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# Impact of green digital finance on sustainable development: evidence from China's pilot zones

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## Abstract

To investigate the impact of Green Digital Finance (GDF) policies on sustainable regional development goals, this study exploits the implementation of China's green finance reform and innovation pilot zones as a quasi-natural experiment to examine the theory and impact of policy channels on sustainable development. A difference-in-differences model was applied to evaluate the impact of policies in these zones based on data from 285 cities in China from 2014 to 2020. Research has shown that the GDF is conducive to achieving sustainable development goals through the effects of financial inclusion and energy transitions, which promote the transformation and upgrading of industrial structures. The impact of the GDF pilot-zone policies on the sustainable development of cities at different levels, locations, resource endowments, and green total factor productivity is heterogeneous. This study provides accurate empirical evidence of the effects of the extensive implementation of the policies adopted in the pilot zones and the expansion of the scale of these zones, and it provides policy recommendations for the GDF.

**Keywords:** Green digital finance, Sustainable development, Financial inclusion, Energy transition, Transformation and upgrading of industrial structure

## Introduction

In response to the major challenge posed by global climate change, the United Nations has drawn up the Sustainable Development Goals (SDGs), which have always been an important topic discussed by international academic communities. According to estimates from the United Nations Conference on Trade and Development (UNCTAD), developing countries need to invest approximately USD 4 trillion each year in fields related to sustainable development for the global economy to achieve the SDGs. Underfunding from these nations means that the annual global financing gap reaches USD 2.5 trillion each year (United Nations Conference on Trade and Development (UNCTAD) 2014). Before 2019, the deficit gradually narrowed owing to economic growth and the continuous improvement of the financial system. However, this trend was reversed when the coronavirus disease (COVID-19) pandemic broke out in 2019, resulting in a global economic downturn. In this context, local green investments related to SDGs in developing countries have decreased by 42%, and cross-border green project investments have decreased by the same percentage, further widening the financing gap (UNCTAD 2021). Evidently, facing financial constraints as a result of the pandemic, countries worldwide have not been able to muster the finances to effectively support the global realization of the SDGs by relying only on traditional financing for green financing (Devidze 2022). Green finance, the most important subset of sustainable financing, must ensure adequate funds through innovative development (World Bank 2017), and fintech represents the key driver for financial innovations that will achieve the SDGs (Arner et al. 2020). Digital technology is becoming a revolutionary solution that will fundamentally change traditional financial markets (UN Task Force on Digital Financing of SDGs 2020) and drive the development of green finance.

"Green finance" and "digital finance," previously two independent topics, have developed together over the years. However, financial organizations for sustainable development and agencies providing digital technologies have always acted separately. Governments often plan to encourage sustainable finance and promote digital finance or fintech in parallel, with little overlap between these two policies, thus missing the opportunity to realize the common interests of inclusive finance and sustainable finance through digitalization (Sustainable Digital Finance Alliance (SDFA) 2018). The People's Bank of China (PBC 2016) defines green finance as an economic activity that supports environmental improvements, responds to climate change, conserves and efficiently uses resources, and provides financial services for project financing, project operations, and risk management in terms of environmental protection, energy conservation, clean energy, green transportation, green buildings, and other fields. Digital finance involves products that integrate technological and financial innovations. Organizations have provided various definitions of this term, the most succinct being that defined by the World Bank, which refers to the impact of the Internet and other relevant digital technologies on the financial sector (Sustainable Digital Finance Alliance (SDFA) 2018). Digital finance can promote regional economic growth through technological innovation (Lin and Xiao 2022). In combination with the characteristics of green and digital finance, the GDF can be analyzed in relation to the greening of digital finance, which mainly involves the consideration of environmental risks in digital financing and investment projects, and in relation to the digitalization of green finance, which mainly refers to the use of digital technology or tools to pursue innovation in green, environmentally friendly financial products and services. The latter is emphasized in this study, which focuses on the impact of the digitalization of green finance on sustainable regional development. Under such circumstances, the GDF has emerged as a completely new topic (Oertli 2020).

The concept of GDF has not been officially and explicitly defined, despite thorough analyses from multiple perspectives by academic communities. Marianne Haahr (2021), CEO of the Green Digital Finance Alliance (GDFA 2021), believes that the GDF aims to innovate services, products, strategies, and business models using emerging digital technologies or tools, such as AI, big data, blockchain, and the Internet of Things (IoT), to meet clients' green finance needs. This study argues that, in a broader sense, GDF is a sustainable financing solution provided by the financial system through technological innovation to achieve the SDGs. Morgan (2022) argues that digital technology can promote the development of green finance in four ways. First, technologies such as big data, machine learning (ML), artificial intelligence (AI), distributed ledgers (DLT), and IoT are applied to evaluate information for project investments more accurately and promptly. Second, digital technologies are used to simplify processes, reduce costs, and attract investors to innovative business models. Third, inclusive financing and investment are driven by narrowing the information gap between financial services and potential clients. Fourth, intelligent investment consultants and convenient digital payment systems were used to attract investors to green financial products. However, there are few relevant data and materials on GDF. Against this background, it is necessary to conduct economic studies from different perspectives across multiple disciplines as soon as possible. To fill this research gap, this study examines the recent development of China's GDF using the difference-in-differences (DID) method and a double fixed effects model to study the impact of financial digitalization policies in China's green finance pilot zones on sustainable regional development.

The remainder of this paper is structured as follows: Section "Literature Review" introduces literature on sustainable development and its Sinicization, as well as on GDF; Section "Hypotheses" gives an account of the financial digitalization policies of China's green finance reform pilot zones and presents theories and hypotheses; Section "Research Design" describes the data sources and methodology in this study; Section "Empirical Analysis" describes the observed results; Section "Acting Mechanism Test" validates the existence of the active channel of impact; and Section "Conclusions and Suggestions" wraps up the argument with recommendations.

## Literature review

Relevant studies can be divided into those that primarily introduce sustainable development and its Sinicization and those that provide an overview of the development of GDF.

### Sustainable development and its sinicization

In September 2015, the United Nations published a global plan titled *Transforming our World: The 2030 Agenda for Sustainable Development*, which set out actions to address the global challenges of environmental degradation and poverty by 2030 (UNGA 2015). The Agenda is a non-binding agreement that allows governments to formulate their own national policies and independently design development goals according to the requirements of the SDGs (Allen et al. 2019). As a guide for joint action by the government, private sector, and non-governmental organizations (Hajer et al. 2015), the agenda can effectively guide countries in their transition to the ultimate goal of sustainable development (Le Blanc 2015; D'Amato et al. 2019).

To implement the SDGs, it is necessary to make major adjustments in many areas of society and the economy. The SDGs initiated a new phase for countries and regions to share responsibilities at the global level (Bexell and Jonsson 2017). For example, China's Belt and Road Initiative (BRI) follows the principles of sustainable development in line with the Global SDGs (State Council Information Office of the People's Republic of China 2021) and seeks an approach that contributes to the implementation of the 2030 Agenda (Ministry of Foreign Affairs of the People's Republic of China 2016). The joint contribution of the BRI is supported conceptually and materially by the United Nations, which, in turn, benefits from China's focus on sustainable development (Li and Shapiro

2020). Based on its SDGs and the real situation on the ground, China has formulated a roadmap for sustainable development with Chinese characteristics, advocating that the promotion of sustainable social and economic development is not only representative of the era but also the only path for China to realize high-quality development (China Center for International Economic Exchanges (CCIEE) et al. 2020). Zhou et al. (2021) argued that sustainable development comprises three systems: economic development, social development, resources, and the environment. Ren and Wen (2018) argued that high-quality economic development in China is an advanced, optimal state of sustainable development, such that both high-quality and sustainable development are essentially the same. The primary theme of sustainable development in China is high-quality development. Ma et al. (2022) argued that a sustainable development strategy must be a comprehensive approach to achieving sustainable economic, societal, and ecological development. Ma et al. (2019) found that high-quality development represented an efficient, stable, and open development model. Pang et al. (2019) argued that the key to high-quality development is to realize higher efficiency by improving economic vitality and creativity. There are two prevailing views on measuring quality development. First, a single indicator was selected for the measurement. For example, Xu et al. (2018) chose total factor productivity (TFP) as the core of economic development so that TFP measurements could be used as an indicator of high-quality development (Guo and Zhou 2020). The economic contribution of the rate of technological progress (Liu et al. 2020) or green TFP (Yu et al. 2020) has also been used to characterize high-quality development. In the second method, a comprehensive indicator system was established. A comprehensive index should consider the five development concepts of innovation, coordination, greenness, openness, and shared development (Ou et al. 2020).

In summary, China's high-quality development and the United Nations' SDGs are derived from the same source, and the sustainable development of China's economy can be measured using indicators of the country's high-quality development.

### Green digital finance

The development of GDF requires certain preconditions. Government policies based on the objectives of the Paris Climate Agreement and SDGs play an important role in the reasonable development and utilization of GDF (Coskun and Unalmis 2022). The development of GDF in developing countries will help them raise more green project funds from Chinese and foreign investors (Nassiry 2018). Many countries have begun to formulate GDF policies. The Korean New Deal directs the transition to a digital and green economy, showing great strategic significance. However, the New Deal is also limited by its placement within the framework of two independent projects: the Digital New Deal and Green New Deal (Hyun 2022). Digital finance has rapidly developed in India in recent years. To promote the realization of the SDGs, the Indian government has applied digital technology to green finance; however, without effective supervision, asset security risks have begun to appear (Singh et al. 2022). Arguably, the government can deepen the regulation of the GDF; however, the regulatory and legal factors to be considered are very complex and require a well-considered arrangement of the regulatory system (Singh 2022).

Second, the GDF not only plays an important role in the development of green projects but also plays a positive role in the sustainable development of many countries. The digitization of green finance has accelerated the flow of capital into green energy projects. However, the current development of the GDF varies from country to country, and the GDF needs a seedbed of green projects (Moufakkir and Qmichchou 2019). Paradise (2022) discussed the important role of the GDF in achieving the SDGs in China's BRI and emphasized the consideration of environmental standards in BRI projects. Gurbanov and Suleymanli (2022) analyzed the development of GDF in Georgia, including the level of digitalization, and emphasized that GDF should be used to attract more investments from the private sector. Rasoulinezhad and Taghizadeh-Hesary (2022) evaluated expert opinions on the key to developing Iran's GDF market using qualitative methods, finding a consensus that policymakers should emphasize key areas, including the accessibility and transparency of the GDF market, profitability of green projects, and responsibility of developers of GDF financing tools.

Finally, fintech and financial innovation play crucial roles in GDF development. Devidze (2022) described the recent situation of the GDF, including obstacles to the development of green finance, and proposed the expansion of digital technology in green financing. The GDF can provide private investors with fast and inexpensive access to the data (interest rates, taxes, etc.) of green financing tools, such as green bonds, through the network infrastructure at any time and place (United Nations 2018). By analyzing the role of Swiss green financial technology in preventing environmental pollution, Puschmann et al. (2020) argued that green fintech can promote the innovation of financing tools for green energy projects. By conducting qualitative research on three Finnish companies, Ruman et al. (2022) demonstrate that small and micro enterprises play a key role in financial innovation and sustainable development with green financial products developed through the use of financial technology. Schloesser and Schulz (2022) showed how DLT can be effectively applied to innovative climate financing and analyzed its sustainability and future governance structure. However, there are areas that require attention during the development of GDF. The high costs of research and development in the GDF are not favorable for the development of smart cities (He et al. 2020). Digital finance technology, especially next-generation fintech, can promote green finance; however, a single fintech application operating alone may pose environmental risks rather than developing sustainable finance (Morgan 2022).

Given that the GDF is a new green financing tool in energy economics and finance, much work remains to be done to conduct empirical research and discussions on China's green digital development. This study empirically demonstrated the contribution of micro-digital finance development to local sustainable development in the context of China's national green finance policies, which were used to measure the level of China's GDF. The channels of the impacts of GDF on sustainable development were explored, providing important research on this subject.

## Hypotheses

### Implementation of policy

Empirical studies of the relationship between finance and growth usually show a positive correlation between financial development and economic growth (Puschmann and

Leifer 2020); a more developed financial system indicates faster economic growth, and financial innovation has a positive impact on economic growth (Financial Stability Board (FSB) 2017). To better support the SDGs through China's economic growth, the *Guidance on Developing a Green Financial System* was issued by seven ministries and commissions[1] in 2016 (PBC 2016), making China the first country in the world to promote policies to explicitly support the development of a green financial system. Since 2017, the Chinese government has established a successive series of green finance reform and innovation pilot zones ("pilot zones")[2] covering ten cities from seven provinces and municipalities, which were announced in three batches; this marked the entry of China's green finance into a new phase that combined top-down, top-level design and bottom-up, regional exploration. The green finance reform and innovation plans[3] in these zones are consistent with the working objectives of each pilot zone to focus on institutional innovation. This is to encourage the innovative development of green finance to drive the development of advanced industries, complete the green transformation and upgrading of traditional industries, and make full use of the decisive role of the market in resource configurations to promote high-quality sustainable regional development. By the end of 2020, the balance of green loans in the pilot zones, which then consisted of nine cities in six provinces and regions, had reached 236.8 billion yuan, accounting for 15% of the total loan balance, whereas the balance of green bonds had reached 135 billion yuan, up 66%[4] year-over-year, proving that policies related to green finance had been successfully implemented in the pilot zones.

Led by the implementation plans in each pilot zone,[5] digital technology has made important contributions to the innovative development of green finance (PBC 2022; PBC Research Bureau 2022). The seven aspects of this study are listed in Table 1.

As shown in Table 1, the policies in China's pilot zones have significantly promoted the development of regional GDF. In combination with available data, the digital finance index developed under the green finance policy in the pilot zones represents the development of the GDF. Therefore, in this study, the DID method was used to demonstrate the impact of GDF development on sustainable regional development, and theoretical hypotheses were proposed to explain the impact channels.

## Theories and hypotheses

This study draws on the theoretical framework proposed by Berman and Bui (2001) to build a theoretical model of the impact of GDF policy on sustainable development. There are two views on the impact of the GDF: Berman and Bui (2001), based on the

[1] The People's Bank of China, Ministry of Finance, National Development and Reform Commission, Ministry of Environmental Protection, China Banking Regulatory Commission, China Securities Regulatory Commission, and China Insurance Regulatory Commission.

[2] The first pilot zones, launched on June 23, 2017, comprise eight cities across five provinces and regions: Huzhou and Quzhou in Zhejiang Province; Hami, Changji Hui Autonomous Prefecture, and Karamay in Xinjiang Uygur Autonomous Region; Gui'an New Area in Guizhou Province; Guangzhou in Guangdong Province; and Ganjiang New Area in Jiangxi Province. The second batch of pilot zones included Lanzhou New Area, Gansu Province, which was launched on November 28, 2019, and the third was Chongqing, launched on August 19, 2022.

[3] Source: Website of the People's Bank of China (www.pbc.gov.cn).

[4] Source: *China Regional Financial Operation Report (2021)* by the People's Bank of China, www.pbc.gov.cn/outongjiaoliu/113456/113469/4264899/index.html.

[5] Source: Website of the People's Bank of China (www.pbc.gov.cn).

**Table 1** Seven major contributions. Source: Authors' compilation

| Aspects | Details |
|---|---|
| Building a green financial information management system | A green credit management and information inquiry platform capable of "T + 1" high-frequency data collection, loan business verification, data monitoring and analysis, and systematic performance evaluation, with traceable, comparable, and measurable data |
| Identifying green finance projects | A digital green project database that incorporates the green finance information management system; the big data system is used to capture project information, intelligently identify green projects, and support offline manual evaluation |
| Building a green finance big data system | The system contains ten primary functional modules: visual presentation, statistical monitoring of green finance, green finance evaluation, green financing, green professional services, green finance information sharing, green finance support toolbox, cross-regional innovation platform, international collaboration, and e-government. There are also 40 secondary functional modules. The system is capable of collecting, managing, processing and analyzing data, providing green professional services, automatically linking financing information, and utilizing and managing monetary policy tools |
| Establishing a cloud platform with integrated services for green finance | Three main service functions: assessing the greenness of enterprises and projects, matching capital and project information, and rapidly connecting banks and enterprises. It provides small and medium enterprises with financial services such as bank loans, equity financing, and green assessment, and supports their green and sustainable development |
| Empowering green credit through digital finance | Green loans for small and microbusinesses are developed from online commercial banks, and a green financial service system for small and microbusinesses is underway. Green inclusive finance is supported by the development of digital banks |
| Supporting green bonds | China Central Depository & Clearing Co., Ltd. (CCDC) has researched and established the China Bond-Green Bond Environmental Benefit Information Disclosure Index System and the Green Bond Database; it has taken the lead in applying this system in the pilot zones |
| Supporting the development of carbon finance | A digital platform has been built for carbon accounts that integrates carbon finance with industry, energy, construction, transportation, and other fields in the pilot zones. The use of carbon efficiency codes is encouraged. A digital index is established for carbon efficiency |

theory of local static balance, hold that changes in environmental regulations and other factors impact the industrial structure and thus employment. Wang and Wang (2020) stated that green finance leads to changes in environmental regulations and other factors by guiding the redistribution of resources, thus changing the industrial structure and ultimately affecting sustainable development. Notably, both employment and sustainable development are mainly affected by changes in the industrial structure caused by new environmental regulations and other factors, which are in turn affected by the GDF. Therefore, based on the characteristics of sustainable development, this study readjusted the assumptions of the model. A region is considered an independent production sector, and the production goal is to improve the level of sustainable development. According to the characteristics of sustainability, the realization of production goals requires the input of green production factors in line with environmental regulations. Green production factors can be regarded as the costs of investment in environmental governance and industrial green transformation. The input quantity was determined using the minimization principle for production costs and regional resource constraints. Therefore, green factors of production can be regarded as "quasi-fixed," while capital, labor, and technology can be regarded as variable factors.

Production cost minimization is the basis of the calculations for the production factor input. The total production factor includes $M$ variable factors and $N$ "quasi-fixed" factors, so the variable cost function of sustainable development can be expressed as follows:

$$C = f(T; V_1, V_2, \ldots, V_M; F_1, F_2, \ldots, F_N) \tag{1}$$

where $C$ represents the variable cost of sustainable regional development, $T$ represents the output level of sustainable regional development, and $V_M$ $(m = 1, 2, \ldots, M)$ is the price of the $m$-th variable. $F_N$ $(n = 1, 2, \ldots, N)$ is the $n$-th "quasi-fixed" factor input. According to Shepard's lemma, the demand function of variable factor capital $E$ can be expressed by output level $T$, variable factor price $V_M$, and "quasi-fixed" factor input $F_N$. The linear function $E$ is expressed as follows:

$$E(T; V_1, V_2, \ldots, V_M; F_1, F_2, \ldots, F_N) = \mu + \varphi T - \sum_{m=1}^{M} \gamma_m V_m - \sum_{n=1}^{N} \tau_n F_n \tag{2}$$

Among these variables, $\mu$, $\varphi$, $\gamma$ and $\tau$ are relevant parameters, and the positive and negative values of $\tau$ are determined by the substitutive or complementary relationship between green production factor input and variable factor capital under the pilot zone policy. $P$ represents the level of GDF policy in the pilot zone, and σ expresses the marginal effects in capital factors as affected by GDF policy in the pilot areas; λ represents the other factors in the pilot area. The relationship between the variable capital factors and the policy can be expressed as follows:

$$E(T; V_1, V_2, \ldots, V_M; F_1, F_2, \ldots, F_N) = \sigma P + \lambda \tag{3}$$

Then, taking the derivative of Eq. (3), the influence of GDF policy $P$ in the pilot area on capital factors can be obtained:

$$\sigma = \frac{dE}{dP} = \varphi \frac{dT}{dP} - \sum_{m=1}^{M} \gamma_m \frac{dV_m}{dP} - \sum_{n=1}^{N} \tau_n \frac{dF_n}{dP} \tag{4}$$

Assuming that the market is in perfect competition, the GDF policy in the pilot zones will not affect the prices of variable factors. When $\sum_{m=1}^{M} \gamma_m \frac{dV_m}{dP} = 0$, the formula for the impact of the GDF policy on sustainable development in the pilot zone is as follows:

$$\frac{dT}{dP} = \frac{1}{\varphi}\underbrace{\left(\underbrace{\frac{dE}{dP}}_{\text{Financial inclusion effect}} + \underbrace{\tau_n \sum_{n=1}^{N} \frac{dF_n}{dP}}_{\text{energy transition effect}}\right)}_{\text{upgrading of the industrial structure}} \tag{5}$$

In Eq. (5), the first term $\frac{dE}{dP}$ in parentheses to the right of the equals sign, is the financial inclusion effect, which can be understood as the contribution of the GDF policy to the transformation and upgrading of the industrial structure in the pilot zone by influencing capital. The second term $\tau_n \sum_{n=1}^{N} \frac{dF_n}{dP}$ represents the energy transition effect, which can be understood as the contribution of the GDF policy to the transformation of the industrial structure in the pilot zone through the input of environmental governance. The combination of the two effects will affect the transformation of the regional industrial structure as a whole and then affect the level of sustainable development through the multiplier effect of the influence coefficient $\varphi$. Currently, China faces insufficient capital supply and low resource allocation efficiency to promote sustainable development. Finance is the core driving force of modern economic growth and is the key to increasing capital supply and improving the efficiency of resource allocation (Zhang and Zhu 2014). The financial inclusion effect of the GDF in Eq. (5) resolves the problem of insufficient capital supply, and the energy transition effect improves the efficiency of industrial resource allocation.

The above theoretical derivation shows that the GDF policy in the pilot zone upgrades the industrial structure through the combined effects of financial inclusion and energy transition, and then further promotes sustainable development through industrial structure transformation. According to the derivation results and related policies, the principle underlying this mechanism is described in Fig. 1, and the influence of these two effects on sustainable development through the industrial structure is analyzed in detail in the schematic diagram.

The transformation of the industrial structure under the GDF policy will contribute to the following changes: improved innovation among enterprises, green coordination of industries, increased utilization of factor resources, strengthened competitiveness in international trade, and improvements in ecological civilization. The upgraded industrial structure will promote high-quality sustainable development of the economy. The development of the GDF has had a positive impact on regional SDGs, promoted rural economic growth in the least-developed and middle-income countries, boosted the development of small and medium enterprises, and facilitated green regional economic growth through the transformation of traditional industries (Gong et al. 2019). The transformation of China's industrial structure is represented by upgrades to underproducing industries that make them efficient and the transformation of industries, including the "three-high industries" (high pollution, energy consumption, and emissions), into high value-added, green, and low-carbon industries. The allocation of resources should be optimized to improve overall international competitiveness and promote high-quality sustainable development. Therefore, as the immediate benefits of environmental sustainability gradually diminish

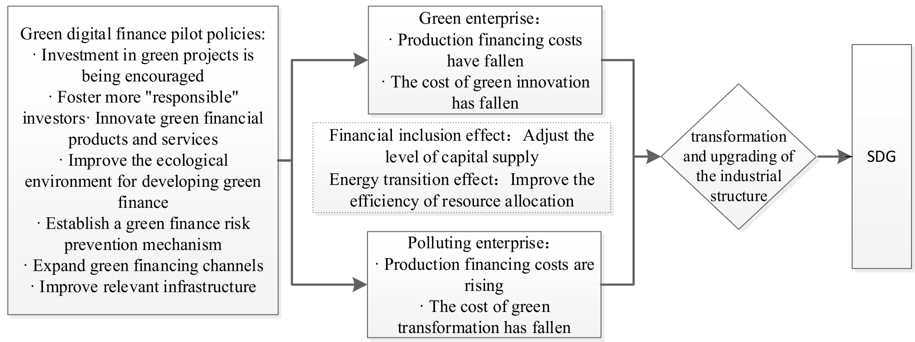


**Fig. 1** The channels of influence of GDF policy on sustainable development

and a contradiction between economic development and environmental regulation emerges, the government must guide industries, especially the pillars and three-high industries, into high-quality sustainable development through structural transformation and technological upgrades (Fan et al. 2020). That is, in Eq. (5) above, $\varphi > 0$.

*Hypothesis 1:* Green digital finance promotes sustainable development by transforming and upgrading industrial structures.

The transformation of the industrial structure is often accompanied by improvements in the organizational structure and continuous improvement of TFP. This process depends on the improvement of technological factors in the private sector, which is funded primarily by external financing that depends on financial inclusion. The GDF's digital technology attribute is considered a key driver of inclusive finance. This can help the private sector obtain financing and ultimately facilitate the transformation of industrial structures (Arner et al. 2020). Digital finance can use big data to assess clients' credit risks, thereby greatly reducing the information asymmetry between financial institutions and consumers (Dendramis et al. 2018). For example, P2P lending platforms have increased over the last two decades. The P2P lending market was valued at USD 3.5 billion in 2013, rose to USD 67.9 billion in 2019, and is projected to reach USD 559 billion by 2027 (Swaper 2021). Digital finance technology can rapidly generate, collect, analyze, and verify a large amount of data related to environmental and social benefits (including nonstandard data) at a low cost, helping enterprises solve asymmetric financing information and preventing decisions based on inaccurate data (United Nations Environment Inquiry (UNEI) 2018). Blockchain technology can unlock the financing necessary for enterprises' sustainable development (Uzsoki and Guerdat 2019). Thus, in Eq. (5), $\frac{dE}{dP} > 0$.

*Hypothesis 2a* Green digital finance promotes the transformation and upgrading of industrial structures through financial inclusion.

The transformation of the industrial structure has the same goal as the energy transition, namely, sustainable development. Both the environmental protection and digital technology attributes of the GDF can guide the energy transition. Based on data from listed companies, Niu et al. (2020) indicate that a green finance policy can play a role in controlling pollutant emissions and improving environmental quality because it can channel more financial resources toward environmental protection and direct green financial resources away from environmentally harmful enterprises and toward green, energy-saving, and environmentally friendly enterprises, effectively restricting the development of environmentally harmful enterprises. Yu et al. (2022) believe that the development of digital finance can positively impact renewable energy consumption (REC), optimize industrial structure, and promote technological progress. In accordance with the requirements of the *United Nations Framework Convention on Climate Change*, Meniga provides digital banking solutions to financial institutions worldwide, and seeks projects that can reduce, avoid, or eliminate greenhouse gas emissions from developing countries. According to the study conducted by Meniga, carbon-conscious digital banking can help corporate clients reduce their carbon footprint by an average of 20%. The adoption of these technologies in the banking industry has had a substantial impact on regional industrial transformations (Meniga 2021). That is, in Eq. (5) above, $\tau_n \frac{dF_n}{dP} > 0$.

*Hypothesis 2b* Green digital financing promotes the transformation and upgrading of industrial structures through energy transitions.

## Research design

### Modeling

When constructing an econometric model, DID and its derivative models are often used to discuss the impacts of policies (Liu and Sun 2021). Based on the credibility revolution in econometrics, this method simulates random experiments through feasibility studies to avoid misleading regression results caused by intrinsic errors, thereby transitioning from correlation to causality (Angrist and Pischke 2010). The exogenous effects of new policies or institutional innovation reforms on economic systems are measured in the context of natural or quasi-natural environments (Chen and Wu 2015; Hu and Lin 2018).

The implementation of pilot-zone policies has led to differences in GDF and sustainable development levels between cities in the pilot zone and outside of it when measured at the same time point. There were also changes in the GDF and sustainable development levels in the pilot zones before and after the implementation of the policies. Based on the above two conditions, DID can be used to estimate a model that identifies the magnitude of the impact of the GDF on sustainable development within the green finance pilot zones while effectively controlling for prior differences between the pilot zones, non-pilot zones, and other prescriptive policies. Meanwhile, the selection of pilot zones considers the central, eastern, and western regions of China and cities from the first to the fifth tier, which can be regarded as meeting the conditions for a quasi-natural environment. Therefore, the DID method can be used to evaluate the impact of these policies. The DID model is constructed as follows:

$$eqd_{it} = \alpha_0 + \alpha_1 gdf_{it} + ifi + \sum \gamma_j cro_{it}^j + \mu_i + \lambda_t + \varepsilon_{it} \tag{6}$$

**Table 2** Variable definitions

| | Variable | Meaning |
|---|---|---|
| Dependent variable | $eqd_{it}$ | Principal component method to construct sustainable development indices |
| Core explanatory variable | $gdf_{it}$ | $gdf_{it} = Treated \times Time \times ifi$ |
| Replacing explanatory variables of the coverage | $gdfc_{it}$ | $gdfc_{it} = Treated \times Time \times ific$ |
| Replacing explanatory variables of the use depth | $gdfu_{it}$ | $gdfu_{it} = Treated \times Time \times ifiu$ |
| Replacing explanatory variables of the digitalization | $gdfd_{it}$ | $gdfd_{it} = Treated \times Time \times ifid$ |
| Mechanism variables | *fin* | The log value of the ratio of the balance of deposits and loans of financial institutions to the population at the end of the year |
| | *es* | The ratio of coal consumption to total energy consumption |
| | *adi* | $adi = 1 - tl = 1 - \sum_{i=1}^{n}(y_i/y)\ln(\frac{y_i}{l_i}/\frac{y}{l})$ |
| Control variables | *pop* | The log value of the number of permanent urban residents |
| | *inv* | The log value of real estate development investments |
| | *gov* | The log value of fiscal budgetary expenditure |
| | *inl* | The proportion of the added value of the secondary industry in regional GDP |

The dependent variable $eqd_{it}$ refers to the sustainable development level of city $i$ in year $t$, the core explanatory variable $gdf_{it}$ represents the development level of green digital finance, and the control variable $cro_{it}^{j}$ represents a series of control variables affecting the sustainable development of city $i$ in year $t$, $\varepsilon_{it}$ is the error perturbation term, $\mu_i$ is the fixed effect of city,. $\lambda_t$ is the year fixed effect, $\alpha, \beta, \gamma, \delta, \sigma$ and $\theta$ in the following are regression coefficients, subscript $i$ and $t$ represent city and year, respectively.

## Selection of variables

Table 2 lists the main variables selected in this study and their definitions.

### *Dependent variable*

*Establishing sustainable development indices*. Sustainable development comprises three systems: economic development, social development, resources, and the environment (Zhou et al. 2021). With reference to the method used by Shi and Zhang (2019), comprehensive indicators were constructed to measure China's high-quality sustainable development level based on economic fundamentals, social progress achievements, and ecological progress achievements, as shown in Table 3.

The indicators for economic fundamentals are selected as follows: Economic intensity refers to economic vitality. A higher degree of economic activity indicates that a city's economic development is more prosperous, residents' living standards and quality of life are higher, and economic development has a greater driving force and potential. The real per capita GDP of a city was used to measure economic intensity. Second, the urbanization rate is an important symbol of urban change that matches the process of industrialization. Although studies have shown that higher rates of urbanization are not always better, the urbanization rate in China is currently less than 70%, which is still far behind the average

**Table 3** Sustainable development evaluation indicator system

| Primary indicator | Secondary indicator | Characterization indicator | Indicator description | Attribute |
|---|---|---|---|---|
| Sustainable development | Economic fundamentals | Economic intensity | Log value of real GDP per capita | Positive |
| | | Urbanization rate | Urban population/number of year-end permanent residents | Positive |
| | | Wage level | Average wage of active employees | Positive |
| | | Degree of openness | Log value of the actual foreign investment | Positive |
| | Social progress achievements | Education development level | Number of college students per ten thousand people | Positive |
| | | Level of scientific and technological development | Number of invention patents | Positive |
| | | Consumption development level | Log value of total retail sales volume of social consumer goods | Positive |
| | | Infrastructure level | Log value of road area per capita | Positive |
| | Ecological progress achievements | Carbon emissions | Log value of carbon dioxide emissions | Negative |
| | | Gas emissions | Log value of sulfur dioxide emissions | Negative |
| | | Liquid emissions | Log value of industrial wastewater emissions | Negative |
| | | Dust pollution | Log value of industrial dust emissions | Negative |
| | | Green development | Log value of park and greenbelt size | Positive |

urbanization rate of 75% in developed countries. Therefore, we chose this as the positive indicator. Third, the wage level represents the average income of workers in a certain region and period. Economic development can thus provide more distributable social products. Fourth, the extroversion of economic development is closely related to the concept of "open development," and the actual foreign investment of each city that has relatively complete data is selected for measurement in this study.

The results of social progress manifest in the accumulation of human capital through education, science, technology, consumption, and infrastructure. The accumulation of human capital promotes innovative development across the overall urban system. Therefore, achievements in social progress reflect "shared and "innovative developments."

Ecological progress is intrinsically linked to "green development." Therefore, major indicators, such as greenhouse gas and pollutant emissions and the greening level of cities, were selected to indirectly reflect the ecological progress of sustainable development.

Negative indicators were converted to positive indicators using the treatment method designed by Ye (2003). The positive treatment of the negative indicators is as follows:

$$y_{ij} = \max_{1 \le i \le n} \left\{ x_{ij} \right\} - x_{ij} \tag{7}$$

where $x_{ij}$ represents the $j$th original indicator value of the $i$th city, $y_{ij}$ is the $j$th indicator value of the $i$th city after normalization, and $\overline{x_{ij}}$ is the average value of the $j$th indicator. Finally, principal component analysis $eqd_{it}$ was used to reduce the dimensions and generate a comprehensive index of sustainable development.

#### *Core explanatory variable*

Construction of the GDF variables. In this study, the digital finance index in the green finance pilot zones is adopted as the core explanatory variable and is measured using the interactive term of the DID dummy variable and the digital finance variable,$gdf_{it}$. It is specifically expressed as the product of a city in the pilot zone, the year the policy was implemented in the pilot zone, and the digital finance index $gdf_{it} = Treated \times Time \times ifi$. In this equation, *Treated* is the dummy variable identifying a pilot-zone city, 1 if the city is in any of the eight pilot zones in five provinces (regions)[6] and 0 if it is not; *Time* is the dummy variable for policy implementation, 1 if it falls within the implementation period (2017 and later) and 0 if it falls before 2017; and *ifi* is the value of the digital finance development index divided by 100, sourced from the *Peking University Digital Inclusive Finance Index (2011–2020)* of the Institute of Digital Finance, Peking University (Guo et al. 2021). Thus, the core explanatory variable $gdf_{it}$ is a digital finance variable representing whether city $i$ implemented a green finance policy for pilot zones in year $t$. If city $i$ was affected by the pilot zone policy in year $t$, there was a specific value; otherwise, the value was zero.

#### *Mechanism variables*

As analyzed above, it is theoretically assumed that the policies of the pilot zone can be used to transform the industrial structure through two channels: financial inclusion and energy transition, thereby promoting sustainable development. Therefore, in this study, the financial inclusion variable (*fin*) and the energy transition variable (*es*) are adopted as two specific acting channels of GDF in the pilot zone on industrial structure. The variable transformation and upgrading of industrial structure (*adi*) represents the general mechanism for the policies in the pilot zone affecting sustainable development. In this case, the financial inclusion variable (*fin*) is measured by the log value of the ratio of the balance of deposits and loans of financial institutions to the population at the end of the year, since it is generally assumed that the more adequate the capital supply, the greater the financial inclusion. The energy transition variable (*es*) is measured by the green negative energy structure index, that is, the ratio of coal consumption to total energy consumption. Finally, the variable of transformation and upgrading of industrial structure (*adi*) is measured by the degree of industrial structure coordination, referring to the calculation used by Gan et al. (2011), where the difference between 1 and the Theil index *tl* is multiplied by 100.

[6] Considering that the launch dates of the second and third batches of pilot zones are recent (November 2019 and August 2022, respectively) and that the relevant data of Hami City and Changji Hui Autonomous Prefecture of Xinjiang Uygur Autonomous Region are severely lacking among the first pilot zone cities, the other eight cities in the five provinces of the first pilot zones are used as the treatment group sample. These eight cities are Huzhou, Quzhou, Karamay, Anshun, Guiyang, Guangzhou, Nanchang, and Jiujiang.

$$adi = 100 \times (1 - tl) = 100 - 100 \times \sum_{i=1}^{n} \left(y_i/y\right) \ln\left(\frac{y_i}{l_i}/\frac{y}{l}\right) \quad (8)$$

where $y$ is the total output; $l$ is the number of employees; and $y_i$ and $l_i$ are the added value and number of employees in the primary, secondary, and tertiary industries, respectively ($i = 1, 2, 3$).

#### *Control variables*

With reference to the factors that may affect China's high-quality sustainable development and the integrity of available data in previous research (Fu and Cao 2021), the control variables selected in this study include population size (*pop*), which constitutes the basis of labor and consumption and plays a vital role in regional economic development. This was measured using the log value of the number of permanent urban residents. The real estate investment level (*inv*) is measured using the log value of real estate development investments, as they account for a large proportion of urban investments and have a significant impact on urban economic development. Government intervention (*gov*) is a fiscal budgetary expenditure that can affect economic development directly through the multiplier effect or indirectly through the degree of regional marketization. The industrialization level (*inl*) is an important symbol of modernization and a necessary prerequisite for rapid economic growth; the industry is measured by the proportion of the added value of the secondary industry to the regional GDP.

### Samples and data sources

To empirically demonstrate the impact of policies in the pilot zone at the city level on sustainable development in Eq. (6), this study uses data from 2014 to 2020 to limit the research period. In combination with data availability, 285 cities were selected for inclusion in the sample, eight of which were policy-participating and were used in the treatment group; the other 277 cities in the non-pilot zones were the control group. Data on sustainable development index measurement, deposit and loan balances in financial institutions, coal consumption, energy consumption, regional GDP, added value of the secondary industry, output value of the tertiary industry, number of permanent urban residents, real estate development investment, fiscal budget expenditure, and other proxy variables were derived from the *China Urban Statistical Yearbook* (2015–2021), CSMAR Database, and Wind Database. The digital finance development index is sourced from the *Peking University Digital Inclusive Finance Index (2011–2020)* of the Institute of Digital Finance, Peking University. The descriptive statistical characteristics of the main variables are shown in Table 4.

## Empirical analysis

### Benchmark regression

#### *Parallel trend test*

The parallel trend is a necessary condition for DID estimation (Fu et al. 2015); that is, sustainable development trends in pilot-zone and non-pilot-zone cities must be parallel. There were significant differences in the sustainable development trends between

**Table 4** Descriptive statistics of variables

| Variable | Observations | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| *eqd* | 1995 | 3.0140 | 0.9013 | 0.1110 | 8.2398 |
| *gdf* | 1995 | 0.0419 | 0.3294 | 0 | 3.1034 |
| *ifi* | 1995 | 2.1045 | 0.4266 | 1.0561 | 3.3448 |
| *ific* | 1995 | 2.0007 | 0.4322 | 1.0337 | 3.2649 |
| *ifiu* | 1995 | 2.0466 | 0.5236 | 0.7106 | 3.4975 |
| *ifid* | 1995 | 2.5524 | 0.4351 | 1.3465 | 5.8123 |
| *pop* | 1995 | 5.8771 | 0.6988 | 3.1191 | 8.0938 |
| *inv* | 1995 | 14.3724 | 1.2574 | 9.7211 | 17.6654 |
| *gov* | 1995 | 15.0467 | 0.7365 | 12.0587 | 18.2405 |
| *inl* | 1995 | 43.8378 | 11.1903 | 10.4074 | 80.0700 |
| *es* | 1995 | 34.9936 | 11.8343 | 0.0166 | 64.2154 |
| *fin* | 1995 | 11.4917 | 0.7337 | 9.7788 | 15.3782 |
| *adi* | 1995 | 8.8648 | 5.6006 | 1.5019 | 47.9644 |

the two types of cities. In this study, the event study method (Jacobson et al. 1993) was used to test for parallel trends in policy implementation. The test results are expressed as follows:

$$eqd_{it} = \alpha_2 + \sum_{t=-3}^{3} \theta X_{it} + \sum \gamma_j cro_{it}^j + \mu_i + \lambda_t + \varepsilon_{it} \tag{9}$$

where $X_{it}$ is a dummy variable indicating whether the policies in the pilot zone were implemented in city i in year t, with 1 indicating that the policies were implemented, and 0 otherwise. The other proxy variable coefficients have the same meaning as in Eq. (6). In the event study method, the coefficient $\theta$ should be used to test for parallel trends, representing the difference in GDF development between pilot-zone and non-pilot-zone cities in the t-th year of implementation of the pilot zones.

In this study, data from before the implementation of the policy were used as a reference; those before the implementation of the policy were divided into Phases -1 and -2, the year of the implementation of the policy was the time point period, and those after the implementation of the policy were divided into Phases 1 to 3. The results of the parallel-trend tests are shown in Fig. 2. The estimated value of the urban coefficient $\theta$ is nonsignificant before the implementation of the policy but is significant with a positive upward trend after policy implementation in the pilot zone, indicating its positive impact.

The hollow dots represent the estimated coefficient θ of Eq. (9), and the dotted lines represent the upper and lower bounds of the 95% confidence interval.

### *Benchmark regression results*

Table 5 lists the regression results of Model (6), which tested the impact of the GDF level on sustainable regional development. Columns (1) and (2) represent measurements taken with no control variables added. The regression results of the core explanatory variables in the current period are shown in Columns (1) and (2). The *gdf* coefficient is significantly positive regardless of whether a two-way fixed effect is adopted, indicating that GDF policy promotes sustainable urban development. Then, as shown in Fig. 2, the

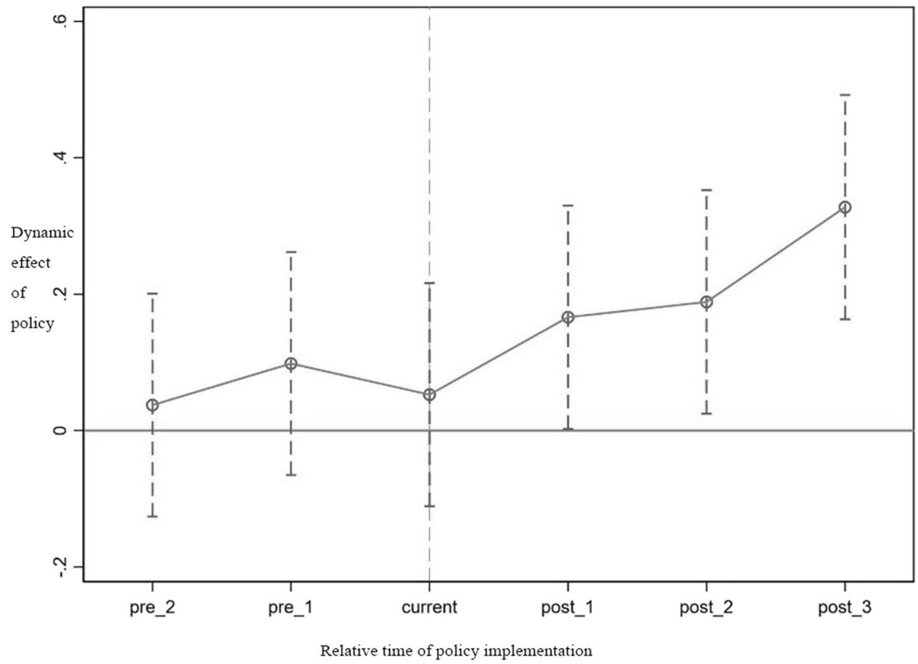


**Fig. 2** Parallel trend test

effect of the policy began to appear in the post-policy period, beginning at post_1. Given that the pilot zone was launched on June 23, 2017, it will take time for companies to change their business strategies. Therefore, it is necessary to verify the hysteresis of the policy effect in empirical regression. In addition, $gdf_{-1}$ of the core explanatory variable with a lag phase is selected for regression, and the results are shown in Columns (3) and (4). The results show that the core explanatory variables are significant within the 1% confidence level in the current period and the lag period, and the impact coefficient of the lag period is larger than that of the current period, indicating that there is a certain lag in the effects of GDF policy. Therefore, $gdf_{-1}$ is selected as the core explanatory variable in the following paper (considering that the establishment of the experimental area is relatively short and the data span is limited, validation is no longer considered at delays of two or more periods). Comparing Columns (3) and (4), the $gdf_{-1}$ coefficient is significantly positive regardless of whether a two-way fixed effect is adopted, and the empirical results in Column (4) under the two-way fixed effect condition with the most rigorous control conditions are selected for analysis of economic significance. When other factors remain unchanged after the implementation of the GDF policy in the pilot area, the urban sustainable development index increases by 0.0619 units.

#### Heterogeneity analysis

According to the *Green Finance Reform Plan* for each pilot zone issued by seven ministries and commissions under the State Council, including the People's Bank of China, the main working objectives for each pilot zone are consistent with the fundamentals of green finance reform and innovation. Driven by the innovative development of green finance, the baseline objectives are to promote green transformation and industry upgrading, focus on institutional innovation, give full play to the decisive role of

**Table 5** Benchmark regression results

| Variable | *eqd* | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| *gdf* | 0.0529*** | 0.0504*** | | |
| | (0.0174) | (0.0172) | | |
| $gdf_{-1}$ | | | 0.0681*** | 0.0619*** |
| | | | (0.0188) | (0.0188) |
| *ifi* | 0.5300*** | 0.4915*** | 0.6117*** | 0.4942*** |
| | (0.0176) | (0.0812) | (0.0217) | (0.1017) |
| *pop* | 0.2643*** | 0.2730*** | 0.2535*** | 0.2741*** |
| | (0.0711) | (0.0722) | (0.0787) | (0.0826) |
| *inv* | 0.0953*** | 0.0766*** | 0.0518*** | 0.0471*** |
| | (0.0141) | (0.0144) | (0.0170) | (0.0172) |
| *gov* | 0.0857*** | 0.0700*** | 0.0605** | 0.0355 |
| | (0.0297) | (0.0299) | (0.0317) | (0.0323) |
| *inl* | − 0.0016*** | − 0.0007 | − 0.0020** | − 0.0012 |
| | (0.0022) | (0.0009) | (0.0010) | (0.0011) |
| Constant | − 10.8952*** | − 1.7632*** | − 1.3574** | − 0.8683 |
| | (1.6092) | (0.5839) | (0.6694) | (0.6739) |
| Firm | Yes | Yes | Yes | Yes |
| Year | No | Yes | No | Yes |
| Observations | 1995 | 1995 | 1710 | 1710 |
| Adjusted $R^2$ | 0.7065 | 0.7173 | 0.6495 | 0.6562 |

The coefficient values in parentheses are the standard errors of the corresponding regression coefficient

***, **, *Significance levels at 1%, 5%, and 10%, respectively, the same below

the market in capital output and resource allocation, and better deploy government resources to promote sustainable regional development. In addition, the selected pilot zones were fully representative because the selection considered different stages of economic development between regions and spatial conditions. Pilot zones were selected across eastern, central, and western China and spanned first- to fifth-tier cities, each of which actively explored the construction of a green financial system based on its own characteristics. This allows the different impacts of GDF policies on sustainable development in different regions to be well analyzed. The level of sustainable development is not only affected by the city level and geographical location, but also shows different development characteristics due to differences in resource endowment and production efficiency. In view of this, to further study the individual differences in policy effects under different economic and social characteristics and resource factor endowments, four heterogeneity factors were selected for investigation. First, vertical differences in city levels: city levels were divided into one- to five-tier cities. Second, there are geographical differences in the horizontal regions. It is divided into three parts according to the province in which the city is located: the eastern, central, and western regions. Third, there are differences in resource endowments. The sample cities were divided into resource-based and non-resource-based cities, according to the Notice of the National Sustainable Development Plan for Resource-Based Cities (2013–2020) issued by the State Council in

2013.[7] Fourth, there is an efficiency difference in urban green development. By measuring green total factor productivity (GTFP) using the Super Efficiency SBM Model (Liu et al. 2023), the high and low comparison of total factor productivity with the median is divided into high and low GTFP cities.

#### *Heterogeneity of vertical differences*

There are differences in the impact of the GDF policies on the sustainable development of cities at different levels. Owing to the different resource endowments and strategic positioning for national development in each city, the development stages and scales of these cities differ, as do the development conditions of the GDF in cities at different levels. In addition, the pilot zones were distributed across cities of different levels, and development experience in the GDF was mainly accumulated in cities at different levels. Based on the above, this section analyzes the heterogeneity of the impacts of GDF pilot-zone policies on the sustainable development of cities at different levels.

Table 6 lists the regression results for heterogeneity in vertical differences. First, there are 49 first- and second-tier cities, including three in the treatment group, which are Guangzhou, Guiyang, and Nanchang. The regression results show that the coefficient is positive but nonsignificant. According to the *Master Plan for the Construction of Green Finance Reform and Innovation Pilot Zones*[8] and the corresponding data analysis, these pilot-zone cities mainly undertake tasks such as establishing a green finance organization system, expanding the financing channels for green industries, innovating and developing green finance products and services, and building data processing centers and disaster recovery centers at a top administrative level. It takes even longer to demonstrate the impact of these tasks on sustainable development. Second, there are 70 third-tier cities, including two in the treatment group, which are Huzhou and Jiujiang. The regression results show that the coefficient is positive but still nonsignificant. The reason lies mainly in the fact that the two pilot-zone cities shoulder similar tasks as those in the first- and second-tier cities, such as establishing a green finance organization system, supporting financial institutions in setting up green franchises, researching and offering green bank ratings using digital technology, expanding green industry financing channels, supporting financial institutions in issuing green financial bonds, developing green insurance, and establishing a green credit system. At present, the two cities have made remarkable achievements in ecological improvements within the framework of the GDF policies. For example, Huzhou has seen an increase in average air quality of 19.20 percentage points over the past five years compared to the initial phase of the implementation of the pilot project in 2017. Jiujiang City has received praise from experts for the development of the Poyang Lake Scenic Spot and low-carbon fisheries. However, green finance policies still need to be digitized for a certain number of existing economic resources to promote the development of the environment and industrial transformation, and the substitution effect of environmental changes on economic development takes longer to be seen. Third, through a general analysis, the reasons why the policy impact coefficient

[7] Source: *Notice of National Sustainable Development Plan for Resource-Based Cities (2013–2020)* issued by the State Council, https://www.gov.cn/zfwj/2013-12/03/content_2540070.htm

[8] Source: Website of the People's Bank of China (www.pbc.gov.cn).

**Table 6** Heterogeneity of vertical differences

| Variable | *eqd* | | | |
|---|---|---|---|---|
| | **First, second-tier cities** | **Third-tier cities** | **Fourth-tier cities** | **Fifth-tier cities** |
| $gdf_{-1}$ | 0.0363 | 0.0457 | 0.0272** | 0.2487*** |
| | (0.0348) | (0.0391) | (0.0109) | (0.0543) |
| *ifi* | 0.8435** | 0.0539 | 0.5096*** | 0.8530*** |
| | (0.3508) | (0.2400) | (0.1770) | (0.1996) |
| *pop* | 0.4288* | 0.1058 | 0.1970 | 0.5669*** |
| | (0.2532) | (0.2062) | (0.1432) | (0.1794) |
| *inv* | − 0.1501 | − 0.0752 | 0.0861*** | 0.0672*** |
| | (0.0950) | (0.0464) | (0.0275) | (0.0235) |
| *gov* | − 0.1548 | 0.1266* | 0.1204** | 0.0019 |
| | (0.1832) | (0.1186) | (0.0500) | (0.0421) |
| *inl* | − 0.0058 | − 0.0048 | − 0.0004 | 0.0006 |
| | (0.0048) | (0.0025) | (0.0016) | (0.0015) |
| Constant | 4.6123 | 1.6323 | − 2.4290* | − 3.256 |
| | (3.1368) | (2.1564) | (1.0456) | (1.1147) |
| Firm | Yes | Yes | Yes | Yes |
| Year | Yes | Yes | Yes | Yes |
| Observations | 294 | 420 | 492 | 504 |
| Adjusted $R^2$ | 0.6690 | 0.6642 | 0.7709 | 0.6276 |

in the first-, second-, and third-tier pilot-zone cities is nonsignificant are analyzed as follows: First, there is a relatively short implementation period for the policies in the pilot zones. The planning period for complete policy implementation in the pilot zones is five years, and the data period used in this paper ends two years before the anticipated completion date. Second, the large economic scale of high-level cities complicates the situation, as the policies in the pilot zones require a long time to be thoroughly implemented socioeconomically. Therefore, in first-, second-, and third-tier cities, pilot-zone policies require a long time to highlight the positive impact of GDF development on sustainable development.

There were 82 fourth-tier cities, including two in the treatment group—Anshun City and Quzhou City—and 84 fifth-tier cities, including one in the treatment group—Karamay City. The regression results for all fourth- and fifth-tier cities were significantly positive, indicating the positive impact of the policies in the pilot zone on the sustainable development of these cities. In particular, these results have a larger coefficient of impact on fifth-tier cities than on higher ones, suggesting that the promoting effect of the GDF on sustainable development is, in turn, more significant in low-tier cities. This is because of the phased discrepancy between the social and economic development of fourth- and fifth-tier cities and that of high-tier cities. First, low-tier cities have relatively simple industrial characteristics and social structures; therefore, it seems easier for GDF policies to play a role in these cities. For instance, compared with large cities, small towns with green industrial characteristics and small and medium green cities built with the support of the GDF are easier to transform, and progress in green buildings and green infrastructure is more evident. Objectively, it is easier to select different financing tools for GDF, encourage small and medium cities and characteristic towns to adopt construction and heating methods featuring clean energy and energy conservation, and complete joint pollution prevention and control systems for air, soil, rivers, and other water environments. GDF policies have effectively promoted comprehensive reform for small and medium cities and characteristic towns in the pilot zones and have accelerated the intensive, compact, efficient, and green development of urban and rural areas in the pilot zones. Second, low-tier cities have tight funding channels for green transformation and relatively few policy tools. GDF policies in the pilot zones can expand financing channels and diversify policy tools for local green transformation. In general, low-tier cities are characterized by low institutional barriers, low historical burdens, and prominent economic characteristics. In these cities, it will be easier to develop the GDF according to regional characteristics by expanding and diversifying green financing channels and innovating green financial products to meet local green transformation financing needs in a timely and efficient manner. Therefore, the GDF policies in low-tier pilot zones produce a relatively large marginal effect on the promotion of local sustainable development.

#### *Heterogeneity of horizontal regions*

There are differences in the impact of the GDF pilot-zone policies on sustainable development in different regions. Given that pilot-zone cities have been designated in the eastern, central, and western regions of China, it must be considered that economic development is unbalanced across regions and that different regions have different industrial structures and resource endowments. Therefore, in this section, the heterogeneity of the GDF pilot-zone policies on the sustainable development of the three regions is tested to examine their impact under different development conditions.

Table 7 lists the regression results for horizontal heterogeneity. The regression results show that the GDF pilot-zone policies have a significantly positive impact on the sustainable development of cities in the eastern and western parts of China but a nonsignificant impact on cities in the central part of the country. The impact coefficient of the GDF pilot-zone policies on the sustainable development of cities in the eastern part of China is lower than the national average, and that in the western part of China is higher than the national average, indicating regional differences in the promotion effect of the GDF policies. Eastern China has generally chosen to trade growth at the expense of the environment in past development. Long-term overinvestment has hampered the positive effect of the GDF pilot-zone policies on sustainable development, making the impact coefficient slightly lower than that for the western region, which has sparsely populated land, an agriculturally focused economy, and recent plans to strengthen the protection of ecological resources. The green environmental protection of GDF and the financial inclusion attribute of digital finance are in line with the theme of sustainable development in the western region, which appears to be more suited to the development of GDF (Fang and Lin 2019). Nanchang and Jiujiang are pilot-zone cities in the central region. The impact of the GDF pilot-zone policies is nonsignificant due to the focus on the long-term benefits to the ecological economy of local development. Furthermore, the promoting effect of GDF on sustainable development takes some time to be seen.

**Table 7** Heterogeneity of horizontal (regional) differences

| Variable | *eqd* | | | |
|---|---|---|---|---|
| | **Eastern** | **Central** | **Western** | **Nationwide** |
| $gdf_{-1}$ | 0.0629* | 0.0024 | 0.0872*** | 0.0619*** |
| | (0.0339) | (0.0284) | (0.0308) | (0.0188) |
| *ifi* | 0.1530 | 1.6546*** | 0.3648** | 0.4942*** |
| | (0.1920) | (0.1415) | (0.2202) | (0.1017) |
| *pop* | 0.3213** | 0.4450*** | 0.0686 | 0.2741*** |
| | (0.1500) | (0.1245) | (0.1510) | (0.0826) |
| *inv* | − 0.0215 | 0.0635** | 0.0338 | 0.0471*** |
| | (0.0405) | (0.0253) | (0.0233) | (0.0172) |
| *gov* | 0.0640*** | 0.3004*** | 0.0110 | 0.0355 |
| | (0.1171) | (0.0873) | (0.0342) | (0.0323) |
| *inl* | − 0.0013 | − 0.0023* | 0.0019 | − 0.0012 |
| | (0.0025) | (0.0014) | (0.0016) | (0.0011) |
| Constant | 0.3962 | − 8.0013*** | 0.5782 | − 0.8683 |
| | (1.9232) | (1.4230) | (0.9927) | (0.6739) |
| Firm | Yes | Yes | Yes | Yes |
| Year | Yes | Yes | Yes | Yes |
| Observations | 606 | 600 | 504 | 1710 |
| Adjusted $R^2$ | 0.5807 | 0.7680 | 0.7494 | 0.6562 |

#### *Heterogeneity of different resource endowments and GTFP*

The impact of the GDF pilot zone policies on the sustainable development of cities with different resource endowments and GTFP in pilot areas is different, and the specific regression results are shown in Table 8. The implementation of the GDF pilot zone policies has a positive impact on the sustainable development level of both resource- and non-resource-based cities. The effect on resource-based cities is significant at the 1% level, and the regression coefficient is larger. This shows that the GDF pilot-zone policies have a more obvious effect on the transformation and upgrading of resource-based cities with high energy consumption, high-pollution enterprises, and traditional industries, and the effect of easing the dilemma of industrial structural constraints is stronger. Thus, it can promote the sustainable development of the region. From the results of the policy impact in different regions under different GTFP levels, the influence coefficient was positive regardless of the regional GTFP level. However, the effect of high GTFP in the region is significant at the 1% level, and the regression coefficient is larger. The results show that high-GTFP cities, relying on GDF pilot-zone policies, have more effectively promoted green and clean production and technological innovation, opened up a new path for economic development and environmental optimization, and can continuously and stably drive financial support for green innovation, drive the transformation and upgrading of industrial structures, and achieve sustainable regional economic development. Therefore, the regression coefficient was significantly higher than that of low-GTFP cities.

**Table 8** Heterogeneity of different resource endowments and GTFP

| Variable | *eqd* | | | |
|---|---|---|---|---|
| | **Resource-based** | **Non- resource-based** | **High-GTFP** | **Low-GTFP** |
| $gdf_{-1}$ | 0.0913*** | 0.0292 | 0.1058*** | 0.0143 |
| | (0.0309) | (0.0203) | (0.0285) | (0.0209) |
| *ifi* | 0.5548*** | 0.4520*** | 0.4773*** | 0.4893*** |
| | (0.1331) | (0.1064) | (0.1155) | (0.1157) |
| *pop* | 0.1571 | 0.3685*** | 0.1853* | 0.3614*** |
| | (0.1300) | (0.0907) | (0.1022) | (0.1025) |
| *inv* | 0.0918*** | 0.0554*** | 0.0834*** | 0.0579*** |
| | (0.0207) | (0.0207) | (0.0195) | (0.0221) |
| *gov* | 0.1079* | 0.0566* | 0.0743** | 0.0677 |
| | (0.0651) | (0.0329) | (0.0369) | (0.0560) |
| *inl* | − 0.0006 | − 0.0012 | 0.0009 | − 0.0024* |
| | (0.0014) | (0.0013) | (0.0014) | (0.0013) |
| Constant | − 2.1183* | − 1.6415** | − 1.4405* | − 1.9212** |
| | (1.1365) | (0.7205) | (0.7727) | (0.9778) |
| Firm | Yes | Yes | Yes | Yes |
| Year | Yes | Yes | Yes | Yes |
| Observations | 812 | 1183 | 994 | 1,001 |
| Adjusted $R^2$ | 0.6686 | 0.7531 | 0.6772 | 0.7610 |

## Robustness tests

### *Propensity score matching and difference-in-differences (PSM-DID)*

This method applies to endogeneity problems that may arise from sample selection and reverse causality. Because the dependent proxy variable used to measure urban sustainable development is a comprehensive index generated using principal component analysis, it is difficult for the variable to affect the GDF pilot zone policies as an explanatory variable, which largely eases the endogeneity of the econometric model. Additionally, it was found through PSM-DID models testing endogeneity and robustness that the estimated value of the $gdf_{-1}$ coefficient passed the significance test at levels of 10% and 1% for both the closest matching method and the kernel matching method. The regression results are shown in Table 9. This further shows that the GDF policies in the pilot zone have driven sustainable development in the city.

### *The procedure for replacing explanatory variables*

According to the construction of the GDF index mentioned above, $gdf_{it}$ is specifically expressed as the interactive term of the pilot zone city, active policy implementation, and the digital finance index, or $gdf_{it} = Treated \times Time \times ifi$. where *ifi* has three sub-indices: *ific* digital finance coverage breadth, *ifiu* digital finance use depth, and *ifid* digital finance digitization degree. Three sub-indices of GDF development were constructed according to the method used to construct the above GDF proxy variable: coverage of GDF $gdfc_{it} = Treated \times Time \times ific$, service depth $gdfu_{it} = Treated \times Time \times ifiu$ and degree of digitization $gdfd_{it} = Treated \times Time \times ifid$. According to the regression results of the new explanatory variables in Table 10, the regression results of the three

**Table 9** PSM-DID regression results

| Variable | *eqd* | |
|---|---|---|
| | **CM** | **KM** |
| *gdf* | 0.1718* | 0.0628*** |
| | (0.4210) | (0.0188) |
| *ifi* | 1.4036* | 0.4684*** |
| | (0.6973) | (0.1019) |
| *pop* | -0.2602 | 0.2625*** |
| | (0.3547) | (0.0836) |
| *inv* | -0.2230 | 0.0439** |
| | (0.1149) | (0.0177) |
| *gov* | -0.4130 | 0.0388 |
| | (0.3431) | (0.0324) |
| *inl* | -0.0046 | -0.0012 |
| | (0.0067) | (0.0011) |
| Firm | Yes | Yes |
| Year | Yes | Yes |
| Observations | 1710 | 1710 |
| Adjusted $R^2$ | 0.6541 | 0.6556 |

sub-indices are significantly positive, indicating the robustness of the conclusion that the GDF pilot zone policies promote sustainable urban development. In addition, the coverage breadth coefficient was the largest, indicating a larger marginal contribution to sustainable development in the current phase.

#### *Urban placebo test*

With reference to the method used by Cai et al. (2016), a placebo test was conducted by randomly replacing cities in the treatment group to avoid the impact of unobservable missing variables on the basic regression results. The urban placebo method consisted of randomly selecting eight cities from the sample as the false treatment group and using the other cities as the false control group in the DID analysis to estimate the coefficient of the impact of pilot zone policies on sustainable development. In this study, the urban placebo method was repeated 1,000 times, and the test results are shown in Fig. 3. The distributions of the kernel density and p-values were then plotted. In the plot, the x-axis represents the estimated coefficient value of the variables of GDF, the y-axis represents the density value and p-value, the curve shows the kernel density distribution of the estimated coefficient, and the blue dot is the p-value of the estimated coefficient. The vertical dotted line shows the basic regression estimate of 0.0619, and the horizontal dotted line has a significance level of 0.1. According to the plot, the regression coefficients follow a normal distribution with 0 at the center, and most of the p values are greater than 0.1 (nonsignificant at the 10% level). The value of the baseline regression coefficient is on the right side of the normal distribution of the plot of false regression coefficients and is significant, indicating that the estimation result is non-accidental. Therefore, it can be concluded that the excludable basic estimation results were caused by the impact of unobservable factors.

**Table 10** Replacing explanatory variables in the benchmark regression

| Variable | $gdf_{-1}$ | $gdfc_{-1}$ | $gdfu_{-1}$ | $gdfd_{-1}$ |
|---|---|---|---|---|
| *eqd* | 0.0619*** | 0.0669*** | 0.0569*** | 0.0547*** |
| | (0.0188) | (0.0195) | (0.0184) | (0.0171) |
| Control Variable | Yes | Yes | Yes | Yes |
| Constant | -0.8683 | -0.8857 | -0.8883 | -0.8769 |
| | (0.6739) | (0.6737) | (0.6741) | (0.6740) |
| Firm | Yes | Yes | Yes | Yes |
| Year | Yes | Yes | Yes | Yes |
| Observations | 1710 | 1710 | 1710 | 1710 |
| Adjusted $R^2$ | 0.6562 | 0.6564 | 0.6559 | 0.6561 |

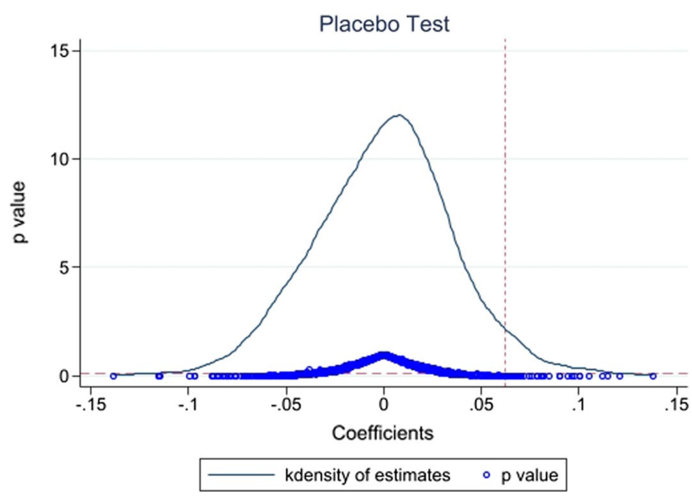


**Fig. 3** Urban placebo test

#### *Acting mechanism test*

According to the theory described above, this section divides the impact of pilot zone policies on sustainable development into two stages for mechanism analysis and extends the mediating effect test method used by Hayes (2009) into two stages of progressive mediating effect tests for verification. In the first stage, the GDF pilot zone policies promote the transformation and upgrading of the industrial structure through financial inclusion and energy transition effects. Thus, the variables of financial inclusion and energy transition are tested as two specific channels of impact on industrial transformation and upgrading. In the second stage, sustainable development is further influenced by the transformation of the industrial structure; therefore, the variable for the transformation and upgrading of the industrial structure is tested as an intermediary mechanism through which the GDF pilot-zone policies impact sustainable development.

### Financial inclusion and energy transition effects

#### *Financial inclusion effect*

First, the financial inclusion effect was verified and represents the impact of the GDF pilot zone policies on the transformation and upgrading of the industrial structure by

**Table 11** Financial inclusion and energy transition effects

| Variable | (1)<br>*adi (path c)* | (2)<br>*fin (path a)* | (3)<br>*adi (paths c′ and b)* | (4)<br>*es (path a)* | (5)<br>*adi (paths c′ and b)* |
|---|---|---|---|---|---|
| $gdf_{-1}$ | 0.5661** | 0.2338*** | 0.0882 | -0.9248*** | 0.4672*** |
| | (0.1650) | (0.0229) | (0.1641) | (0.2505) | (0.1636) |
| *fin* | | | 2.0438*** | | |
| | | | (0.1842) | | |
| *es* | | | | | -0.1069*** |
| | | | | | (0.0173) |
| Control Variable | Yes | Yes | Yes | Yes | Yes |
| Firm | Yes | Yes | Yes | Yes | Yes |
| Year | Yes | Yes | Yes | Yes | Yes |
| Observations | 1710 | 1710 | 1710 | 1710 | 1710 |
| Adjusted $R^2$ | 0.9381 | 0.9257 | 0.9430 | 0.9657 | 0.9397 |
| The p value of the indirect effect | | 0.0000 | 0.0015 | | |

increasing urban financial inclusion. Column (2) of Table 11 shows the estimated results of the impact of GDF pilot zone policies on the development of financial inclusion. The $gdf_{-1}$ coefficient is 0.2338, which passes the significance test at the 1% level, indicating that the pilot zone policies are conducive to the inclusive development of urban finance. According to the estimated results of the impact of financial inclusion in Column (3) of Table 11, the *fin* coefficient is 2.0438, which passes the significance test at the 1% level, indicating that financial inclusion can promote the transformation and upgrading of the industrial structure. The comprehensive indirect effect result shows that the p-value is 0.0000, passing the significance test at the 1% level, demonstrating that the financial inclusion effect serves as an intermediary mechanism between the GDF pilot-zone policies and industrial transformation with a positive impact. This also indicates that the GDF pilot-zone policies promoted the transformation and upgrading of the industrial structure.

#### *Energy transition effect*

First, the energy transition effect is verified and represents the impact of the GDF pilot zone policies on the transformation and upgrading of the industrial structure by promoting urban energy transition. Column (4) of Table 11 shows the estimated results of the impact of GDF pilot zone policies on the upgrading and transformation of industries. The $gdf_{-1}$ coefficient is -0.9248, which passes the significance test at the level of 1%, indicating that the GDF pilot-zone policies can optimize the energy structure by effectively restricting the use of coal energy and promoting the development of clean energy. According to the estimated results of the impact of energy structure optimization in Column (5) of Table 11, the *fin* coefficient is -0.1069, which passes the significance test at the 1% level, indicating that coal energy hinders industrial transformation and upgrading. The comprehensive indirect effect result shows that the p-value is 0.0015, passing the significance test at the 5% level, demonstrating that the energy transition effect serves as an intermediary mechanism between the GDF pilot-zone policies and industrial

**Table 12** Industrial structure transformation and upgrading mechanisms

| Variable | (1)<br>*eqd (path c)* | (2)<br>*adi (path a)* | (3)<br>*eqd (paths c′ and b)* |
|---|---|---|---|
| $gdf_{-1}$ | 0.0619*** | 0.5661** | 0.0567*** |
| | (0.0188) | (0.1650) | (0.0187) |
| *adi* | | | 0.0091*** |
| | | | (0.0030) |
| Control Variable | Yes | Yes | Yes |
| Firm | Yes | Yes | Yes |
| Year | Yes | Yes | Yes |
| Observations | 1710 | 1710 | 1710 |
| Adjusted $R^2$ | 0.9678 | 0.9381 | 0.9680 |
| The p value of the indirect effect | | 0.0236 | |

upgrading with a positive impact. This also indicates that the GDF pilot-zone policies promoted the transformation and upgrading of the industrial structure.

### Industrial structure transformation and upgrading mechanism

According to the above theoretical analyses, the impact of the GDF pilot-zone policies on sustainable development is further verified by the industrial transformation mechanism below. Column (2) of Table 12 shows the estimated results of the impact of pilot zone policies on the transformation and upgrading of the industrial structure. The $gdf_{-1}$ coefficient is 0.5661, which passes the significance test at the 1% level, indicating that the GDF pilot zone policies are conducive to the transformation and upgrading of the industrial structure. According to the estimated results of the impact of the transformation of industrial structure on sustainable development in Column (3) of Table 12, the *adi* coefficient is 0.0091, which passes the significance test at the 1% level, indicating that increased financial inclusion can promote sustainable development. The comprehensive indirect effect result has a p-value of 0.0236, which means that it passes the significance test at the 5% level, demonstrating that the transformation and upgrading of the industrial structure serve as an intermediary mechanism between GDF pilot-zone policies and industrial transformation with a positive impact. This also indicates that the GDF pilot-zone policies promoted the transformation and upgrading of the industrial structure.

## Conclusions

The GDF pilot zone policies are an important step in sustainable development. In this study, the implementation of GDF pilot zone policies was viewed as a quasi-natural experiment. First, the theoretical mechanism of the impact of the GDF policies on sustainable development was explored. Then, a DID model was used to evaluate the impact of GDF policies on sustainable development in the pilot zones based on relevant data from 2014 to 2020. A series of heterogeneity and robustness tests were conducted, and the theoretical mechanism was empirically tested using a two-step progressive intermediary method. The main conclusions are as follows:

First, the GDF pilot zone policies can promote sustainable development. Evaluated at the prefecture level, the GDF pilot zone policies effectively promoted sustainable development. Compared with non-pilot-zone cities, cities that implemented GDF pilot-zone policies increased their urban sustainable development index by 0.0619. The robustness of this conclusion was validated using the parallel trend test, PSM-DID estimations, replacement of relevant explanatory variables, and the urban placebo method.

Second, the impact of the GDF pilot-zone policies on the sustainable development of cities at different levels, locations, resource endowments, and GTFP is heterogeneous. Based on the current policy effect, the GDF pilot-zone policies have a more obvious effect on resource-based cities, high-GTFP cities, low-level cities, and western and eastern cities.

Finally, the GDF pilot zone policies promote the transformation and upgrade of industrial structures through financial inclusion and energy transition effects, which can further promote sustainable development. The financial inclusion effect of the GDF addresses the challenge of insufficient capital supply through solutions available in the green industry, while the energy transition effect resolves the reasonable allocation of resources, both contributing to the transformation and upgrading of the industrial structure as one mechanism of the GDF pilot-zone policies that promote sustainable development.

Based on these conclusions, the policy implications of this study are as follows:

First, we summarize the experiences of GDF pilot zone policies and promote capacity expansion over time. The establishment of pilot zones was a unique path toward China's progressive reform. In areas where conditions allow, unprecedented experiments are conducted and reform experiences are researched to provide replicable practices for other regions; specifically, sustainable development is promoted through the development of GDF. Therefore, it is necessary to draw experiences from the ten pilot zones across eastern, central, and western China in a timely manner and apply successful practices to other areas in China or the world on a larger scale to gain experience with global GDF in facilitating sustainable development. Simultaneously, pilot zones should be strategically expanded through the establishment of the Northeast Green Finance Reform and Innovation Pilot Zone. Pilot zones have been established in the southeastern, northwestern, southwestern, and central regions of China; however, there are no pilot zones in the northeastern region.

Second, it is guided by greater marginal benefits, the targeted selection of expansion pilot areas, and the promotion of GDF-related policies. To accelerate the realization of sustainable development and achieve new breakthroughs, priority can be given to regions where the marginal effect of GDF policies is greater for the expansion or promotion of relevant policies, and the positive effect of GDF in promoting sustainable development can be expanded. According to this study, cities with a high GTFP among low-level and resource-based cities in the western or eastern regions are preferred for expanding or promoting relevant policies.

Third, construction of the GDF infrastructure should be accelerated. Despite the negative impacts of the COVID-19 pandemic, the resulting quarantines have forced the world to recognize the need to strengthen its digital infrastructure (Rasoulinezhad and Taghizadeh-Hesary 2022). The GDF infrastructure should be built focusing on green and low-carbon attributes. A new green project database or green project list should be established, along with an enterprise information collection and credit reporting system. From this, a green financial statistics system can be established, and FinTech applications can be developed. In the future, we will vigorously support the low-carbon transformation of small and medium enterprises. GDF talent should be provided with education and introduced to the industry. Green and low-carbon consciousness can be increased, along with digital financial literacy.

Fourth, international exchange and collaboration in the GDF field should be strengthened. Thus, a high-level, open GDF system should be developed. First, the GDF can contribute to sustainable development in countries along the Belt and Road Initiative (Paradise 2022). Full use of bilateral and multilateral cooperation mechanisms can strengthen GDF collaboration along with multilateral international frameworks, such as the G20, the Belt and Road International Alliance for Green Development, and BRICS countries. Therefore, foreign green investments should be actively developed. We should improve the level of environmental information disclosure by Chinese financial institutions, relevant enterprises, and participating institutions in international investment projects such as the BRI (Paradise 2022).

**Abbreviations**

| | |
|---|---|
| GDF | Green digital finance |
| SDGs | Sustainable development goals |
| UNCTAD | United nations conference on trade and development |
| COVID-19 | Coronavirus disease 2019 |
| GDFA | Green digital finance alliance |
| REC | Renewable energy consumption |
| ESG | Environmental, social, and governance |
| ML | Machine learning |
| AI | Artificial intelligence |
| DLT | Distributed ledgers |
| TFP | Total factor productivity |
| GTFP | Green total factor productivity |
| IoT | Internet of things |
| GDP | Gross domestic product |
| BRI | Belt and road initiative |
| BRICS | Brazil, Russia, India, China, South Africa |

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**Author contributions**
YX: Investigation, Data curation, Visualization, Software, Writing-original draft. ML: Conceptualization, Methodology, Funding acquisition, Writing-review & editing. LW: Investigation, Data curation, Validation & language editing. All author(s) read and approved the final manuscript.

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**Availability of data and materials**
The data used to support the findings of this study are available from the corresponding author upon request.

## Declarations

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All Authors declare that they have no competing interest.

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