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A Study on the Impact of Digital Transformation on Green Resilience in China

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Abstract: Enhancing green resilience is an important element in realizing environmental protection and green development, and with the continuous development of digital technology, digital transformation has become a new driving force for enhancing green resilience. Based on the panel data of 31 provinces in China from 2013 to 2021, this study examines the impact of digital transformation on green resilience. The results show that digital transformation can significantly enhance green resilience, and this conclusion is still valid after considering a series of robustness tests and endogenous problems; the heterogeneity analysis shows that in the eastern and central regions, the enhancement of green resilience by digital transformation is still significant, while in the western region, digital transformation has curbed green resilience but is not significant; both resource-based and non-resource-based provinces' digital transformation has enhanced green resilience, and the enhancement is more significant in resource-based provinces; in different levels of green resilience, digital transformation has a stronger impact on provinces with high levels of green resilience, showing the "Matthew effect"; the mediation effect results show that digital transformation can enhance green resilience by attracting government investment, fostering industrial integration and increasing public environmental concern; the threshold results show that digital transformation contributes to green resilience across the sample. However, with the development of digital platforms, the growth rate of digital transformation on the promotion of green resilience will first increase and then gradually decrease and eventually rebound, showing an "N-shaped" relationship.

Keywords: digital transformation; green resilience; digital platforms

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1. Introduction

With the rapid development of China's economy, a series of problems have emerged in the ecological environment, such as haze, water pollution, land desertification, etc. [1]. The Chinese government is increasingly focusing on synergistic economic and environmental development [2], increasing the capacity of the system to cope with risks and improving its resilience. Under the concept of the "Two Mountains Theory" [3], improving green resilience and achieving green transformation is not only an inevitable requirement for maintaining ecological stability and achieving the "dual carbon" goal, but also the key to promoting green and sustainable economic development. Green resilience refers to the ability to quickly return to the original state when the synergistic development of resources, environment, economy, and innovation is disrupted [4] and still remain sustainable [5]. Green resilience reflects both green development, including economic, environmental, and ecological development, and the ability to resist, cope, and recover from crises in the face of environmental change, natural disaster shocks, and economic crises. The purpose of enhancing green resilience is to increase the resistance, adaptability, and restoration of urban green ecology, thereby improving the ability of cities to cope with environmental problems and, ultimately, promoting the coordinated development of the economy, society, and the environment. Much of the existing literature focuses on climate resilience, low

carbon resilience, and ecological resilience [6–13], but there is a lack of research related to green resilience that emphasizes synergistic development of the environment and the economy. In the context of advancing global environmental governance, increasingly more countries and regions have begun to emphasize the importance of green development and sustainable development. Some scholars have pointed to the significance of enhancing green resilience [14]. Therefore, how to mitigate the impact of these shocks to improve the adaptability of cities, and how to continue to fight the battle against pollution to achieve "green-ecological-low-carbon-resilience" system governance are important issues that we need to address urgently.

The 14th Five-Year Plan proposes that "we should actively promote energy saving and consumption reduction of new infrastructure, and moreover, we should give full play to the role of green empowerment of information infrastructure, promote the deep integration of digitization and greening, and help economic and social development to open a green and low-carbon road" [15,16]. New infrastructure, as an important area of energy saving and carbon reduction, is the cornerstone of the digital economy, and even more so, it is a crucial part for driving the digital transformation of the entire society. Digital transformation is the use of digital intelligence to upgrade or reengineer a business to achieve business growth and efficiency improvements, thereby contributing to sustainable development [17]. Currently, we are in the era of the digital economy, with the continuous development of digital technology represented by big data and artificial intelligence, and digital transformation has become the path to high-quality development [18,19]. Digital transformation not only poses a technological challenge, but also plays an irreplaceable role in greening the transition and promoting green development [20]. The existing literature has examined the digital transformation on carbon emissions, green development [21–27], etc., but there is a lack of research on its ability to cope with shocks from a resilience perspective. Some scholars have pointed out that it is particularly important to analyze urban greening and coping with the impact of environmental pollution from a resilience perspective [28]. We need to build an environmental governance system that is " lead by the government, dominated by enterprises, and with the participation of social organizations and the public" (in the report of the 19th National Congress of the Communist Party of China (CPC), part IX seeks to accelerate the reform of the ecological civilization system and the construction of a beautiful China, and item (b) focuses on solving outstanding environmental problems: raising the standards for pollution emissions, strengthening the responsibility of emitters, and improving the system of environmental protection credit appraisal, mandatory disclosure of information, and severe penalties and fines; build an environmental governance system led by the government, with enterprises as the main body and the participation of social organizations and the public; actively participate in global environmental governance and implement emission reduction commitments), which will help us further explore the path to fully unleash digital transformation for green resilience, and, at the same time, provide a basis for verifying the feasibility of China's governance policies. Based on the above background, does digital transformation enhance green resilience? What are the underlying mechanisms? These questions are worth exploring and are of great significance.

Focusing on the research on digital transformation and the digital economy, scholars at home and abroad mainly study the measurement of the digital economy and digital transformation as well as the impacts. As the ecological environment continues to deteriorate, reducing carbon emissions and realizing green development are a consensus among all sectors of society [29]. In conjunction with the research in the paper, at the macro level, scholars have two aspects of research for reference. First, the exploration of the digital economy for green development [21,22]. Most existing scholars believe that the digital economy can promote green development, and then they analyze the heterogeneity from different perspectives, such as Dai and Yang [23] between industries with different energy intensities, as well as Wei and Hou [24] between different regions, different administrative levels, and different policy intensities to test the heterogeneity. Furthermore, many scholars

have identified mechanisms for the digital economy to promote green development, such as technological innovation and industrial optimization [25], and so on. Second, there is the impact of the digital economy on carbon emissions. Most of the existing scholars agree that the development of the digital economy will reduce carbon emissions, and they believe that the development of the digital economy has an inverted U-shaped nonlinear characteristic on urban carbon emission reduction [26,27]. According to their mechanism test, they believe that upgrading the industrial structure [30], green technology innovation [31], and energy structure improvement [32,33] play a mediating role. As the research continues, a series of policies on enterprise digital transformation have been introduced, such as *the Guide for Digital Transformation of Small and Medium-sized Enterprises* and *the Circular on the Pilot Work of Financial Support for Digital Transformation of Small and Medium-sized Enterprises*. These documents all emphasize the importance of digital transformation. At the same time, related scholars have also studied the economic impact of digital transformation at the micro level, such as the impact of enterprise digital transformation on greening transformation [34–36] and the impact of enterprise digital transformation on carbon emission reduction [37].

Resilience was first derived from the Latin word "resilio", and it has gone through three stages of "engineering resilience—ecological resilience—evolutionary resilience" [38]. As green economic development and ecological issues are increasingly emphasized, a series of terms on resilience have been proposed, including climate resilience, ecological resilience, and low-carbon resilience. The following three areas are available: first, the research on climate resilience. As climate change has caused significant threats to human survival [39,40], scholars have constructed a climate resilience index to study its dynamics [6] and influencing factors [7]. The second is the research on low-carbon resilience. The domestic and international literature mainly analyzes the concepts and challenges of low-carbon resilience [8,9], and there are also scholars who have conducted regional case assessments for low-carbon resilience [10]. The third is studies on ecological resilience. Scholars have studied the dynamic evolution of ecological resilience [11], and some scholars have studied the influencing factors of ecological resilience, including environmental regulation [12] and new urbanization [13]. All of the above studies provide implications for this study. A review of the literature reveals that green resilience is a relatively new concept that has not yet been uniformly defined by academics. Scholars at home and abroad have mainly conducted research on green development, ecological resilience, and climate resilience. Although green resilience has similarities with several of the above concepts, it is very different, so it is significant to study the concept of green resilience and how to enhance it.

In summary, in terms of research objects, on the one hand, the existing literature focuses only on climate, low-carbon, and ecological resilience, without considering the coordinated development of the environment and the economy. On the other hand, the existing literature focuses on the influencing factors of green development and carbon emissions but lacks a consideration of their ability to cope with shocks. That is, few scholars have studied green resilience, and there is a lack of measurement of green resilience. In terms of research content, most scholars study the impact of digital transformation on green development, ecological resilience, etc., but the impact of digital transformation on green resilience still needs to be explored. Therefore, our possible innovations are in the following four aspects. Firstly, based on the resilience theory, the connotation of green resilience is clarified, and the index system of green resilience is constructed, which provides a new perspective for the research on resilience theory. The second is innovatively incorporating micro-level digital transformation and macro-level green resilience into the same research framework, exploring the research on the green resilience aspects of digital transformation. Thirdly, we study the intrinsic mechanism of digital transformation on green resilience from the perspective of "Macro (government)-Meso (industry)-Micro (public)", which confirms the mediating roles of government investment, industry integration, and public environmental participation, and it completes the framework of the thesis. Fourth, the digital platform is introduced as its threshold variable to further study the nonlinear impact

of digital transformation on green resilience and to provide reference for the use of digital transformation to enhance green resilience.

2. Theoretical Analysis and Hypothesis Formulation

2.1. Direct Impacts of Digital Transformation to Enhance Green Resilience

In the context of innovation and datatization theories, digital technology, because of its highly innovative and spatially transversal nature, can reduce the cost and increase the efficiency of resource waste and environmental protection, ultimately enhancing the resistance, adaptability, and restorative of green resilience. First, digital transformation can, in some way, improve green quality, limiting pollutant emissions [41], reducing energy consumption [42], and, ultimately, increasing resistance in green resilience. Digital transformation can promote the optimization of industrial structures and economic development, and the new technologies it brings can promote the development of traditional industries in an environmentally friendly and efficient way, which will reduce the dependence on natural resources and the impact on the environment. At the same time, digital transformation can optimize the industry's production and management processes, enhance innovation, and, thus, reduce energy consumption and pollutant emissions [43]. Secondly, digital transformation can enhance adaptability in green resilience by improving energy efficiency, green governance, and green building capabilities. The digital platform can help city managers better grasp urban energy consumption and environmental pollution, formulate more scientific urban energy management and environmental protection strategies, and realize the sustainable development of urban construction. At the same time, digital transformation can access all urban operational data in real time through big data, artificial intelligence, and other technologies. It realizes the real-time monitoring and data analysis of urban governance [44], which, in turn, analyzes and predicts environmental problems and improves the accuracy and relevance of urban governance, thereby increasing the efficiency and transparency of urban governance. Finally, digital transformation can help companies better manage and utilize green resources, attract green investments, and improve green innovation, thereby improving environmental quality [45] and enhancing restoration in green resilience. As environmental awareness increases, more and more investors are paying attention to corporate environmental behavior and green investment. Digital transformation can enable enterprises to more accurately understand market demand and consumer preferences, and then adjust the production method of products, and it can help enterprises to realize the recycling of resources and waste minimization; moreover, it can also enhance the transparency and openness of corporate information, thereby improving the environmental image of corporations and attracting more green investments. Most importantly, digital transformation can increase green resilience by facilitating the development of green technologies, accelerating digital collaboration on green innovations, increasing the efficiency and scope of green innovations, and transferring these technologies to a wider range of sectors through digital platforms. Therefore, we propose research hypothesis H1:

Hypothesis H1: *Digital transformation can increase green resilience.*

2.2. Indirect Impacts of Digital Transformation to Enhance Green Resilience

The purpose of enhancing green resilience is to increase the resistance, adaptability, and restoration of urban green ecology, thereby improving the ability of cities to cope with environmental problems and, ultimately, promoting the coordinated development of the economy, society, and the environment. The issue of environmental governance has become a common concern for stakeholders such as the government, industry, and the public [46]. To enhance green resilience, it is necessary to adjust and optimize the industrial and energy structures, focus on pollution control, and actively advocate green lifestyles with the financial and policy support of the government, which requires the joint efforts of the entire society to achieve. Therefore, this study examines the impact of

digital transformation on green resilience from three perspectives: government, industry, and public. We argue that digital transformation can leverage digital technologies and platforms to attract government investment, promote industrial integration, and raise public environmental awareness, thereby increasing green resilience.

(1) Government investment

Digital transformation, because of its green and innovative nature, can facilitate the promotion of the integration of digital and traditional environmental governance technologies, as well as the transformation of traditional governance technologies into new ones [47,48]. Digital governance attracts government investment because of its advantages in improving the efficiency of government governance, regulatory capacity, and responsiveness to crises. In turn, government investment is an important underpinning of environmental improvement and can drive digital governance, further increasing green resilience. First, digital transformation can improve public services; for example, smart park-related digital systems and platforms can realize the real-time monitoring and early warning of public resources and services. It can improve the ability of urban infrastructures' operation and security and the level of daily urban management, as well as enrich the means of social governance [49], thus improving the livability and attractiveness of the city, which, in turn, attracts government investment. Second, digital transformation can optimize the business environment [50], drive innovative business models, and, thus, promote green innovation and transformation. It is important for green economic growth and tax revenues, and, therefore, attracts government investment, further enhancing green resilience. Government investment plays an important role in improving the environment and promoting green development [51]. For cities or regions, achieving a green transition and becoming more resilient requires strong government support. Government investment can improve the environmental construction of sewage treatment, garbage disposal, air purification, and other environmental protection infrastructure to effectively improve the quality of the environment and reduce environmental pollution. It can also further the development of green industries, such as energy-saving and environmental protection industries and new energy industries. The development of these industries can drive economic growth, while also improving energy utilization efficiency and playing a certain role in environmental protection [52]. In addition, governments can formulate relevant policies and incentives, such as providing financial subsidies or tax concessions, to encourage enterprises and residents to take more environmentally friendly and sustainable actions. Therefore, we propose research hypothesis H2:

Hypothesis H2: *Digital transformation can increase green resilience by increasing government investment.*

(2) Industrial integration

Industrial integration refers to the dynamic process through which different industries integrate and penetrate into each other, eventually forming a new industry and developing together, and it is an important way to realize high-quality development [53]. Among them, the integration of advanced manufacturing and modern service industries is the most important part of industrial integration and the core of enhancing China's economic competitiveness. In the context of the industrial Internet theory and the theory of industrial integration and development, digital transformation can promote the integration between different industries [54] and facilitate industrial upgrading due to the strong permeability and integration of digital transformation. It embeds Internet technology into manufacturing, thus promoting the servitization of the manufacturing industry [55]. Digital transformation can promote the deep integration of manufacturing and service industries, forming new modes such as smart services and intelligent manufacturing. At the same time, digital transformation has a positive impact on the production methods and organizational models of various industries, and it can also promote the integration of different types of

industries [56]. In the traditional manufacturing process, the methods of "polluting while producing" and "polluting first, treating later" have caused great damage to the environment and society. It is this type of industrial integration that promotes the optimization of the industrial structure, prompting the manufacturing industry to move closer to the low-pollution service industry, thus improving the greening level of the manufacturing and service industries. At the same time, industrial integration can promote cooperation between different industries, bring about more technological innovation, and boost the improvement of production methods and production equipment, thus achieving resource sharing and optimal allocation [57], reducing environmental pollution, and improving green resilience. Therefore, we propose research hypothesis H3:

Hypothesis H3: *Digital transformation can increase green resilience by facilitating industry integration.*

(3) Public environmental concern

Increasing green **resilience is** not only influenced by aspects such as government investment and technological advances, but also by increased public environmental concern [58]. Due to its wide **coverage** and shared nature, digital transformation provides a more convenient platform for the public to access environmental knowledge and participate in environmental activities and other actions, which will increase public concern for the environment [59] and, thus, increase green resilience. On the one hand, digital production and digital consumption brought about by digital transformation will transform the public's concept of production or consumption, which will take into account the environment while pursuing material goods, making the public more responsible for environmental protection [60]. On the other hand, digital media and communication tools can improve the efficiency of information dissemination, expand the reach of environmental protection, and provide the public with a more convenient and faster way to learn about environmental issues. It will help to motivate individuals and communities to take action to reduce negative impacts on the ecosystem. Finally, digital transformation enables effective interaction and collaboration between the public and governments, enterprises, and environmental organizations. It provides avenues for the public to participate in online discussions and contribute ideas, so that the public can actively participate in environmental decisions and actions. It will prompt governments to pay more attention to environmental protection and take stronger measures to promote green development and low-carbon transition. Therefore, we propose research hypothesis H4:

Hypothesis H4: *Digital transformation can improve green resilience by increasing public environmental concern.*

2.3. Threshold Effects of Digital Transformation

A digital platform is based on the platform economy, integrates existing resources and technologies, and continuously develops and converges new technologies in the digital service hub of an organization [61]. It is the core of digital transformation [62] and the advanced stage of new digital construction, which has now become the strategic choice of countries around the world for a new round of technological revolution. On the one hand, digital platforms make data and clouds readily accessible and usable resources through their powerful data-processing capabilities and cloud service support. They save costs and reduce carbon footprints, thus facilitating digital transformation. On the other hand, the digital platform not only aggregates and integrates new digital technologies, but also has platform connectivity and intelligence capabilities that enable it to flexibly respond to and meet the changing needs of the business and promote the deep integration of various businesses, which is a key driving force for digital transformation [63]. Therefore, the development of digital platforms will have an impact on the degree of digital transformation

and, subsequently, on green resilience. At the initial stages, digital platforms break down data barriers within enterprises and realize the flow and sharing of data, and industries realize the online and intelligentization of business processes through digital platforms, thereby continuously promoting enterprise digital transformation and, thus, enhancing green resilience. However, as the development of digital platforms reaches a certain scale, it may lead to increasingly prominent data security and privacy protection issues, leading to uneven distribution of resources, information asymmetry, increased operating costs, and other issues [64], and the government and enterprises need to invest more resources and energy to strengthen data management and normative guidance. It will lead to a slowdown in the development of digital transformation, which will weaken the promotion of green resilience. As the platform technology continues to mature and the regulatory system is gradually improved, some of the negative impacts of digital platforms will be mitigated, and digital transformation will be pushed into a higher stage, so that the impact of digital transformation on green resilience will pick up. Therefore, we propose research hypothesis H5:

Hypothesis H5: *The impact of digital transformation on green resilience is an "N-shaped" curve that first rises, then decreases, and finally rebounds slightly.*

Its impact mechanism is shown in Figure 1:

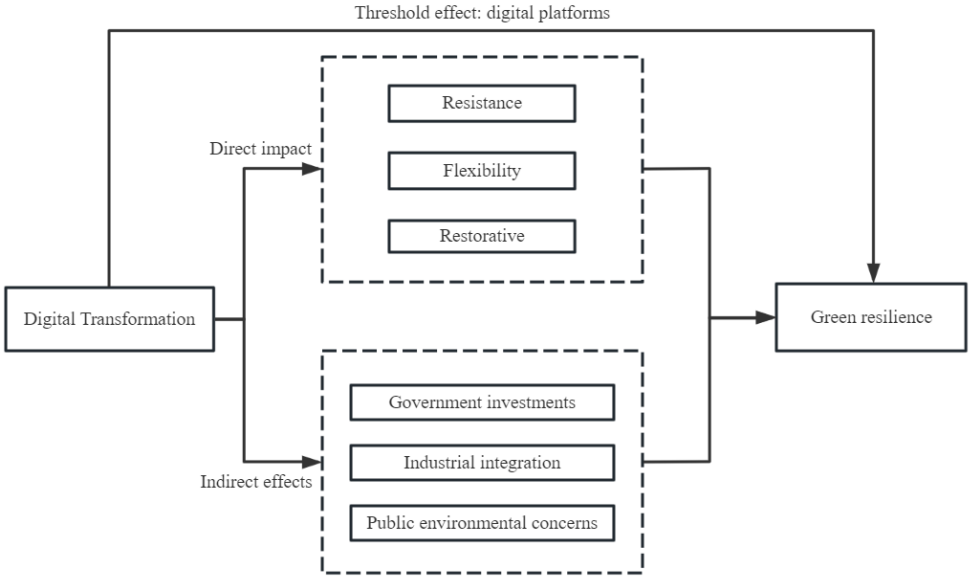


Figure 1. Mechanism map of the impact of digital transformation on green resilience.

3. Model Specification, Variable Selection, and Data Description

3.1. Model Specification

To explore the impact of digital transformation on green resilience, we develop the following econometric model:

$$Gee_{it} = \alpha_0 + \alpha_1 Dige_{it} + \sum_{j=1}^{k} \gamma_j controls_{it} + \delta_i + \eta_t + \varepsilon_{it} \quad (1)$$

i is the province, t is the year, Gee_{it} denotes green resilience, $Dige_{it}$ is the level of digital transformation, and $controls_{it}$ is the control variable. δ_i is the province fixed effect, η_t is the year fixed effect, and ε_{it} is the random error term in the baseline model, with the coefficient α_1 reflecting the effect of digital transformation on green resilience.

3.2. Variable Selection

3.2.1. Explained Variable: Green Resilience (Gee)

Regarding the measurement of resilience, there are three main approaches in the existing literature: The first is the subjective experience method, which mainly includes the questionnaire method and an in-depth interview method [65], but it is too subjective. The second is a single indicator measured using the sensitivity index [5], but it cannot comprehensively reflect the nature and attributes of resilience. The third is the construction of an indicator system [66], which has the advantage of being comprehensive and accurate. In this study, based on the concept of green resilience and the theory of resilience, we draw on the existing literature [67–72] and combine it with the Green Development Indicator System jointly issued by the National Development and Reform Commission (NDRC) and other departments to establish indicators from the three dimensions of resistance, adaptability, and restoration, and we use the entropy value method to calculate their weights. Specific indicators are shown in Table 1.

Table 1. Green resilience indicator system.

Target Layer	Tier 1 Indicators	Secondary Indicators	Tertiary Indicators	Properties	Indicator Weights
Green resilience	Resistance	Green quality	Percentage of tertiary sector value added (%)	+	0.0149
			GDP/total fixed assets (%)	+	0.0147
			Per capita disposable income (yuan)	+	0.0260
			Population density (persons/km^2)	−	0.0132
		Pollution emission	Total chemical oxygen demand emissions (tons)	−	0.0094
			Total ammonia nitrogen emissions (tons)	−	0.0042
			Total industrial sulphur dioxide emissions (tons)	−	0.0047
			Industrial solid waste generation (tons)	−	0.0051
			Carbon emissions (tons)	−	0.0087
	Adaptability	Green governance	Non-hazardous treatment rate of domestic waste (%)	+	0.0018
			Comprehensive utilization of general industrial solid waste (tons)	+	0.0353
			Daily urban sewage treatment capacity (million cubic meters)	+	0.0383
			Volume of domestic waste removed (tons)	+	0.0341
		Green construction	Private car ownership (10,000 vehicles)	−	0.0052
			Gas penetration rate (%)	+	0.0019
			Water penetration rate (%)	+	0.0007
			Cell phone penetration rate (units/100 persons)	+	0.0170
	Restorative	Green resource	Public green space per capita (square meter)	+	0.0083
			Greening coverage in built-up areas (%)	+	0.0019
			Water resources per capita (m^3/person)	+	0.2201
			Forest cover (%)	+	0.0267
			Share of clean energy generation (%)	+	0.0883
			Electricity consumption (Billion kWh)	−	0.0056
		Green investment	Total investment in environmental infrastructure (billion yuan)	+	0.0350
			Investment in pollution control (million yuan)	+	0.0496
			Total expenditure on environmental protection (billion yuan)	+	0.0273
			Total expenditure on agriculture, forestry, and water affairs (billion yuan)	+	0.0224
		Green innovation	R&D investment (million yuan)	+	0.1146
			Number of green patent acquisitions (units)	+	0.0869
			Number of green invention applications (units)	+	0.0780

Resistance refers to the ability of a system to maintain its original state in the face of ecological, economic, and social shocks, reflecting the system's ability to cope with shocks when it encounters a green crisis. "Percentage of tertiary sector value added" [67], "GDP/total fixed assets", "Per capita disposable income" [68], and "Population density" [69] all reflect green quality. The higher the "Percentage of tertiary sector value added", "GDP/total fixed assets", and "Per capita disposable income", the higher the quality of the economy and the level of economic development. On the contrary, the higher the "Population density", the more polluting waste is likely to be created, and the resistance of the environment will be weakened as a result. "Total chemical oxygen demand emissions", "Total ammonia and nitrogen emissions", "Total industrial sulphur dioxide emissions", "Industrial solid waste generation" [70], and "Carbon emissions" all reflect pollutant emissions. The more pollutants emitted, the weaker the resistance.

Adaptability refers to the ability of a system to adjust its internal structure and functioning to new environmental conditions in the face of pressures and shocks, such as natural disasters, environmental changes, and socio-economic risks, and it is relevant to urban governance and construction. "Non-hazardous treatment rate of domestic waste", "Comprehensive utilization of general industrial solid waste", "Daily urban sewage treatment capacity", and "Volume of domestic waste removed" [69] all reflect the level of urban governance. The more attention a city pays to the management of pollutants and waste, the more it can maintain urban stability. "Private car ownership", "Gas penetration rate", "water penetration rate", and "Cell phone penetration rate" [71] all reflect the green construction of cities. The fewer the private cars in a city, the less pollution it causes to the environment. The higher the gas penetration rate, the water penetration rate, and the cell phone penetration rate, the higher the standard of living of the people and the better able they are to maintain urban stability.

Restoration refers to the ability of a system to quickly return to the original stable state when the coordination of resources, environment, and economy is disrupted, related to the city's resource endowment and investment in construction, as well as the need for the system to innovate in order to quickly return to its initial state after a shock. "Public green space per capita", "Greening coverage in built-up areas", "Water resources per capita", "Forest cover" [69], and "Share of clean energy generation" all reflect the green resources of the city, and "Electricity consumption" reflects the consumption of green resources. The more green resources there are, the less they are consumed, and the more restorative the system will be after a shock. "Total investment in environmental infrastructure", "Investment in pollution control", "Total expenditure on Environmental protection" and "Total expenditure on agriculture, forestry and water affairs" [72] all reflect green investment in cities. The more the green investments, the more restorative the system is. "R&D investment" [67] indicates the level of innovation investment in the city. The more the investments, the stronger the support for innovation. "Number of green patent acquisitions" and "Number of green invention applications" [72] indicate the level of innovation output of a firm. The higher the output, the faster the restorative capacity of the system.

We use the entropy method to calculate the green resilience level, and the specific steps of the entropy method are as follows:

(1) Standardization of green resilience indicators

Positive indicators:

$$X_{ij} = \frac{x_{ij} - \min(x_{1j}, x_{2j}, \ldots x_{nj})}{\max(x_{1j}, x_{2j}, \ldots x_{nj}) - \min(x_{1j}, x_{2j}, \ldots x_{nj})} + 0.0001 \quad (2)$$

Negative indicators:

$$X_{ij} = \frac{\max(x_{1j}, x_{2j}, \ldots x_{nj}) - x_{ij}}{\max(x_{1j}, x_{2j}, \ldots x_{nj}) - \min(x_{1j}, x_{2j}, \ldots x_{nj})} + 0.0001 \quad (3)$$

x_{ij} is the standardized value of indicator j for province i (i = 1, 2,. . ., 31; j = 1, 2,. . ., 29), max (x_{1j}, x_{2j},. . ., x_{nj}) and min (x_{1j}, x_{2j},. . ., x_{nj}) are the maximum and minimum values, X_{ij}. denotes the standardized value after processing. Since the logarithmic processing is involved in the follow-up but the standardized values may be 0, their treatment of being shifted by 0.0001 [73] units does not affect the calculation results.

(2) Determination of entropy value of green resilience indicator

① Calculate the weight of the jth indicator for the ith province:

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}}, (i = 1, 2, \ldots, 31;\ j = 1, 2, \ldots, 29) \tag{4}$$

② Calculate the entropy value of the jth indicator:

$$e_j = -k \sum_{i=1}^{n} P_{ij} \ln P_{ij} \tag{5}$$

$i = 1,\ 2,\ \ldots,\ 31;\ j = 1, 2, \ldots,\ 29;\ e_j \geq 0;\ k = \frac{1}{\ln n} > 0, n = 279.$

③ Calculate the information entropy redundancy:

$$g_j = 1 - e_j,\ (j = 1,\ 2,\ \ldots, 29) \tag{6}$$

(3) Determination of the weight of each evaluation indicator

The weight W_j of the jth evaluation indicator is calculated by the following formula:

$$W_j = \frac{g_j}{\sum_{j=1}^{m} g_j}, (j = 1,\ 2,\ \ldots, 29) \tag{7}$$

(4) Calculate the level of green resilience:

$$Dige_{it} = \sum_{j=1}^{n} W_j X_{ij} \tag{8}$$

3.2.2. Core Explanatory Variable: Digital Transformation (Dige)

The core of the digital economy is the "digital enterprise", which refers only to traditional enterprises to complete the digital transformation in order to form the core force of economic development. Therefore, differing from the previous digital economy construct indicator method, we start from the micro level of the digital transformation of enterprises and measure the level of digitization by the degree of digital transformation of enterprises in each province. There are two main measurement methods in the existing literature on digital transformation indicators: (1) text analysis [74,75]; (2) entropy method [76,77]. We first measure digital transformation using textual analysis and, again, later in the robustness test, we use entropy. The specific steps of the text analysis method are as follows: (1) use Python's crawler function to organize all A-share listed companies' annual reports and transform them into text form. (2) Screen ST, ST*, and enterprises with seriously missing main data. (3) We draw on Fang et al. [75]'s research to extract keywords about digital transformation from four aspects: Internet business model, informationization, big data technology, and artificial intelligence. Moreover, we refer to the government's report to form a digital transformation vocabulary and use Python to extract the digital transformation word frequency from the text of listed companies so as to measure the degree of digital transformation of listed companies. The specific vocabulary is shown in Figure 2. (4) According to the enterprise's province in the basic information of the enterprise, we sum up the enterprise data of each province and then match them to 31 provinces, which is used to measure the degree of digital transformation of the provinces (cities). (5) We logarithmically process the obtained provincial digital transformation data.

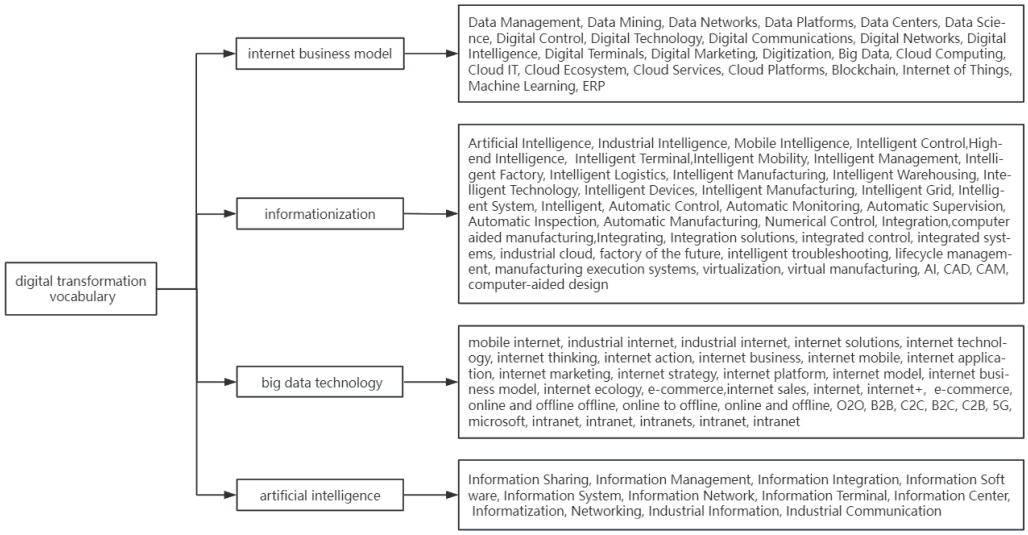


Figure 2. Digital transformation vocabulary.

3.2.3. Control Variables

Drawing on the existing literature, we selected five control variables:

(1) The level of urbanization (Urban), which is expressed as the ratio of urban population [78,79]. As population and economic activities concentrate in towns and cities, there are multiple positive impacts, such as reduced transaction costs and economies of scale, which increase green resilience.

(2) The level of infrastructure (Road), which is expressed as the per capita ownership of the road area [20]. Improved infrastructure helps reduce transportation costs and pollution and will enhance green resilience.

(3) Scientific and technological innovation (Tec), which is expressed as the logarithm of scientific and technological expenditures [80]. Science and technology innovation provides green production methods for all types of industries through new technologies, forming a green and low-carbon industrial development system.

(4) The level of openness to the outside world (Open), which is expressed as foreign direct investment/GDP [79]. Opening up to the outside world has promoted an international specialized division of labor, and it has also enabled the widespread diffusion and dissemination of "environmentally friendly" technologies and pollution control techniques, thereby increasing green resilience.

(5) The level of economic development (Eco), which is expressed as per capita GDP [20,79]. Economic development can provide adequate financing for green development and environmental governance.

3.3. Data Description

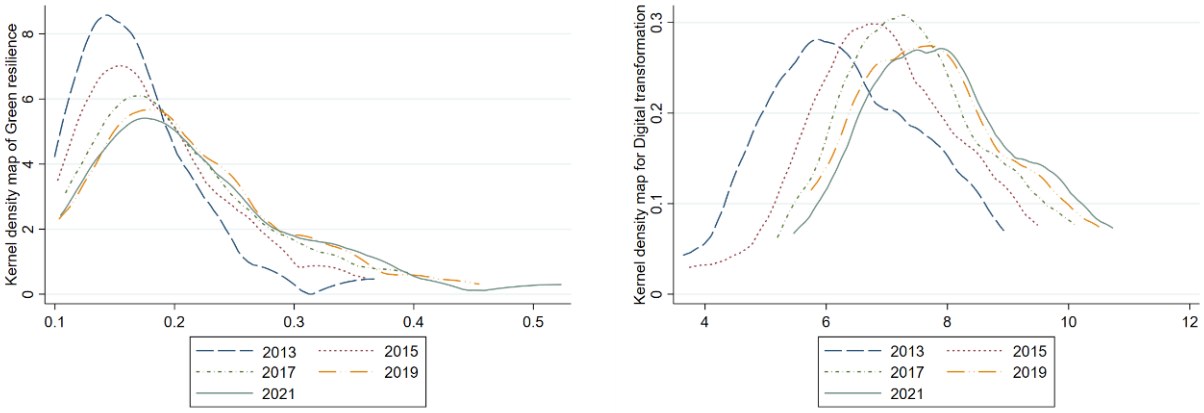
We use data from 31 provinces from 2013 to 2021 as the research sample with the aim of understanding the progress and challenges of digital transformation and green resilience, and developing targeted policies and measures for each province. The digital transformation data were obtained through text analysis, and other data were obtained from China Statistical Yearbook, China Urban Construction Statistical Yearbook, China Environmental Statistical Yearbook, and provincial statistical yearbooks. To visualize the overall picture of the variables, Table 2 shows the descriptive statistics of the main variables.

To further understand the time-series evolution characteristics of digital transformation and green resilience, we select five years (2013, 2015, 2017, 2019, and 2021) to plot the kernel density map based on the requirements of highlighting the key change points, simplified visualization of the drawing, and saving space resources, as shown in Figure 3. Figure 3a is a kernel density map for green resilience, and Figure 3b is a kernel density map for digital transformation. In particular, we can see from Figure 3a that the curve is

shifted to the right, indicating an increase in green resilience. The peak is highest in 2013, and the peak gets "shorter" each year, indicating that the overall gap in green resilience is gradually widening. We can see in Figure 3b that the position of the curve is shifted to the right, indicating an improvement in digital transformation. The highest peak is in 2017, indicating that the overall gap in digital transformability shows a trend of narrowing and then slightly widening.

Table 2. Descriptive statistics for the variables.

Variable	N	Mean	SD	Min	Max
Dige	279	7.337	1.404	3.638	10.73
Gee	279	0.199	0.0745	0.0997	0.523
Urban	279	0.599	0.124	0.239	0.896
Road	279	16.75	4.885	4.110	26.78
Tec	279	4.3874	1.1254	1.4268	7.0637
Open	279	0.0181	0.0168	6.19×10^{-5}	0.121
Eco	279	10.93	0.419	10.05	12.12



(**a**) (**b**)

Figure 3. Kernel density map. (**a**) Kernel density map of green resilience. (**b**) Kernel density map for digital transformation.

4. Empirical Results

4.1. Baseline Results

In Table 3, the impact of digital transformation on green resilience is tested using the two-way fixed effect of province and time. Among them, column (1) represents the regression results without adding control variables, and columns (2) and (3) represent the regression results with control variables added sequentially. The results show that digital transformation improves green resilience at the 1% significance level, validating Hypothesis 1.

In terms of control variables, the level of urbanization plays a dampening effect on green resilience. It may be that the concentration of population and industry brought about by urbanization increases the pressure on the environment and weakens the ability of cities to cope with natural disasters or other environmental stresses. The contribution of infrastructural levels to green resilience is small and insignificant. It may be that ecological and environmental factors have been neglected in the design and construction of traditional urban infrastructures, which may not be effective in promoting green resilience. Technology and innovation acts as a disincentive to green resilience. It may be due to the fact that the current focus of science, technology, and innovation is mainly on high-technology industries and knowledge innovation, while technologies that can improve the green resilience of a city or region have not been sufficiently emphasized and developed. The

level of openness to the outside world acts as a disincentive to green resilience. The likely reason is that opening up to the outside world has enabled more polluting firms to enter the local market, which has impacted the local environment and ecosystems and is not conducive to green resilience. The level of economic development contributes to green resilience. It is because a higher level of economic development means that more resources and funds can be invested in environmental protection and ecological construction, helping to improve the ability of cities to cope with environmental pressures and, thus, increase green resilience.

Table 3. Baseline results.

	(1)	(2)	(3)
Variable	**Gee**	**Gee**	**Gee**
Dige	0.027 ***	0.073 ***	0.059 ***
	(6.0698)	(16.0796)	(10.7780)
Urban		−0.237 ***	−0.449 ***
		(−9.0072)	(−9.6718)
Road		0.001 **	0.000
		(2.3992)	(0.1799)
Edu		−0.094 ***	−0.071 ***
		(−29.0270)	(−22.3741)
Open			−0.449 **
			(−2.9211)
Eco			0.094 ***
			(5.0251)
Constant	−0.002	0.214 ***	−0.659 ***
	(−0.0697)	(12.9777)	(−4.3388)
Province FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	279	279	279
R^2	0.242	0.642	0.682

Note: Standard errors are reported in parentheses; **, and *** indicate significant at the 5%, and 1% levels, respectively.

4.2. Robustness Tests

In order to ensure the reliability and rigor of the study's conclusions, we use the fixed-effects model to develop robustness tests from five aspects:

(1) Replacement of core explanatory variable. We use the entropy method to re-measure the digital transformation index, in which the weights of Internet business model, informatization, big data technology, and artificial intelligence are 0.2508, 0.2038, 0.2956, and 0.2499, respectively. The result is reported in column (1) of Table 4. After replacing the explanatory variables, Dige1 still contributes to green resilience at the 1% significance level, which is consistent with the baseline results.

(2) Replacement of explained variable. We use principal component analysis to re-measure green resilience. The result is reported in column (2) of Table 4. The coefficient of Dige is still positive at the 1% significance level, indicating that digital transformation can significantly improve green resilience.

(3) Excluding municipalities [81]. Considering that the levels of economic development and digital transformation of Beijing, Shanghai, Tianjin, and Chongqing differ significantly from those of other provinces, the above four municipalities are excluded, and the regression is re-estimated for the remaining 27 provinces. The result is reported in column (3) of Table 4. It can be found that digital transformation can improve green resilience.

(4) Bilateral shrinkage of 1% quartiles is applied to both the explained variables and core explanatory variables. The result is reported in column (4) of Table 4. It shows that digital transformation contributes to green resilience. And the conclusion still holds.

(5) Adding control variables. In this study, two control variables (human capital level (Edu) and industrial structure (Serv)) are added and regressed again. The human capital level (Edu) is expressed by the number of undergraduate students; the industrial structure (Serv) is expressed by the ratio of the secondary and tertiary industries. The result is reported in column (4) of Table 4, verifying the robustness of Hypothesis 1.

Table 4. Robustness test.

	(1) Explanatory Variable	(2) Explained Variable	(3) Excluding Municipalities	(4) Bilateral Shrinkage	(5) Adding Control Variables
Variable	Gee	Gee1	Gee	Gee	Gee
Dige		0.242 ***	0.061 ***	0.058 ***	0.027 ***
		(7.5806)	(10.6212)	(12.0918)	(4.4434)
Dige1	0.367 ***				
	(18.9247)				
Controls	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Observations	279	279	243	279	279
R^2	0.730	0.713	0.687	0.690	0.651

Note: Standard errors are reported in parentheses; *** indicate significant at the 1% levels, respectively.

4.3. Endogenous Problems

4.3.1. Instrumental Variable Method

Considering the possible problem of reverse causation, we use the IV-2SLS method for regression and create the following equation:

$$Dige_{it} = \lambda_0 + \lambda_1 IV_{it} + \sum_{j=1}^{k} \gamma_j controls_{it} + \delta_i + \eta_t + \varepsilon_{it} \quad (9)$$

$$Gee_{it} = \varphi_0 + \varphi_1 Dige'_{it} + \sum_{j=1}^{k} \gamma_j controls_{it} + \delta_i + \eta_t + \varepsilon_{it} \quad (10)$$

Equation (9) is the one-stage equation of the IV-2SLS method, Equation (10) is the second-stage regression equation of the IV-2SLS method, IV_{it} is the instrumental variable, λ_1 is the correlation between the instrumental variable and the independent variable, *Dige'it* is the one-stage fitted value, and φ_1 reflects the result after controlling for endogeneity problems.

Specifically, we select total post and telecommunications per million people in 1984 as the instrumental variable [82]. Firstly, the development of postal and telecommunication communications can reflect the level of technology at the time and the needs of society for modes of communication, while technology and communications can also influence the degree of digitization of the location, so it satisfies the correlation condition. Secondly, the total volume of the post and telecommunications does not have a direct impact on green resilience, so it satisfies the exogeneity condition. In addition, considering that the original data are cross-section data, we introduce one more piece of time-varying data to construct panel tool variables. Therefore, we use the interaction term between the total post and telecommunications per million people in 1984 and the number of Internet accesses nationwide in the previous year as an instrumental variable (*IV*), and the results are shown in columns (1) and (2) of Table 5. In column (1), the estimated coefficient of *IV* is significantly positive at a 1% significance level, indicating that the correlation of instrumental variables is verified. And according to the results of Kleibergen–Paap's rk LM statistic and Cragg–Donald Wald's F statistic, it can be seen that there is no problem of the under-identification of instrumental variables and weak instrumental variables, indicating that the choice of instrumental variables selection is reasonable. In column (2), the estimated coefficient of *Dige* remains positive at the 1% significance level, indicating that digital transformation can still contribute to green resilience after considering endogeneity problems.

Table 5. Endogenous tests.

Variable	Instrumental Variable Method		Difference-in-Differences Method
	(1) First Stage	(2) Second Stage	(3)
	Dige	Gee	Gee
IV	0.000 ***		
	(25.0151)		
Dige		0.089 ***	
		(8.6585)	
du × dt			0.016 **
			(2.9769)
Controls	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Kleibergen–Paap rk LM	39.232		
Chi-sq (1) *p*-value	0.0000		
Cragg–Donald Wald F	80.930		
10% maximal IV size	16.38		
Observations	269	269	279
R^2	0.703	0.564	0.560

Note: Standard errors are reported in parentheses; **, and *** indicate significant at the 5%, and 1% levels, respectively.

4.3.2. Difference-in-Differences Method

In 2017, the Central Internet Information Office and the National Development and Reform Commission, in conjunction with relevant departments, jointly issued the "*Notice on Carrying Out Comprehensive Pilot Programs for National E-Government Services*" [83], which is an important initiative to promote the development of the digital economy. It will help promote the informatization of government affairs, improve the efficiency of government services, facilitate the digital transformation of enterprises and society, and drive the rapid development of the digital economy. We further empirically investigate the impact of digital transformation on green resilience, adopting a difference-in-differences method using the "Integrated E-Government Pilot" provinces as exogenous shocks. The difference-in-differences method is as follows:

$$Gee_{it} = \psi_0 + \psi_1 du \times dt + \sum_{j=1}^{k} \gamma_j controls_{it} + \delta_i + \eta_t + \varepsilon_{it} \quad (11)$$

$du \times dt$ is the interaction term of the two dummy variables for policy implementation province and implementation year. Specifically, we select eight provinces (cities), including Beijing, Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong, Shaanxi, and Ningxia, as national e-government comprehensive reform pilots in 2017. We set *du* as an individual dummy variable. When *du* is equal to 1, it indicates provinces that have been included in the list of national e-government comprehensive reform pilots, and when *du* is equal to 0, it indicates provinces that have not been included in the list of national e-government comprehensive reform pilots. Meanwhile, we set *dt* as a period dummy variable. *dt* equal to 1 indicates the period after 2017 and *du* equal to 0 indicates the period before 2017. Finally, we use its interaction term ($du \times dt$) as an explanatory variable, use green resilience as an explained variable, and choose the 4th year before the policy implementation as the base period. Figure 4 plots the parallel trends of the double-difference model, which shows that none of the pre-pilot policy estimates for the "Integrated E-Government Pilot" are significant, while the coefficients of the post-pilot policy estimates are significantly positive. Thus, the difference-in-differences model passes the parallel trend assumption and allows for DID regression. The results are shown in column (3) of Table 5. It can be seen that the coefficient of $du \times dt$ is significantly positive at the 1% level, indicating that the results remain robust.

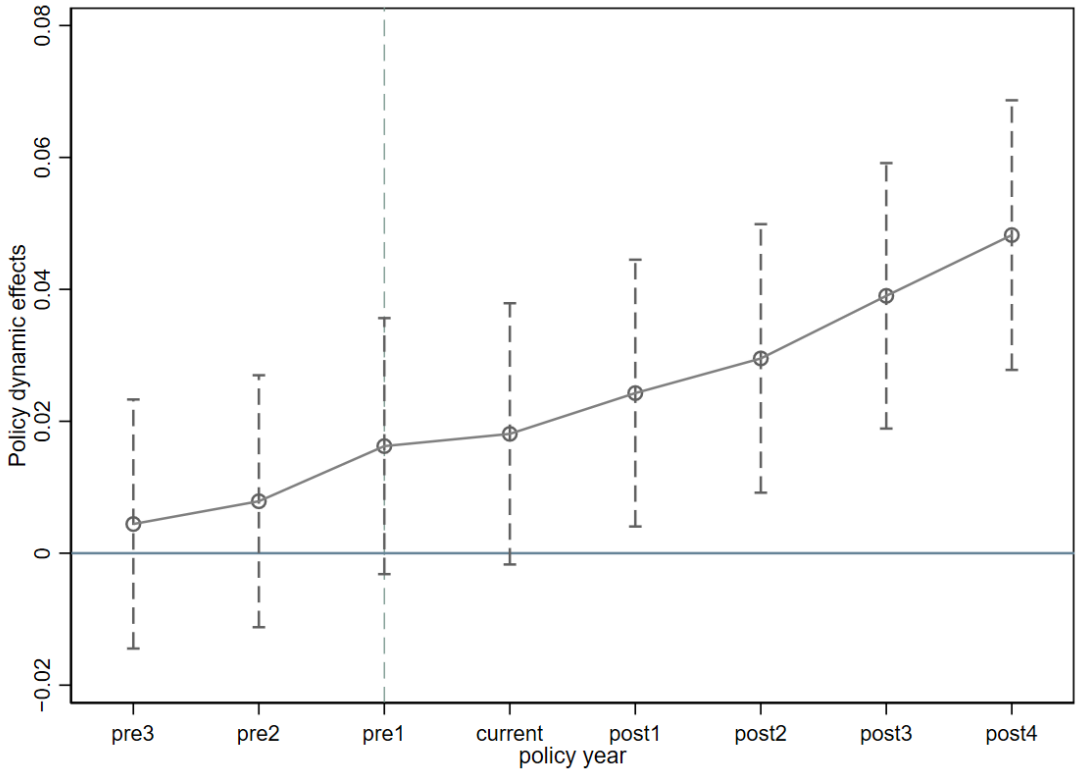


Figure 4. Parallel trend hypothesis test.

4.4. Heterogeneity Analysis

4.4.1. Geographical Location

Considering the different levels of digital transformation and green resilience in different regions, we divided the different regions into eastern, central, and western regions (the east includes Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan; the center includes Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, and Hunan; and the west includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Xizang, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang) according to the different regions. We tested this using a fixed effects model, and the regression results are shown in Table 6. It can be seen that digital transformation in both the eastern and central regions significantly contributes to green resilience, and digital transformation in the eastern region promotes green resilience better, while digital transformation in the western region has a dampening effect on green resilience but is not significant. The likely reason for this is that businesses in the western region are dominated by heavy industry and are most heavily involved in energy, raw materials, and heavy machinery processing. It will exacerbate pollutant emissions and reduce green resources. And these enterprises need to invest a lot of hardware and software in digital transformation and intelligent upgrading, which will not only increase their operating costs, but also consume a lot of time and resources. In addition, the number of engineers and technicians owned by enterprises in the western region is relatively small compared with that in the east and central regions. It will lead to a lower level of scientific and technological development and innovation in the western region, and energy saving and emission reduction technologies are relatively backward. Therefore, it is not conducive to the digital transformation, which ultimately has an inhibiting effect on green resilience.

Table 6. Tests for regional heterogeneity.

Variable	(1) East Gee	(2) Central Gee	(3) West Gee
Dige	0.054 ***	0.036 ***	−0.004
	(6.9312)	(9.4854)	(−0.5603)
Controls	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	99	72	117
R^2	0.854	0.918	0.769

Note: Standard errors are reported in parentheses; *** indicate significant at the 1% levels, respectively.

4.4.2. Resource Endowments

Drawing on the study of Zhang et al. [84], we classified the sample into resource-based and non-resource-based provinces based on the amount of reserves of three natural resources, namely, oil, natural gas, and coal, in each province as the basis of division. Among them, 10 provinces (cities), including Shanxi, Inner Mongolia, Xinjiang, Heilongjiang, Chongqing, Guizhou, Shaanxi, Shandong, Gansu, and Sichuan, are resource-based provinces, and the rest are non-resource-based provinces. We tested this using a fixed effects model, and the regression results are reported in Table 7. The contribution of digital transformation to green resilience is stronger and more significant in resource-based provinces than in non-resource-based provinces. It may be due to the fact that resource-based provinces have a "high-pollution, high-emission" growth model, so there is more room for digital transformation to play a role and contribute more significantly to green resilience. In addition, resource-based provinces are rich in resource reserves, and their factor costs are relatively low, attracting more green investments and innovative technologies. And China has introduced policies to support digital infrastructure, which further facilitates the digital transformation of resource-based provinces, thereby enhancing green resilience.

Table 7. Test of resource endowment heterogeneity.

Variable	(1) Resource-Based Provinces Gee	(2) Non-Resource-Based Provinces Gee
Dige	0.028 ***	0.025 **
	(5.6753)	(3.1244)
Controls	Yes	Yes
Province FE	Yes	Yes
Year FE	Yes	Yes
Observations	90	189
R^2	0.826	0.597

Note: Standard errors are reported in parentheses; **, and *** indicate significant at the 5%, and 1% levels, respectively.

4.4.3. Green Resilience Level

To explore the impact of digital transformation on green resilience under different levels of green resilience, we use a panel fixed effects quantile regression model with the following equation:

$$Q\tau(Gee_{it}) = \chi_0(\tau) + \chi_1(\tau)Dige_{it} + \sum_{j=1}^{k} \gamma_j controls_{it} + \delta_i + \eta_t + \varepsilon_{it} \quad (12)$$

$\chi(\tau)$ is the coefficient at the τ quantile. The results are shown in Figure 5.

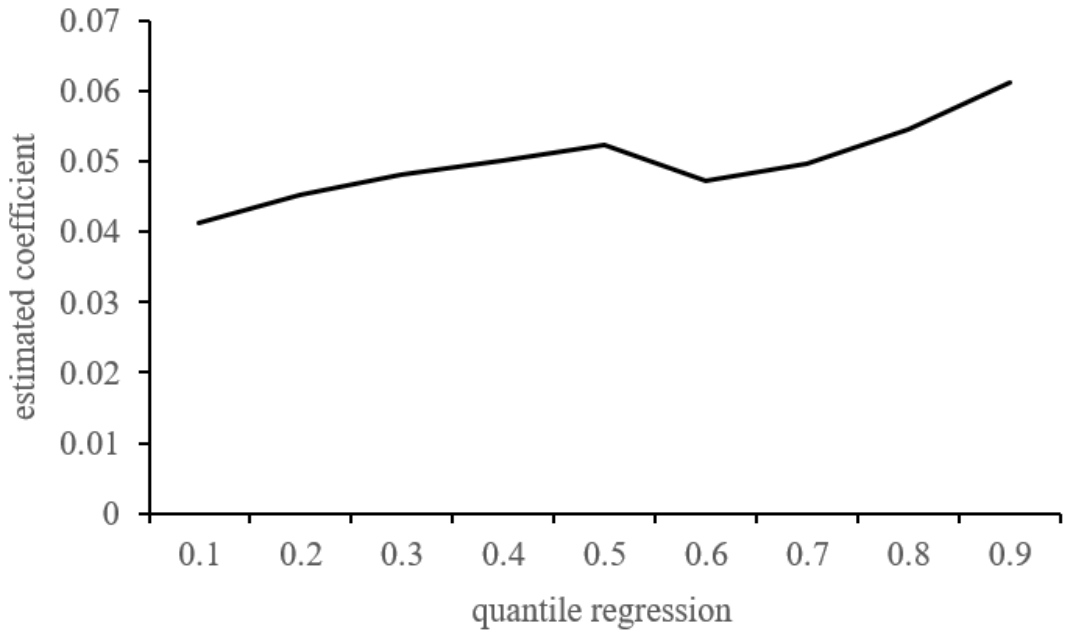


Figure 5. Coefficient values of digital transformation estimated by panel quantile models.

In the 10% to 90% quartile, the impact of digital transformation on green resilience has an upward trend. It indicates that the impact of digital transformation on high green resilience will increase as the level of green resilience increases, and there is a "Matthew effect" of the strong getting stronger and the weak getting weaker. The probable reason is that in regions with high green resilience, there is more emphasis on environmental protection and sustainable development, focusing on the development and utilization of clean energy, as well as more opportunities and scenarios for the application of digital technologies, thus providing a broader space and more opportunities for the digital transformation. However, in regions with low green resilience, the industrial structure and development approach may be more traditional and homogenous, lacking innovation and development momentum. It can make it difficult for digital transformation to be sufficiently supported and driven to unleash the digital dividend.

5. Further Analysis

5.1. Mechanism Tests

The previous section demonstrates that digital transformation can significantly enhance green resilience, and this section further investigates the mechanisms at play. Therefore, this part draws on the study of Wen and Ye [85] to validate the above three paths using the mediation model as follows:

$$M_{it} = \beta_0 + \beta_1 Dige_{it} + \sum_{j=1}^{k} \gamma_j controls_{it} + \delta_i + \eta_t + \varepsilon_{it} \quad (13)$$

$$Gee_{it} = \theta_0 + \theta_1 Dige_{it} + \theta_2 M_{it} + \sum_{j=1}^{k} \gamma_j controls_{it} + \delta_i + \eta_t + \varepsilon_{it} \quad (14)$$

M is the relevant mechanism variable, which represents government investment (Gov), industrial integration (Inte), and public environmental concern (Pec), respectively.

5.1.1. Government Investment

Environmental governance mainly relies on government investment. We choose government investment as a mediating variable to study the mechanism of its digital transformation on green resilience, and government investment is represented by general budget expenditure. The results are shown in columns (1) and (2) of Table 8. Column (1) indicates that digital transformation has a positive effect on government investment, and

column (2) indicates that government investment can improve green resilience and that the coefficient of digital transformation is positive. It proves that digital transformation can promote green resilience by attracting government investment and, thus, verifying hypothesis 2. In addition, we test the mediating effect of government investment between digital transformation and green resilience using Bootstrap mediation effects. The mediation effect test is found to be significant at the 95% statistical level on the confidence interval, and the confidence interval does not contain 0, indicating further support for the mediating role of government investment.

Table 8. Mechanism of action tests.

Variable	(1) Gov	(2) Gee	(3) Inte	(4) Gee	(5) Pec	(6) Gee
Dige	0.211 ***	0.037 ***	0.098 ***	0.014 ***	13.583 ***	0.029 ***
	(9.2158)	(12.1749)	(17.8835)	(4.4836)	(9.4195)	(7.7289)
Gov		0.107 ***				
		(14.5807)				
Inte				0.465 ***		
				(16.1987)		
Pec						0.002 ***
						(8.4288)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	279	279	279	279	279	279
R^2	0.850	0.786	0.820	0.839	0.924	0.790

Note: Standard errors are reported in parentheses; *** indicate significant at the 1% levels, respectively.

5.1.2. Industrial Integration

Industrial integration can promote the optimization of the industrial structure, thus increasing the level of greening. We introduce industrial integration as a mediating variable and draw on previous research [86,87] to construct an indicator system for industrial integration. Specific indicators are shown in Table 9. Then, the coupled coordination degree model is used to measure the level of industrial integration and verify its mediating role. The results are shown in Table 8, columns (3) and (4). Column (3) indicates that digital transformation promotes industry convergence, and column (4) indicates that industrial integration enhances green resilience and that the digital transformation coefficient is positive. It proves that digital transformation can enhance green resilience by facilitating industrial integration and, thus, validating Hypothesis 3. After applying the Bootstrap mediation effect test, the mediating effect of industrial integration remains significant.

5.1.3. Public Environmental Concerns

Public concern for the environment can serve to protect the environment and reduce pollutant emissions. We introduce public environmental concern as a mediating variable, and public concern is expressed by Baidu's "environmental pollution" search index. The results are shown in columns (5) and (6) of Table 8. Column (5) indicates that digital transformation contributes to public environmental concern, and column (6) indicates that public environmental concern enhances green resilience and that the coefficient of digital transformation is positive. It proves that digital transformation can contribute to green resilience by increasing public environmental concern, thus validating Hypothesis 4. Similarly, the mediating effect of public environmental concern remains significant after applying the Bootstrap mediation effect test.

Table 9. Industrial integration indicator system.

Target Layer	Tier 1 Indicators	Secondary Indicators	Properties	Indicator Weights
advanced manufacturing industry	Scale indicators	Total investment in fixed assets in the manufacturing sector (billion yuan)	+	0.0750
		Number of advanced manufacturing enterprises (units)	+	0.1201
		Employment in advanced manufacturing (10,000 persons)	+	0.1362
		Main business income of advanced manufacturing industry (billion yuan)	+	0.1342
	Benefit indicators	Total profit (billion yuan)	+	0.1213
		Average labor compensation wages/employment in manufacturing (yuan/person)	+	0.0149
	Structural indicators	Proportion of fixed asset investment in advanced manufacturing to total fixed asset investment (%)	+	0.0263
		Proportion of advanced manufacturing enterprises to the number of industrial enterprises (%)	+	0.0331
		Proportion of main business income to industrial main business income (%)	+	0.0377
	Innovation indicators	Full-time equivalent of R&D personnel in advanced manufacturing (person years)	+	0.1476
		Internal expenditures on R&D funding for advanced manufacturing (million yuan)	+	0.1535
modern service industry	Scale indicators	Total investment in fixed assets in modern services (billion yuan)	+	0.0901
		Number of enterprises in the modern service sector (units)	+	0.1515
		Employment in modern services (10,000 persons)	+	0.1074
		Value added of modern services (billion yuan)	+	0.1278
	Benefit indicators	Labor productivity (yuan/person)	+	0.0221
		Average labor compensation (yuan/person)	+	0.0750
	Structural indicators	Proportion of fixed-asset investment in modern services to total fixed-asset investment (%)	+	0.0654
		Ratio of the number of enterprises in the modern service sector to the number of enterprises in the tertiary sector (%)	+	0.0160
		Proportion of value added of modern services to value added of tertiary industry (%)	+	0.0054
	Innovation indicators	Full-time equivalent of R&D personnel in modern services (person years)	+	0.1492
		Internal expenditures on R&D funding for modern services (million yuan)	+	0.1902

5.2. Threshold Effect Analysis

5.2.1. Threshold Effect Tests

To investigate the nonlinear impact of digital transformation on green resilience, we use digital platform as a threshold variable. Drawing on Liu et al. [88], the degree of development of digital platforms is expressed as the logarithm of the interaction term of the number of broadband Internet users and online retail sales in each province. Considering that there may be one or more thresholds for the impact of digital transformation on green resilience and that the impact of digital transformation on green resilience may

differ after crossing different thresholds, we model the single-threshold model and the double-threshold model separately as follows:

$$Gee_{it} = \omega_0 + \omega_1 Dige_{it} I(q_i \leq r_1) + \omega_2 Dige_{it} I(q_i > r_1) + \sum_{j=1}^{k} \gamma_j controls_{it} + \varepsilon_{it} \quad (15)$$

$$Gee_{it} = \omega_0 + \omega_1 Dige_{it} I(q_i \leq r_1) + \omega_2 Dige_{it} I(r_1 < q_i \leq r_2) + \omega_2 Dige_{it} I(q_i > r_3) + \sum_{j=1}^{k} \gamma_j controls_{it} + \varepsilon_{\mathrm{it}} \quad (16)$$

r_i is the threshold value; $\omega 1$, $\omega 2$, ω_3, and φ are the coefficients of the influence of the respective variables at different threshold values; and I is the indicative function (taking the value of 1 if the threshold condition is met and 0 if it is not).

The results are shown in Tables 10 and 11. It can be found that the digital platform passes the double-threshold test at 1% significance level but fails the triple-threshold test. Their thresholds are 5.6851 and 16.8552.

Table 10. Threshold effect significance test results.

Variable	Threshold	F	P	Number of BS	1%	5%	10%
Dige	Single Threshold	69.05	0.0000	300	31.5335	26.4930	24.4374
	Double Threshold	40.62	0.0000	300	26.6758	21.9220	19.0781
	Triple threshold	16.48	1.0000	300	117.0467	103.1228	92.3786

Table 11. Threshold effect significance tests and threshold estimates.

Variable	Threshold	Threshold Estimate	Confidence Interval
Dige	Single Threshold	5.6851	[4.3451, 6.4709]
	Double Threshold	16.8552	[16.4818, 17.2270]

5.2.2. Threshold Model Results

Continuing with the empirical evidence, we obtained the parameter estimates of the threshold model, as shown in Table 12. It can be seen that the impact of digital transformation on green resilience is always positive in the sample interval, but it varies with the degree of development of digital platforms, which means that the impact of digital transformation on green resilience is non-linear. When the degree of development of digital platforms is below the threshold value of 5.6851, the estimated coefficient of digital transformation on green resilience is 0.0712; as the degree of development of digital platforms continues to rise and is in the middle of the two thresholds, the impact of digital transformation on green resilience decreases but is still positive at the 1% significance level; when the degree of development of digital platforms is above the threshold value of 16.8552, the impact of digital transformation on green resilience increases again slightly, with an estimated coefficient of 0.0364 at the 1% significance level. It shows that the impact of digital transformation on green resilience shows a non-linear effect of rising, then falling and finally rebounding slightly, showing an "N-shaped" trend, which verifies Hypothesis 5.

Table 12. Panel threshold model estimation results.

Variable	Regression Coefficient
$q_i \leq r_1$	0.0712 ***
	(0.00612)
$r_1 < q_i \leq r_2$	0.0265 ***
	(0.00271)
$q_i > r_2$	0.0364 ***
	(0.00342)
Controls	Yes
Province FE	Yes
Year FE	Yes
Observations	279
R^2	0.736

Note: Standard errors are reported in parentheses; *** indicate significant at the 1% levels, respectively.

6. Discussion of Results

Green resilience has become a key issue as global pollution concerns continue to rise and the importance of sustainable development becomes increasingly evident. Against this backdrop, enhancing green resilience is particularly important. This study examines the impact of digital transformation on green resilience based on provincial data from 2013 to 2021 and draws the following conclusions:

(1) Digital transformation enhances green resilience, and this conclusion still holds after a series of robustness and endogeneity tests [34,43,89,90]. In terms of control variables, the levels of urbanization, scientific and technological innovation, and openness to the outside world play a dampening effect on green resilience, and the level of economic development plays an enhancing effect on green resilience. The level of infrastructural levels has a negligible impact on green resilience.

(2) The heterogeneous results are categorized into three types. First, in terms of regional heterogeneity, digital transformation significantly increases green resilience in both the eastern and central regions, with a more pronounced increase in the eastern region, while digital transformation in the western region curbs green resilience, but the results are not significant [91,92]. Second, from the perspective of resource endowment heterogeneity, digital transformation enhances green resilience in both resource-based and non-resource-based provinces, but it does so better in resource-based provinces than in non-resource-based provinces [89]. Third, from the perspective of different levels of green resilience, at different levels of green resilience, the impact of digital transformation on green resilience will increase with the improvement of green resilience, showing the "Matthew effect".

(3) The results of the mechanism test show that digital transformation can enhance green resilience by attracting government investment [34], facilitating industrial integration [90], and increasing public environmental concern.

(4) The threshold results show that digital transformation has a nonlinear effect on green resilience [43]. When the digital platform is lower than the threshold value of 5.6851, digital transformation has a significant positive contribution to green resilience; with the increasing degree of development of the digital platform, the estimated coefficient of digital transformation decreases from 0.0712 to 0.0265; when the degree of development of the digital platform is higher than the threshold value of 16.8552, the impact of digital transformation on green resilience increases slightly again. Overall, the impact coefficient of digital transformation on green resilience shows an "N-shaped" curve.

7. Research Implications and Policy Recommendations

7.1. Theoretical Implications

(1) This paper clarifies the connotation of digital transformation and green resilience and measures them, providing a new perspective for the study of digital transformation and green resilience.
(2) We study the impact of digital transformation on green resilience and analyze it in terms of regional heterogeneity, resource endowment heterogeneity, and heterogeneity of different green resilience levels. It explores the impact of digital transformation on green resilience and enriches the research.
(3) We further investigate the mechanism of the mediation model from the "government–industry–public" perspective, which helps to clarify the internal mechanism of digital transformation on green resilience and makes the exploration of its indirect impact more systematic.

7.2. Practical Implications

(1) We clarify the current status through descriptive statistics and kernel density analysis. They help to understand the level of development and trends in digital transformation and green resilience; provide timely feedback and adjustments, so as to develop strategies and policies to improve digital transformation and green resilience; and explore the opportunities and potential of digital transformation and green resilience.
(2) Our study on the impact of digital transformation on green resilience helps to clarify the path to enhance green resilience. It provides a theoretical basis for policy measures to enhance green resilience, so that green resilience can be enhanced and green transformation can be realized, thereby improving air quality and reducing energy consumption. It ultimately enhances the ability of cities to face environmental pressures and changes, and further promotes their sustainable development and enhances their green competitiveness.

7.3. Policy Recommendations

Based on the above conclusions and research implications, we make the following recommendations:

(1) Digital transformation has great potential to enhance green resilience. On the one hand, provinces should build a sound digital infrastructure, which includes not only hardware facilities such as high-speed Internet and data centers, but also software services such as cloud computing and big data. These infrastructures will provide the necessary support for the digital transformation of various industries, thereby accelerating the research, development, and application of green technologies and pollution control technologies, and providing the impetus for sustainable development. On the other hand, provinces should further use digital technologies to promote the development of new energy sources and the popularization of green travel modes such as shared bicycles and electric vehicles, so that new energy resources can be developed, managed, and utilized more efficiently; energy consumption and carbon emissions can be reduced; and green and sustainable development can be achieved in the context of digital transformation.
(2) In terms of the heterogeneity results, there is an imbalance in the economic development and the level of digital infrastructure construction in the eastern, central, and western regions of China, leading to an uneven development of digital transformation. Overall, the degree of digitalization in the eastern and central regions is faster than that in the western region, so the eastern and central regions should drive the digital transformation of the western region. In addition, the western region should also accelerate the consolidation of digital infrastructure and improve the utilization of digital infrastructure to promote their own digital transformation. Both resource-based and non-resource-based provinces should commit themselves to the development of a green economy, such as the development of clean-energy industries,

circular economy models, and environmentally friendly industries. It will reduce the consumption of resources and the negative impact on the environment and achieve economic sustainability. At the same time, they should also strengthen urban planning and construction; improve the urban environment and infrastructure; enhance the living environment, cultural facilities, and public services in cities; and attract talent and investment, thereby enhancing their attractiveness and digital transformation. For cities with poor levels of green resilience, they should take advantage of the latecomer advantage of digital transformation and actively engage in environmental governance and green economic development, thereby improving green resilience.

(3) From the results of the mechanism analysis, the government should provide financial support for environmental governance and economic development, increase research support for green technologies and encourage provinces to apply them. At the same time, the government can set up special funds dedicated to projects that support digital transformation and enhance green resilience. The government could also guide the flow of social capital to the areas of digital transformation and green development by providing financial subsidies and tax incentives, forming a diversified investment pattern. Industries can strengthen cooperation with each other and should also focus on their own green transformation and pollutant emissions by strengthening technological innovation and utilizing digital technologies to reduce pollutant emissions. The public can learn about the environment and environmental issues by studying relevant knowledge books and reports. Meanwhile, they can also join environmental organizations and actively participate in some environmental activities, as well as share environmental information on social media and advocate a green lifestyle, so that more people can appreciate the importance of environmental protection.

(4) Threshold results show that China should pay attention to the development of digital platforms, provide strong policy support and a market environment for the development of digital platforms, and encourage them to continuously innovate and expand their business areas. Digital platforms should pay attention to their own skill building, combined with their own advantages and global development needs, to constantly carry out innovative research and development. They can also co-operate with other digital platforms at home and abroad to learn from advanced experience and technology, share resources, complement each other's strengths, enhance their competitiveness and influence, and jointly promote China's digital transformation to a higher stage for mutual benefit and win–win results.

7.4. Shortcomings and Outlook

This paper has the following shortcomings:

First, we explore the impact of digital transformation on green resilience based on data at the provincial level, and we can focus on an industry or enterprise for more detailed exploration in future research. Second, we have not yet studied the spatial effect, and future research can use spatial measurement models to explore the spatial spillover effect of digital transformation. Third, we have studied the mediating role of digital transformation on green resilience based on the "government–industry–public" perspective, and the theoretical analysis of the transmission mechanism of digital transformation is limited, so the perspective of mediating variables can be broadened in the future.

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