based provincial groups, while those with three or fewer are categorized as non-resource-based provincial groups. As shown in Fig. 5.

Thirdly, population mobility mirrors the economic development level and indirectly influences FD and the green transformation process. There are notable differences in economic development and population mobility among cities in China (Razzaq & Yang, 2023), warranting the grouping of different population mobility situations to analyze their Heterogeneity. Based on data from the 2020 Seventh National Population Census, regions with a net population inflow greater than zero are designated as regions experiencing population inflow, and vice versa for regions experiencing population outflow. As shown in Fig. 6.

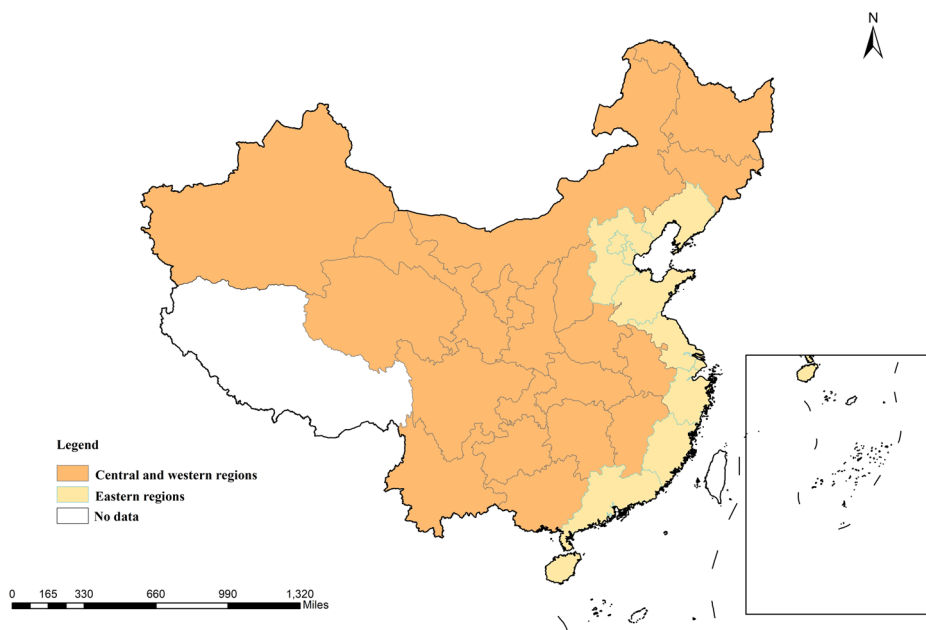


Fig. 4 Eastern and central-western regions

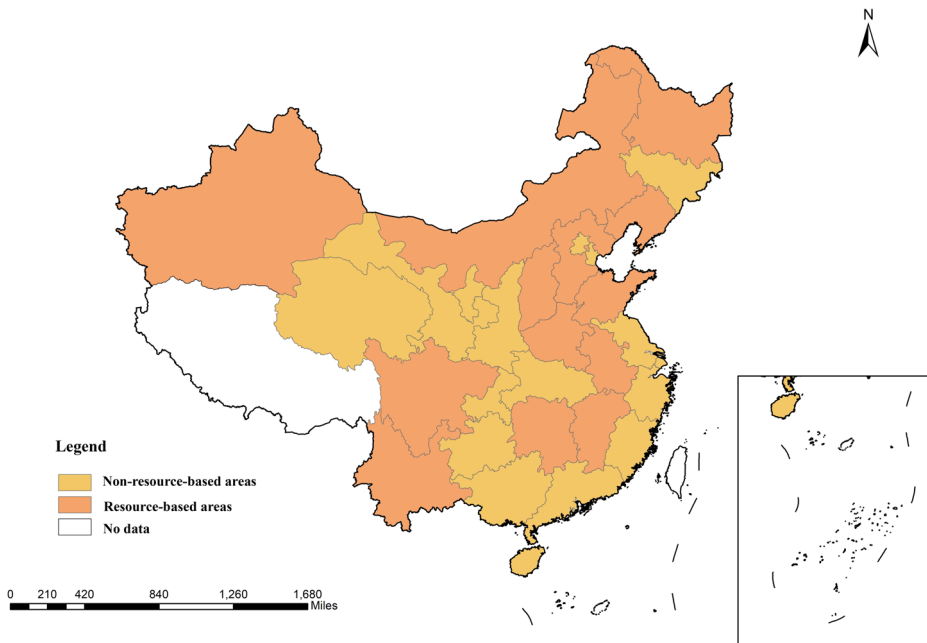


Fig. 5 Resource-based areas and non-resource-based areas

Utilizing the aforementioned groupings, this paper subsequently derives the results of the examination and analysis.

4.4.1 Regional locations

The results of the regional heterogeneity analyses are displayed in Tables 7 and 8. At the 10% significance level, the regression coefficients for GEP in the eastern regions and GC in the central-western regions both do not achieve statistical significance, suggesting that the contribution of GEP in the eastern regions to EQ improvement is not significant, and similarly, the impact of GC in the central-western regions on EQ enhancement is also not significant. Upon examining the heterogeneity of the moderating mechanisms of FD, it is observed that FD exerts a more pronounced impact on economic green transformation in the eastern regions. Specifically, FD in the eastern regions exhibits a significant moderating role between economic green transformation and EQ, while the moderating effect of green financial market development on the relationship between GC and EQ improvement in the central-western regions is not apparent. This discrepancy may be attributed to the eastern region's energy supply being primarily reliant on the central-western regions, with the majority of energy produced in the central-western regions being shipped to the eastern regions. Consequently, the moderating effect of FD in the eastern regions on GEP and EQ is not significant, and as the supplier of green energy, the central-western regions experience a decrease in its green energy consumption, resulting in an insignificant impact of GC on EQ improvement.

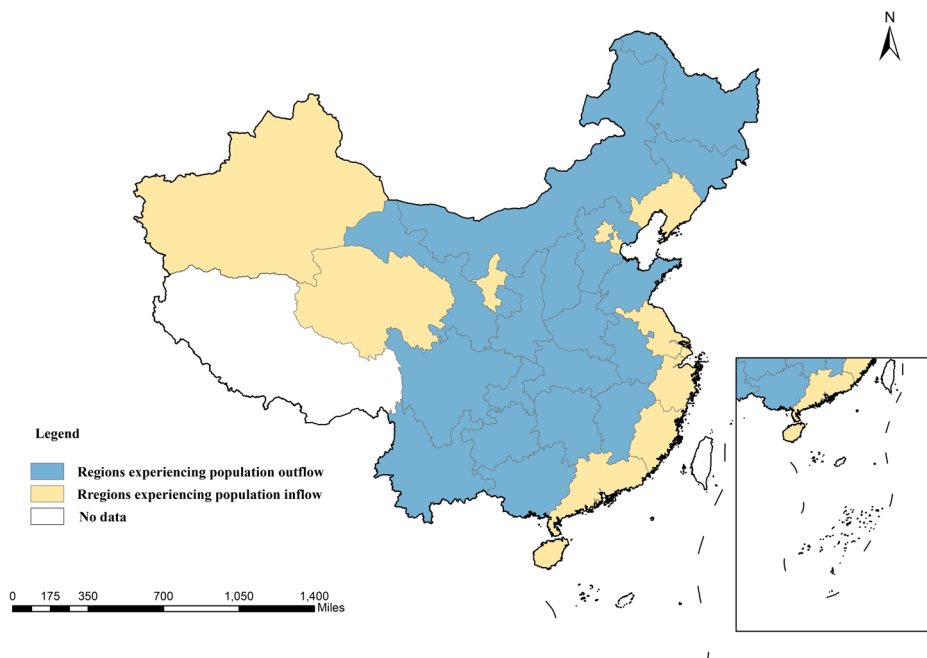


Fig. 6 Regions experiencing population inflow and outflow

4.4.2 Regional resources

The examination results based on the classification of regions as resource-based or not show in Tables 9 and 10, at the 5% significance level, the regression coefficients for resource-based areas are statistically significant. However, departing from the baseline regression model, the impact of GC on EQ in resource-based areas is significantly positive. The essence of GC is to reduce environmental impact and minimize resource depletion. Yet, due to their abundant resources, resource-based areas, compared to non-resource-dependent areas, engage in larger scales of resource and energy extraction and production, potentially leading to over-consumption and resource wastage, which counterintuitively suppresses EQ. In contrast, the regression coefficients for GEP and GIN in non-resource-based areas are not statistically significant, indicating that these activities do not significantly affect EQ. These areas suffer from relative energy scarcity and lower scales of GEP, not achieving the threshold to significantly impact EQ. Moreover, there is a marked disparity in resource endowments across different areas, with non-resource-based areas exhibiting underdeveloped development and application of green technological innovation. Most studies suggest that green technological innovation must reach a certain level to significantly reduce carbon emissions, which results in a subtle impact of GEP and innovation on EQ in non-resource-based areas. In terms of the moderating mechanism, the FD has a more pronounced effect on promoting economic green transformation in non-resource-based areas than in resource-based areas. Specifically, in both resource-based and non-resource-based areas, the moderating effect of FD on the improvement of EQ through GC is not apparent, and in resource-based areas, the moderating effect of FD on the improvement of EQ through GEP is also not statistically significant.

Table 7 Model regression results for the Eastern regions group

	(1)	(2)	(3)	(4)	(5)
	EQ	EQ	EQ	EQ	EQ
GEP	0.0302 (0.132)	-0.0484 (0.139)	-0.105 (0.117)	0.0296 (0.126)	0.0967 (0.121)
GIN	-0.282*** (0.0833)	-0.229** (0.0887)	-0.00492 (0.0849)	-0.231*** (0.0815)	-0.217*** (0.0772)
GIV	-0.241*** (0.0806)	-0.223*** (0.0851)	-0.129* (0.0762)	0.00149 (0.106)	-0.154* (0.0794)
GC	-0.133*** (0.0383)	-0.104** (0.0431)	-0.141*** (0.0354)	-0.121*** (0.0390)	-0.147*** (0.0371)
GDP	0.641*** (0.230)	0.446* (0.255)	0.409** (0.205)	0.620*** (0.222)	0.603*** (0.211)
UR	0.883* (0.465)	0.854 (0.519)	-1.755*** (0.620)	-0.330 (0.618)	0.0174 (0.507)
FDI	0.0794* (0.0435)	0.305 (0.319)	0.0673* (0.0383)	0.0880** (0.0422)	0.0268 (0.0413)
FD		0.0767* (0.0436)	2.590*** (0.466)	0.0863 (0.232)	1.353*** (0.350)
z1		-0.608* (0.357)			
z2			-0.362*** (0.0571)		
z3				-0.433*** (0.125)	
z4					-0.296*** (0.0576)
_cons	2.913** (1.126)	2.061* (1.227)	-0.569 (1.126)	1.934* (1.118)	1.711 (1.055)
N	143	143	143	143	143
R ²	0.593	0.602	0.694	0.630	0.665
adj. R ²	0.537	0.540	0.646	0.572	0.613

This paper posits that the economy of resource-dependent regions, highly dependent on the extraction and processing of natural resources, channels more financial resources towards traditional and non-green industries. Consequently, even with a high level of FD, the moderating effect on GEP and GC is not significant. In contrast, non-resource-based areas, characterized by a relative scarcity of resources, fail to fully develop green production and innovation, which in turn restricts the production of green products and subsequently suppresses their consumption. As a result, FD may exert a limited moderating role in these areas.

4.4.3 Population mobility

The examination results based on the distinction between population inflow and outflow regions show in Tables 11 and 12, at the 10% significance level, the impact of GEP on EQ improvement in population inflow areas is not statistically significant. These areas typically have higher levels of economic development, technological capabilities, educational attainment, social welfare, and standards of Living, with their economic structures predominantly

Table 8 Model regression results for the central and Western regions group

	(1)	(2)	(3)	(4)	(5)
	EQ	EQ	EQ	EQ	EQ
GEP	-0.158*** (0.0559)	-0.190*** (0.0598)	-0.182*** (0.0592)	-0.218*** (0.0581)	-0.202*** (0.0612)
GIN	-0.0852** (0.0422)	-0.0998** (0.0416)	-0.106** (0.0412)	-0.108*** (0.0405)	-0.0947** (0.0425)
GIV	-0.518*** (0.0869)	-0.554*** (0.0871)	-0.417*** (0.0928)	-0.292*** (0.101)	-0.556*** (0.0896)
GC	0.0501 (0.0383)	0.111** (0.0460)	0.0576 (0.0387)	-0.00830 (0.0385)	0.0360 (0.0422)
GDP	0.913*** (0.148)	0.876*** (0.148)	0.697*** (0.158)	0.750*** (0.148)	0.962*** (0.158)
UR	-2.844*** (0.428)	-3.016*** (0.428)	-2.449*** (0.446)	-2.481*** (0.430)	-3.057*** (0.487)
FDI	-0.0774*** (0.0249)	0.181 (0.152)	-0.0945*** (0.0244)	-0.0852*** (0.0237)	-0.0783*** (0.0259)
FD		-0.0620** (0.0251)	1.585*** (0.368)	0.0286 (0.153)	0.165 (0.446)
z1		-0.334*** (0.107)			
z2			-0.271*** (0.0691)		
z3				-0.586*** (0.122)	
z4					0.0196 (0.0840)
_cons	-2.374*** (0.510)	-2.742*** (0.521)	-2.439*** (0.496)	-1.921*** (0.492)	-2.310*** (0.524)
N	247	247	247	247	247
R ²	0.477	0.506	0.518	0.533	0.484
adj. R ²	0.418	0.445	0.459	0.476	0.421

driven by the tertiary sector and a relatively lower proportion of primary and secondary industries. GEP must reach a certain threshold to exert a significant positive impact on EQ. Thus, in regions experiencing population inflow with smaller scales of GEP, the effect on EQ is not pronounced. In regions experiencing population outflow, all core explanatory variables meet the criteria at the 10% significance level. However, GC has a detrimental effect on EQ improvement. This phenomenon can be explained by the Environmental Kuznets Curve (EKC) hypothesis (Dinda, 2004), which suggests that EQ typically exhibits an inverted U-shaped relationship with a region's economic development, with environmental pollution decreasing only after a certain level of economic development is achieved. In China, regions experiencing population outflow often have lower levels of economic development, and before reaching the economic "inflection point," EQ is primarily determined by the level of economic development, leading to a detrimental effect of increased GC on EQ. It is also noteworthy that FD exerts a more substantial moderating influence on the economic green transformation of in regions experiencing population inflow. These areas typically exhibit higher levels of economic development, diversified industrial struc-

Table 9 Model regression results for resource-based areas group

	(1)	(2)	(3)	(4)	(5)
	EQ	EQ	EQ	EQ	EQ
GEP	-0.209*** (0.0570)	-0.205*** (0.0678)	-0.286*** (0.0655)	-0.257*** (0.0637)	-0.205*** (0.0672)
GIN	-0.126** (0.0502)	-0.126** (0.0507)	-0.141*** (0.0474)	-0.132*** (0.0471)	-0.126** (0.0504)
GIV	-0.296*** (0.0782)	-0.294*** (0.0824)	-0.131 (0.0842)	-0.122 (0.0840)	-0.274*** (0.0827)
GC	0.0643** (0.0296)	0.0699** (0.0351)	0.0991*** (0.0295)	0.0751*** (0.0285)	0.0434 (0.0338)
GDP	1.189*** (0.137)	1.181*** (0.140)	0.845*** (0.148)	0.996*** (0.134)	1.128*** (0.143)
UR	-3.558*** (0.450)	-3.552*** (0.467)	-3.095*** (0.445)	-3.398*** (0.433)	-3.326*** (0.486)
FDI	0.0932*** (0.0259)	-0.00886 (0.155)	0.0559** (0.0256)	0.0600** (0.0251)	0.0776*** (0.0280)
FD		0.0925*** (0.0262)	1.595*** (0.371)	-0.0967 (0.141)	0.411 (0.328)
z1		-0.0343 (0.124)			
z2			-0.287*** (0.0611)		
z3				-0.515*** (0.105)	
z4					-0.0878 (0.0595)
_cons	-0.229 (0.635)	-0.278 (0.660)	-0.879 (0.613)	-0.658 (0.601)	-0.149 (0.639)
N	169	169	169	169	169
R ²	0.628	0.628	0.676	0.680	0.633
adj. R ²	0.580	0.575	0.630	0.634	0.581

tures, and are hubs for knowledge and technology spillovers. With population inflow, capital and labor markets per capita become more active, and the population structure becomes younger. Under the promotion of FD, the moderating effect on the economy green transformation of these regional is more pronounced.

5 Conclusions and policy implications

5.1 Conclusions

Facing the increasingly severe environmental challenges, the economic green transformation is paramount. Financial markets, leveraging their functions of funding support, resource allocation, and signal transmission, provide solid backing for the economic green transformation. In this study, we address two core questions: On one hand, based on panel data from 30 provincial-level units in China from 2008 to 2020, we assess whether the economic green transformation of provincial-level in China has a significant impact on the improvement of

Table 10 Model regression results for non-resource-based areas group

	(1)	(2)	(3)	(4)	(5)
	EQ	EQ	EQ	EQ	EQ
GEP	-0.0551 (0.0794)	-0.0583 (0.0793)	-0.0785 (0.0769)	-0.104 (0.0785)	-0.0664 (0.0803)
GIN	-0.0672 (0.0490)	-0.0554 (0.0488)	-0.0338 (0.0478)	-0.0687 (0.0477)	-0.0692 (0.0491)
GIV	-0.538*** (0.0784)	-0.554*** (0.0789)	-0.420*** (0.0832)	-0.284** (0.110)	-0.520*** (0.0849)
GC	-0.141*** (0.0391)	-0.0946** (0.0449)	-0.105*** (0.0398)	-0.143*** (0.0389)	-0.146*** (0.0402)
GDP	0.374** (0.172)	0.295* (0.174)	0.352** (0.165)	0.385** (0.168)	0.356** (0.174)
UR	-0.904** (0.379)	-1.082*** (0.389)	-1.608*** (0.398)	-1.456*** (0.399)	-0.996** (0.396)
FDI	-0.105*** (0.0322)	0.138 (0.190)	-0.0944*** (0.0308)	-0.0967*** (0.0312)	-0.109*** (0.0323)
FD		-0.0762** (0.0331)	1.501*** (0.336)	0.151 (0.185)	0.855* (0.456)
z1		-0.360*** (0.133)			
z2			-0.225*** (0.0513)		
z3				-0.394*** (0.110)	
z4					-0.118 (0.0812)
_cons	-1.155** (0.519)	-1.534*** (0.532)	-1.905*** (0.527)	-1.393*** (0.509)	-1.276** (0.528)
N	221	221	221	221	221
R ²	0.515	0.537	0.563	0.550	0.525
adj. R ²	0.459	0.478	0.507	0.492	0.464

EQ. In exploring this process, we construct a theoretical framework for economic green transformation from the perspectives of upstream, midstream, and downstream, emphasizing that only when GEP (upstream), GIN and GIV (supporting sectors in the midstream), and GC (downstream) all move towards green development can it be considered a true economic green transformation. On the other hand, we investigate the role of FD in the interplay between economic green transformation and EQ. Our findings are as follows:

Firstly, within the sample period, the economic green transformation of provincial-level in China has already achieved certain effects in improving environmental quality, indicating that economic green transformation is conducive to addressing environmental pollution and climate change issues. Secondly, with the development of financial markets, the impact of economic green transformation on environmental quality improvement becomes more pronounced. Among these, FD plays a more significant role in promoting contribution of GC to environmental quality improvement, while its role in promoting GIV is relatively weaker. GIV, compared to GC, may lack sufficient policy support, market incentives, and execution efficiency, which could lead to the underutilization of its potential in EQ improvement. Thirdly, the economic green transformation exhibits heterogeneity, with more pronounced

Table 11 Model regression results for the regions experiencing population inflow

	(1)	(2)	(3)	(4)	(5)
	EQ	EQ	EQ	EQ	EQ
GEP	-0.165 (0.118)	-0.0387 (0.110)	-0.146 (0.109)	-0.132 (0.113)	-0.146 (0.116)
GIN	-0.179*** (0.0679)	-0.141** (0.0621)	-0.0679 (0.0680)	-0.167** (0.0650)	-0.179*** (0.0663)
GIV	-0.385*** (0.0958)	-0.376*** (0.0913)	-0.317*** (0.0972)	-0.218 (0.141)	-0.457*** (0.101)
GC	-0.250*** (0.0442)	-0.185*** (0.0464)	-0.254*** (0.0423)	-0.266*** (0.0440)	-0.282*** (0.0454)
GDP	0.661*** (0.213)	0.375* (0.202)	0.582*** (0.196)	0.674*** (0.203)	0.649*** (0.208)
UR	1.138** (0.551)	0.691 (0.513)	-0.522 (0.605)	-0.00349 (0.629)	0.734 (0.554)
FDI	-0.0550 (0.0356)	0.700*** (0.213)	-0.0389 (0.0337)	-0.0256 (0.0350)	-0.0296 (0.0369)
FD		0.0158 (0.0346)	1.976*** (0.378)	0.584** (0.231)	0.734 (0.464)
z1		-0.679*** (0.150)			
z2			-0.230*** (0.0568)		
z3				-0.331** (0.144)	
z4					-0.00415 (0.0901)
_cons	1.596** (0.805)	0.621 (0.755)	0.0610 (0.822)	1.156 (0.784)	1.511* (0.810)
N	156	156	156	156	156
R ²	0.514	0.607	0.596	0.564	0.547
adj. R ²	0.449	0.548	0.536	0.499	0.479

effects in central and western regions, resource-based areas, and regions experiencing population inflow. Notably, in central and western regions, GIV has a particularly significant impact on environmental quality improvement. The specific economic structure and ecological environment needs of different regions may significantly influence the effectiveness of green finance policies. Fourthly, the impact of FD on the economic green transformation and the improvement of EQ shows heterogeneity, with more significant mechanisms observed in eastern regions, non-resource-based areas, and regions experiencing population inflow.

5.2 Policy implications

Based on the analytical findings of this study, the following policy recommendations are proposed:

Active promotion of green energy development should be conducted throughout the social industrial chain, from upstream to downstream, to optimize EQ and curtail pollutant emission. Specifically, production sectors in upstream should expedite the development and

Table 12 Model regression results for the regions experiencing population outflow

	(1)	(2)	(3)	(4)	(5)
	EQ	EQ	EQ	EQ	EQ
GEP	-0.241*** (0.0468)	-0.235*** (0.0545)	-0.262*** (0.0484)	-0.236*** (0.0534)	-0.233*** (0.0535)
GIN	-0.131*** (0.0367)	-0.131*** (0.0376)	-0.178*** (0.0340)	-0.130*** (0.0369)	-0.129*** (0.0370)
GIV	-0.228*** (0.0691)	-0.229*** (0.0714)	-0.0639 (0.0664)	-0.146* (0.0758)	-0.200*** (0.0704)
GC	0.0588** (0.0261)	0.0751** (0.0338)	0.0925*** (0.0250)	0.0557** (0.0274)	0.0121 (0.0346)
GDP	0.888*** (0.118)	0.866*** (0.123)	0.549*** (0.117)	0.763*** (0.128)	0.800*** (0.125)
UR	-2.896*** (0.332)	-2.858*** (0.353)	-2.031*** (0.333)	-2.598*** (0.362)	-2.480*** (0.382)
FDI	0.0649** (0.0254)	-0.0447 (0.135)	0.0491** (0.0229)	0.0467* (0.0264)	0.0540** (0.0258)
FD		0.0677*** (0.0258)	2.209*** (0.328)	-0.107 (0.135)	0.695** (0.343)
z1		-0.0675 (0.102)			
z2			-0.413*** (0.0558)		
z3				-0.275** (0.108)	
z4					-0.145** (0.0614)
_cons	-0.881* (0.457)	-0.984** (0.478)	-0.957** (0.414)	-1.004** (0.460)	-0.570 (0.481)
N	234	234	234	234	234
R ²	0.658	0.659	0.730	0.669	0.668
adj. R ²	0.619	0.616	0.696	0.627	0.626

utilization of clean energy sources such as wind, solar, and biomass energy, thereby decreasing dependence on fossil fuels. Enterprises, universities, and research institutions should be encouraged to intensify research and development in clean energy technologies, boosting their efficiency and reliability, and hasten the industrialization process to promote the widespread application of clean energy technologies. In light of the resource endowments, industrial bases, and market demands of various regions, development plans for the clean energy industry should be crafted to refine industrial layouts and spur industrial transfer to central and western regions, thereby fostering coordinated regional development. On the consumption side, education and promotion of GC should be augmented to raise public awareness of clean energy, motivating public participation in the construction and operation of clean energy projects and strengthening public support and involvement in clean energy.

GIN entities should be cultivated to enhance green innovation capabilities. Research indicates that green technological innovation needs to reach a specific “inflection point” before it can significantly reduce carbon emissions and enhance EQ. Therefore, in regions that have reached this “inflection point,” emphasis should be concentrated on the research of core green technologies and the intensification of green innovation to facilitate green

transformation and enhance EQ. For regions that have not reached the “inflection point,” vigorously support should be extended to green innovative enterprises, stimulating green innovation at the societal level and furthering the construction of a green technological innovation system. Specific measures encompass establishing green technological innovation platforms to foster cooperation among enterprises, universities, and research institutions, fortifying industry-academia-research integration, and expediting the transformation and industrialization of green technological outcomes. Policies for green technological innovation should be refined, with strategically designed incentive measures to offer tax incentives and financial support for green technology research, application, and promotion, thereby diminishing enterprise innovation costs. The development and recruitment of green technological innovation talents should be intensified, particularly in central and western regions and economically underdeveloped areas, to address the needs of green development.

The scale of GIV should be steadily increased, and a holistic green financial service system should be established. Firstly, GIV and financing products should be innovated upon to broaden the scale of green finance and GIV, optimizing their positive impact on EQ and maximizing environmental benefits. Secondly, acknowledging the disparities in green finance levels among regions in China, efforts should be directed towards constructing a comprehensive green financial service system. While advancing traditional green financial instruments, emerging financial financing instruments such as EQ should be actively pursued and developed. Thirdly, when formulating GIV policies, governments should target areas that prioritize both environmental improvement and economic development and guarantee policy effectiveness. Special attention should be accorded to central and western regions and resource-scarce areas, directing the inflow of green funds. Finally, the oversight and assessment of GIV projects should be intensified to ensure that they adhere to environmental standards and sustainable development requirements. Additionally, a transparent public information disclosure system for GIV projects should be established to enhance project transparency and promote social supervision. Projects that do not meet the requirements should be expeditiously modified or discontinued.

Competition among financial markets should be further intensified, and the design of the financial market system should be further refined to bolster the development of the overall financial market. Firstly, grounded in comprehensive environmental impact assessments, governments should broaden the financial scale and cultivate multi-layered monetary and capital markets and their derivatives to augment the efficiency and depth of financial services for the real economy. Secondly, authorities should tailor credit policies to benefit green industries, leveraging financial instruments to spur the green transformation and upgrading of industries. Furthermore, the pace of GIN in financial products should be accelerated, directing government funds and social capital to diversify funding sources to support green transformation across production, intermediary, and consumption links. Meanwhile, governments need to address regional disparities and institute a scientific and reasonable financial service system to mitigate the negative effects of economic development and catalyze green transformation and local industrial upgrading.

5.3 Limitations and recommendations for future studies

This study employs a holistic perspective spanning the entire chain of pollution emission sources (upstream-midstream-downstream) to construct a theoretical framework for the

green transformation of the economy and systematically analyzes the role of FD in promoting economic green transformation to EQ. Our research not only unveils the mechanisms by which FD influences the green transformation but also underscores the temporal scalability of these mechanisms. Furthermore, this study positions FD as a moderating variable to probe its role in the economic green transformation, while recognizing that environmental regulations and digitalization are also noteworthy areas for future research. Furthermore, there is a shortcoming in the heterogeneity analysis behind the mechanisms, and future studies should investigate this issue from multiple perspectives to offer substantive guidance for China to devise more nuanced regional policies.

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Data availability The datasets generated during the current study are available from corresponding author on reasonable request.

Declarations

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