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Original Research

Research on Sustainable Green Development Based on Dynamic Evolutionary Games from the Perspective of Environmental Regulations and Digital Technology Subsidies

Yanshuo Lu, Wei Cao*, Xiang Liu

School of Economics and Management, Taiyuan University of Technology, Taiyuan 030024, China

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Abstract

The trade-off between economic growth and environmental pollution is a significant challenge for many developing countries. The emergence of digital technology is reshaping economic development and innovation systems, making it crucial to integrate digital technology and green enterprise innovation. However, local government environmental regulations can impact sustainable green development of enterprises. This study constructs a model of a three-party evolutionary game between the government, digital consulting institutions, and enterprises to explore external incentives for promoting sustainable green development among enterprises. Findings suggest that different instruments of environmental regulation have varying effects on sustainable green development of enterprises. High-intensity command-and-control, middle-intensity market-inspired, low-intensity public participation-based, and low-intensity digital technology subsidies are the optimal combination of strategies that can drive sustainable green development among enterprises more quickly and effectively in the long term. This paper proposes an optimal strategy for sustainable green development of enterprises under the game between local governments, enterprises, and digital consulting institutions from a multi-party evolutionary game perspective, providing a reference for policy development plans and theories of sustainable development for China's double carbon target.

Keywords: digital technology, environmental regulation, evolutionary game model, simulation analysis, sustainable green development

*e-mail: caowei@tyut.edu.cn

Introduction

In recent years, achieving sustainable and green development by balancing environmental pollution with economic growth has become a critical concern for many countries, particularly developing ones. The United Nations' 2030 Agenda initiative emphasizes that all nations worldwide should strive to achieve the Sustainable Development Goals (SDGs) by 2030, which call for collective action to promote prosperity while safeguarding the planet. New digital technologies have facilitated sustainable and green development, allowing many developed countries to accumulate technological advantages and make significant progress in promoting sustainable development. Architects in the United States are increasingly utilizing green digital technologies [1], such as Building Information Model (BIM), to improve the environmental sustainability of the building life cycle. Germany has implemented various digital technology projects, such as the Digital Product Passport, to promote sustainable development [2]. Japan is utilizing AI technology to support the achievement of the Sustainable Development Goals [3]. However, developing countries, including China, Brazil, India, Pakistan, and others, lack significant technological advantages. As a result, promoting the integration of digital technology and industry to achieve sustainable green development poses a significant challenge. Therefore, it is crucial to investigate how to attain the Sustainable Development Goals in developing countries and establish a robust and sustainable incentive mechanism.

Take China as an example, since its accession to the World Trade Organization (WTO), China's industrial development has made significant progress. The average annual growth rate has been 10.33%, and the value added to the industry accounts for 26.26% of the world's share, making it a vital contributor to global industrial growth. However, with the rapid growth of industrial value-added, issues such as inefficient industrial development models, overcapacity, and declining environmental carrying capacity have gradually emerged, becoming significant impediments to China's pursuit of high-quality economic development [4]. Meanwhile, the Chinese government has implemented several oversights and exceedingly stringent management mechanisms to protect the natural environment. However, they have often failed to achieve the desired results or have achieved the desired results while undermining economic development [5, 6]. As a result, China's continued reform and development are being significantly fuelled by the sustainable green development of industries due to the "twin constraint" of economic and environment.

The essence of sustainable green development is to improve the eco-efficiency of industry in response to the limited "ecological carrying capacity" caused by negative external factors such as environmental pollution [7, 8]. The emergence of environmental regulation has provided a new way of thinking about environmental pollution that the market alone cannot solve [9]. With government supervision and guidance, enterprises are more likely to take the initiative to engage in sustainable green development as an essential subject of green industrial development [10]. The main reason why enterprises actively choose to engage in sustainable green development is that the existence of environmental regulations will limit their pollution emissions and increase their operating costs [11, 12]. Therefore, the government should be a key player in the sustainable green development of enterprises. Furthermore, the emergence of next-generation information technology can effectively lower the threshold of sustainable green development and enhance its efficiency [13-15]. Large digital consulting institutions such as IBM and McKinsey offer a wide range of digital technical support to help enterprises engage in sustainable green development. In other words, the sustainable green development of enterprises is the result of shared participation and interaction from multiple stakeholders. From the supply side, the advancement in digital technology provides essential digital technical support for the sustainable green development of enterprises [16]; From the demand side, enterprises must go green under the background of "double carbon." From the regulatory side, the government has formulated policies and measures such as subsidies, tax exemptions, and carbon emissions trading, forming a regulatory model that combines mandatory, market-based, and public participation-based approaches [17-19]. However, more research is needed on using heterogeneous environmental regulatory tools and digital technical support for greening business development. With the goal of protecting the ecological environment while considering economic development, the optimal combination of heterogeneous environmental regulatory tools and their implementation intensity can be achieved by bringing together government enterprises and digital consulting institutions into a unified analytical framework. Therefore, this paper constructs a model of the evolutionary game between the government, digital consulting institutions, and enterprises. The model is utilized to investigate the effect of the behavioural strategies of enterprise sustainable green development stakeholders on economic growth and low-carbon development under heterogeneous environmental regulation and digital technology subsidies.

Heterogeneous environmental regulatory tools are suitable for governments to promote sustainable green development while balancing economic development and providing a good monitoring role for developing enterprises and digital consulting institutions. Moreover, they enable the subjects to make behavioural strategy choices driven by their interests, ultimately leading to the industry's sustainable green development. Previous studies have identified three primary categories of environmental regulation in China: market-inspired, command-and-control, and public participation-based

[20, 21]. Among them, market-based environmental regulation mainly relies on market mechanisms to incentivize economic agents to lower carbon emissions or introduce subsidy policies to guide enterprises towards technological innovation and sustainable green development. However, it may initially face challenges such as market failure, technology spill-over, and a shortage of funds. Command-and-control environmental regulation mainly involves the government's direct intervention in industrial enterprises through administrative supervision, constraints, and penalties [22]. Typically, the government will introduce clear emission reduction standards, require enterprises to adopt certain low-carbon technologies, or shut down high-carbon emitting enterprises to promote green industry development [23]. Coase argues that if there are no transaction costs, command-and-control environmental regulation can achieve the optimal allocation of market resources according to neoclassical economics. This outcome occurs mainly because market competition always maximizes the interests of both parties to a transaction at any cost, regardless of the initial institutional arrangements [24]. However, when transaction costs are present, market-incentivized environmental regulation fails. Finally, public participation-based environmental regulation affects the greening of industries mainly through the indirect effects of enterprise technological innovation, mainly through individual and social pressures on enterprises, in the form of moral, economic, and institutional influences [23]. Studies show that public participation-based environmental regulation has a substantial influence on the sustainable green development of Chinese enterprises [25].

Currently, heterogeneous environmental regulation tools are a significant way for governments to engage in the sustainable green development of enterprises and can effectively influence the direction of their development [26-28]. However, a large body of research has yet to reach a uniform conclusion on whether heterogeneous environmental regulatory instruments inhibit or promote the sustainable green development of enterprises. There are three main types of research findings on the influence of heterogeneous environmental regulatory instruments on the sustainable green development of enterprises. The first is the "negativity hypothesis." The main argument is that heterogeneous environmental regulation hinders or at least does not contribute to the sustainable green development of enterprises. Some scholars argue that while environmental regulations promote production efficiency in enterprises in the short term, they inhibit patent output. The long term effects of strict environmental laws on R&D spending could be detrimental. [29, 30] Additionally, because environmental restrictions vary from city to city, highly polluting enterprises will only relocate to places with laxer environmental regulations. [31-33], instead of promoting sustainable green development, this contributes to the spread of pollution and the formation of 'pollution havens.' Other scholarly studies have shown that implementing environmental regulations in China has had an east-to-west bias toward mitigating industrial pollution [25, 34]. The second conclusion is the "Porter hypothesis." Its central argument is based on a long-term perspective, which suggests that environmental regulation will encourage innovation and push enterprises to undertake green innovations, thus offsetting extra expenses associated with environmental regulations [35]. On the other hand, by upgrading technical processes and increasing production efficiency, enterprises can reap additional innovation benefits; environmental regulation can have an "innovation compensation" effect that motivates enterprises to green their development. The Porter hypothesis has been tested by several scholars [36-38]. Some scholars have found that green innovation technologies can be incentivized by environmental regulation [39], and encourage the sustainable green development of enterprises. Environmental regulatory instruments of market-inspired, public participation-based, and command-and-control can greatly facilitate innovation in green products, green processes, and end-of-pipe treatment [40-42]. Other scholars argue that environmental regulation also stimulates R&D and innovation in environmentally relevant technologies and increases investment in environmental capital. However, there is no significant increase in total R&D, suggesting that R&D devoted to the environment is crowding out other R&D [43, 44]. The third conclusion is the "uncertainty hypothesis." Some scholars argue that environmental regulation and sustainable green development have a nonlinear relationship [45]. Additionally, it has been asserted that the role of heterogeneous environmental regulations varies from region to region in China and that no single environmental regulation tool has a specific effect [5]. It is clear from the existing literature that there is no uniform conclusion on whether regulations about environmental promote the sustainable green development of enterprises.

Furthermore, in today's highly developed world of information technology, digital technology can be an excellent tool to reduce costs and promote the efficiency of sustainable green development in enterprises [46-48]. Digital technology encompasses a range of computer-aided technologies, such as big data analytics and cloud computing, among others, and its usage in enterprises can be revolutionary in sustainable areas [49]. Moreover, digitally transformed enterprises can ease financing constraints and attract government subsidies to improve green technology innovation [50]. In addition, digital technology can further promote green product innovation and bring enterprises into a positive cycle of development [51, 52]. However, due to uncontrolled risks and a lack of drivers, organizations providing digital technology support may need more time and motivation to engage in enterprise green innovation and therefore need government guidance and inspiration. However, the existing literature rarely considers the impact

on enterprise sustainable green development from the dual perspective of heterogeneous environmental regulation and digital technology subsidies. This paper presents a three-party evolutionary game model involving the government, digital consulting institutions, and enterprises to explore the external incentives that drive government policies and digital consulting institutions to collaboratively promote sustainable green development among enterprises. The model aims to advance institutional reforms in China and facilitate sustainable green development in China and other developing countries.

This paper's originality lies in:

(1) Innovation from the standpoint of research. The majority of recent studies on the sustainable green development of enterprises under the perspective of environmental regulation are static. Therefore, this paper introduces a dynamic evolutionary game model with three parties.

(2) Innovation in research methodology. Regarding research subjects, most of the current topics on evolutionary games focus on government and enterprises. Failure to take into account the impact of digital technology on enterprises. Therefore, this paper innovatively introduces a digital consulting institution as a third party in the game.

(3) Innovation in research content. this paper introduces an innovative tool for public participation-based in environmental regulation. Meanwhile, the effects of different environmental regulations, like market-inspired and command-and-control regulations, are more discussed in the contemporary literature.

This study makes a significant theoretical contribution to the literature by incorporating digital consulting institutions into a three-party evolutionary game model that considers digital technologies. Additionally, our research offers practical implications for promoting sustainable green development in China and other developing countries.

Construction of a Model for a Three-Party Evolutionary Game

This study examines the operational mechanisms of the government regarding the production of enterprises and digital consulting institutions based on the evolutionary game model. Evolutionary game theory offers several advantages over traditional game theory. Firstly, the evolutionary game model excludes the assumption of perfect competition made by traditional theory, while taking into account the mutual influence of individual parties. In the tripartite evolutionary game model, three types of strategies or players are considered. These players can be individuals, groups, or even species, depending on the specific context of the study. Each player has a set of strategies or behaviours that they can choose from [53]. Secondly, evolutionary games incorporate the concept of time, reflecting the dynamic nature of the game. Different parties can improve themselves through continuous learning within the game. The evolution of strategies in the tripartite game model is driven by the principles of natural selection. Players with strategies that yield higher payoffs have a higher probability of reproducing and passing on their strategies to the next generation. Thirdly, the evolutionary game model accounts for random disturbances by introducing stochastic mutations into the model. Through constant learning and improvement, individual parties can refine their tactics and eventually attain a stable state [54].

Assumptions and Analysis of Evolutionary Game Models

In accordance with current environmental regulations set forth by the Chinese government, this three-party evolutionary game model involves players who are related in the following ways:

(1) The sustainable green development of industries is crucial for creating a liveable ecological environment and addressing various environmental issues. The Chinese government has recognized the importance of sustainable green development and has included it in its national development plan. However, highly polluting and highly emitting enterprises may not prioritize sustainable green development due to the additional costs it incurs, which conflicts with their goal of profit maximization [55]. Therefore, the government must play a role in monitoring and promoting sustainable green development through various environmental regulation tools. Additionally, the emergence of digital technology has lowered the threshold for enterprises to undertake sustainable green development, making it more accessible. Digital consulting institutions can provide technical support to help enterprises achieve sustainable green development. Fig. 1 below illustrates the specific impact mechanism.

(2) China's government: The Chinese government employs three main environmental regulatory tools: market-inspired, public participation-based, and command-and-control [56]. Command-and-control environmental regulation involves direct government efforts to stimulate enterprises to undertake sustainable green development [57]. Market-inspired environmental regulatory instruments regulate and guide enterprises to make appropriate production decisions, primarily through taxes and subsidies [58]. Public participation-based environmental regulation mainly uses the news media to disclose information and force enterprises to lower emissions. Additionally, it raises public awareness of ecological preservation. The government's overall goal is to facilitate the transition from highly polluting to fewer polluting enterprises without unduly damaging the economy. Overly stringent environmental regulations can make enterprises fearful and harm the economy, leading to uneven development and even regression. However, a comfortable living environment

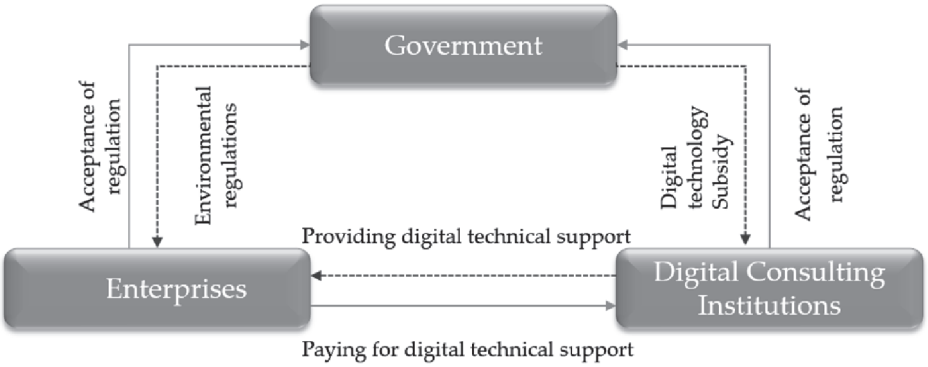

Fig. 1. The three parties' mutual influence mechanism.

is demanded by the public, and the government cannot ignore the public's demand for the environment while developing the economy.

(3) Enterprises: In a situation where environmental policy uncertainty is prominent and ecological environmental protection is "at risk" and "at opportunity", is it better to "take the initiative and seek change" by quickly responding to strategic decisions on digitally enabled environmental protection and seeking or to be "cautious" and avoid the risks associated with environmental policy uncertainty and delay green innovation decisions. The choice faced by enterprises [59]. Enterprises need to weigh the income returns of both to make the optimal choice.

(4) Digital Consulting Institutions: By providing digital technical support to help enterprises to transform digitally, improve management efficiency, optimize enterprise structure and thus lower the threshold of sustainable green development of enterprises [60] and accept government regulation. At the same time, there are huge benefits to be gained from government and enterprises. However, if enterprises are not willing to go green, they will force digital consulting institutions to pay huge sunk costs. Digital consulting institutions are also faced with the choice of whether to provide digital technical support or not.

The above analysis shows that there is a game relationship among the government, enterprises and digital consulting institutions. Therefore, this paper makes the following assumptions:

Hypothesis 1. In a state where external factors are not taken into account, there is a system consisting of government, digital consulting institutions and enterprises, and the government, digital consulting institutions and enterprises all have the characteristics of limited rationality. The government has two strategies to choose from, which are to impose or not to impose environmental regulations, and the government can impose different intensities of environmental regulation. The likelihood that the government will impose environmental regulations is y, and the likelihood that the government will not impose environmental regulation is 1-y. Enterprises have two strategies to choose from, which are to undertake or not to undertake sustainable green development, and the likelihood that enterprises will undertake sustainable green development is x, and the likelihood that enterprises will not undertake sustainable green development is 1-x. Digital consulting institutions have two strategies to choose from, that is to provide or not to provide digital technical support. The likelihood of a digital consulting institution providing digital technical support is z, and the likelihood of not providing digital technical support is 1-z.

Hypothesis 2. Three types of environmental regulation are available to the government to encourage enterprises to participate in sustainable green development, that is, command-and-control, market-inspired and public participation-based, as well as incentives for digital consulting institutions through digital technology subsidies. If enterprises undertake sustainable green development, public satisfaction will be reflected in the government's gain ΔP_2. Conversely, if enterprises do not undertake sustainable green development, public dissatisfaction with the environment is likewise reflected in the government's gain S_g. On the one hand, it might deepen people's comprehension of environmental preservation, and on the other hand, it can facilitate public education by the government. The intensity factors for subsidizing digital consulting institutions, incentivizing the development of enterprises (mainly through taxes and subsidies), penalizing enterprises and communicating to the public about enforcement are α, β, γ, η.

Digital technology subsidies are targeted at digital consulting institutions, with the aim of guiding digital consulting institutions to help enterprises to undertake sustainable green development. The market-inspired environmental regulation tool is to offer incentive subsidies to enterprises. Incentive subsidies are allocated to enterprises before they undertake sustainable green development and used for process improvement and waste treatment in enterprises. Enterprises can request to the government for incentive subsidies based on their own innovation practices, a form of positive incentive behaviour. Command-and-control environmental regulation, which penalizes enterprises for not carrying out sustainable green development and can reduce

the incidence of "subsidy fraud" by enterprises. The importance placed on the social environment is primarily a representation of public participation-based environmental regulation.

Hypothesis 3. The sustainable green development of an enterprise can be divided into three main areas: green waste treatment, green process optimization, green raw material acquisition. If an enterprise undertakes sustainable green development, it will innovate in these three dimensions, otherwise it will maintain its traditional development approach. The basic benefit for an enterprise is Pm if it chooses a traditional technology, while the benefit for a green technology innovation increases by ΔP_1. The original benefit for a digital consulting institution is Pu.

Hypothesis 4. There are costs associated with the greening of an enterprise. When the digital consulting institution chooses to help the sustainable green development of enterprises, the cost to the digital consulting institution is C_u while the cost to the enterprises is C_1; when the digital consulting institution chooses not to facilitate the sustainable green development of enterprises, the cost to the enterprises is C_2. The variables indicated in the aforementioned hypotheses are depicted in Table 1.

The Payment Function

In a three-party evolutionary game, the payments of each player are influenced by the strategies of the other two game players. Fig. 2 shows the four strategy combinations when the government imposes environmental regulation, where T in digital consulting institution means providing digital technical support and F means not providing digital technical support. There are also four strategy combinations when the government does not engage in environmental regulation.

Based on the four assumptions and three-party evolutionary game flow chart above, constructing a payment matrix for the three parties, as depicted in Table 2.

Three-Party Expected Payment and Replication Dynamic Equations

The Replication Dynamic Equations of Enterprises

Let E_{11} represents the expected payment of enterprises if it undertakes sustainable green development, and E_{12} represents the payment of enterprises if it does not undertake sustainable green development. $\bar{E}_1$ represents the average expected payment of enterprises. E_{11}, E_{12}, and $\bar{E}_1$ can be expressed as Equation (1), Equation (2), and Equation (3):

$$E_{11} = yz(P_m + \Delta P_1 + \beta T - C_1) + y(1-z)(P_m + \Delta P_1 + \beta T - C_2) + z(1-y)(P_m + \Delta P_1 - C_1) + (1-z)(1-y)(P_m + \Delta P_1 - C_2) \quad (1)$$

Table 1. Parameter symbol description.

Symbols	Measure
P_m	Enterprises originally gained without sustainable green development
ΔP_2	Social benefits when enterprises undertake sustainable green development
P_u	Digital consulting institutions originally gained
ΔP_1	Additional benefits gained when enterprises undertake sustainable green development
C_1	The expense of sustainable green development for enterprises when digital consulting institutions collaborate
C_2	The expense of sustainable green development for enterprises when the digital consulting institutions are not collaborative
C_u	Costs incurred by digital consulting institutions in providing digital technical support
S_g	Government losses when enterprises do not undertake sustainable green development (mainly in terms of government reputation, public pressure, etc.)
J	Government provides digital technology subsidies to digital consulting institution institutions
T	Government-imposed market-inspired environmental regulation
F	Government-imposed command-and-control environmental regulation
α	The intensity of government provision of digital technology subsidies
β	The extent to which the government imposes market-inspired environmental regulations
γ	The extent to which the government imposes command-and-control environmental regulations
η	The extent to which the government imposes public participation-based environmental regulations
x, y, z	Strategic choices for three-party behaviour

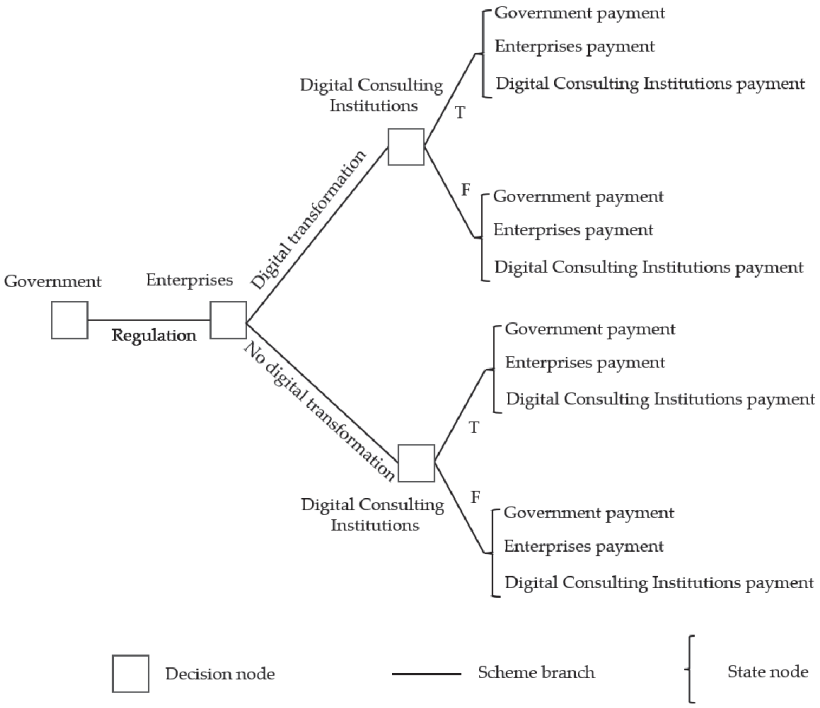

Fig. 2. Three-party evolutionary game flow chart

$$E_{12} = yz(P_m - rF) + (1-z)y(P_m - rF) + z(1-y)P_m + (1-x)(1-y)P_m \quad (2)$$

$$\overline{E}_1 = xE_{11} + (1-x)E_{12} = P_m - xC_2 + x\Delta P_1 - y\gamma F - xzC_1 + xzC_2 + xy\beta T + xy\gamma F \quad (3)$$

Therefore, the enterprise replication dynamic equations can be portrayed as Equation (4):

$$F(x) = \frac{dx}{dt} = x\left(E_{11} - \overline{E}_1\right) = x(1-x)[z(C_2 - C_1) + y(\beta T + \gamma F) + \Delta P_1 - C_2] \quad (4)$$

The Replication Dynamic Equations of the Government

Let E_{21} represent the expected payment of the government if it imposes environmental regulation, and

Table 2. Payment matrix among the three subjects.

Enterprises	Digital Consulting Institutions	Government					
		Imposing environmental regulation (y)			Not to impose environmental regulation (1-y)		
		Enterprises payment	Government payment	Digital Consulting Institutions payment	Enterprises payment	Government payment	Digital Consulting Institutions payment
Sustainable green development (x)	Provide digital technical support (z)	$P_m + \Delta P_1 + \beta T - C_1$	$\Delta P_2 - \alpha T - \beta T$	$P_u + \alpha T + \eta C_1 - C_u$	$P_m + \Delta P_1 - C_1$	ΔP_2	$P_u + \eta C_1 - C_u$
	No digital technical support (1-z)	$P_m + \Delta P_1 + \beta T - C_2$	$\Delta P_2 - \beta T$	P_u	$P_m + \Delta P_1 - C_2$	ΔP_2	P_u
No sustainable green development (1-x)	Provide digital technical support (z)	$P_m - \gamma F$	$\gamma F - \alpha T - S_g$	$\alpha J - C_u$	P_m	$-S_g$	$-C_u$
	No digital technical support (1-z)	$P_m - \gamma F$	$\gamma F - S_g$	0	P_m	$-S_g$	0

E_{22} represent the payment of the government If it does not implement environmental regulation. $\overline{E}_2$ represents the average expected payment of the government. E_{21}, E_{22}, and $\overline{E}_2$ can be expressed as Equation (5), Equation (6), and Equation (7):

$$E_{21} = xz(\Delta P_2 - \alpha J - \beta T) + z(1-x)(\gamma F - \alpha J - S_g) + x(1-z)(\Delta P_2 - \beta T) + (1-x)(1-z)(\gamma F - S_g) \quad (5)$$

$$E_{22} = xz\Delta P_2 + z(1-x)(-S_g) + x(1-z)\Delta P_2 + (1-x)(1-z)(-S_g) \quad (6)$$

$$\overline{E}_2 = yE_{21} + (1-y)E_{n2} = xS_g - z\Delta P_2 - S_g + y\gamma F + xy(\Delta P_2 - \beta T - \gamma F) + yz(\Delta P_2 - \alpha J) \quad (7)$$

Therefore, government's replication dynamic equations can be written as Equation (8):

$$F(y) = \frac{dy}{dt} = y(E_{21} - \overline{E}_2) = y(1-y)[x(\Delta P_2 - \beta T - \gamma F) + z(\Delta P_2 - \alpha J) + \gamma F] \quad (8)$$

The Replication Dynamic Equations of Digital Consulting Institutions

Let E_{31} represent the expected payment of digital consulting institutions if it provides digital technical support, and E_{32} represents the payment of digital consulting institutions If it does not provide digital technical support. $\overline{E}_3$ represents the average expected payment of digital consulting institutions. E_{31}, E_{32}, and $\overline{E}_3$ can be expressed as Equation (9), Equation (10), and Equation (11):

$$E_{31} = xy(P_u + \alpha J + \eta C_1 - C_u) + (1-x)y(\alpha J - C_u) + x(1-y)(P_u + \eta C_1 - C_u) + (1-x)(1-y)(-C_u) \quad (9)$$

$$E_{32} = xyP_u + x(1-y)P_u \quad (10)$$

$$\overline{E}_3 = zE_{31} + (1-z)E_{32} = xP_u - zC_u + xz\eta C_1 + yz\alpha J \quad (11)$$

Therefore, the replication dynamic equations of digital consulting institutions can be portrayed as Equation (12):

$$F(z) = \frac{dz}{dt} = z(E_{31} - \overline{E}_3) = z(1-z)(y\alpha J + x\eta C_1 - C_u) \quad (12)$$

Model Analysis

Finding the equilibrium point of the stable strategy requires that F(x), F(y), and F(z) values be 0. The stable equilibrium for the evolution of the three parties can be obtained, respectively: E1 = (0, 0, 0), E2 = (0, 1, 0), E3 = (0, 0, 1), E4 = (1, 0, 0), E5 = (0, 1, 1), E6 = (1, 1, 0), E7 = (1, 0, 1), E8 = (1, 1, 1). The stability of these equilibria can be obtained by Jacobian matrix stability analysis.

Since stable strategies in evolutionary games between equilibrium points can only occur in pure strategies, mixed strategies (x*, y*, z*) are first ruled out. Next, the local stability analysis of the Jacobian matrix can obtain the stability of the equilibrium point of the evolutionary game system, and the Jacobian matrix can be expressed as Equation (13):

$$Jacobian = \begin{vmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{vmatrix} = \begin{vmatrix} (2x-1)\begin{bmatrix} C_2 + C_1 - \Delta P_1 - zC_2 \\ -y(\gamma F + \beta T) \end{bmatrix} & -x(x-1)(\gamma F + \beta T) & x(x-1)(C_1 - C_2) \\ y(y-1)(\gamma F - \Delta P_2 + \beta T) & (2y-1)\begin{bmatrix} z(\alpha J - \Delta P_2) - \gamma F \\ +x(\gamma F + \beta T - \Delta P_2) \end{bmatrix} & -y(y-1)(\Delta P_2 - \alpha T) \\ -z(z-1)\eta C_1 & -z(z-1)\alpha J & (2z-1)\begin{bmatrix} C_u - y\alpha J \\ -x\eta C_1 \end{bmatrix} \end{vmatrix} \quad (13)$$

Taking the E1(0, 0, 0) as an example, its Jacobi matrix can be found by analysing its stability as: $J_1 = \begin{pmatrix} \gamma F & 0 & 0 \\ 0 & \Delta P_1 - C_2 & 0 \\ 0 & 0 & -C_u \end{pmatrix}$.

It is known that the eigenvalues of E1(0,0,0) are $\lambda 1 = \gamma F$, $\lambda 2 = \Delta P_1 - C_2$, $\lambda 3 = -C_u$. In order to get the rest of the eigenvalues, The results are displayed in Table 3 after each equilibrium point is gradually inserted into the Jacobian matrix.

We are concerned about the stable point of enterprises that do not undertake sustainable green development, that is, x = 0. Since E1 = (0,0,0) and E4 = (0,0,1) have eigenvalues that are necessarily greater than 0, it is impossible for both to be stable points. So only E3 = (0,1,0) and E7 = (0,1,1) need to be discussed. Therefore, Proposition I and Proposition II are proposed and argued.

Proposition 1. When $\alpha J - C_u < 0$ and $\Delta P_1 - C_2 + \gamma F + \beta T < 0$, it is the only Evolutionary Stable Strategy (ESS) point that enterprises and digital consulting institutions both choose negative strategies, only the government chooses positive ones.

Proposition 1 shows that if enterprises choose a positive strategy (undertake sustainable green development), it will cost more. Therefore, enterprises will not choose to undertake sustainable green development, that is, x = 0. and meanwhile digital consulting institutions will not choose to provide digital technical support, that is, z = 0. The governments can impose tougher environmental regulations and numerical subsidies to achieve the goal of promoting enterprises' choice to undertake sustainable green development.

Thus, the first conclusion can be drawn from the above analysis: if the strength of government environmental regulations or subsidies is not strong enough, then it is difficult for enterprises to undertake sustainable green development. The first conclusion is also understandable in practice. When the costs

Table 3. Jacobi matrix eigenvalues.

Equilibrium Points	λ_1	λ_2	λ_3
$E_1 = (0,0,0)$	γF	$\Delta P_1 - C_2$	$-C_u$
$E_2 = (1,0,0)$	$\eta C_1 - C_u$	$C_2 - \Delta P_1$	$\Delta P_2 - \beta T$
$E_3 = (0,1,0)$	$\alpha J - C_u$	$-\gamma F$	$\Delta P_1 - C_2 + \gamma F + \beta T$
$E_4 = (0,0,1)$	C_u	$\Delta P_1 - C_1$	$\Delta P_2 + \gamma F - \alpha T$
$E_5 = (1,1,0)$	$\beta T - \Delta P_1$	$\eta C_1 - C_u + \alpha J$	$C_2 - \Delta P_1 - \gamma F - \beta T$
$E_6 = (1,0,1)$	$C_1 - \Delta P_1$	$C_u - \eta C_1$	$2\Delta P_2 - \alpha J - \beta T$
$E_7 = (0,1,1)$	$C_u - \alpha J$	$\alpha J - \gamma F - \Delta P_2$	$\Delta P_1 - C_1 + \gamma F + \beta T$
$E_8 = (1,1,1)$	$C_u - \eta C_1 - \alpha T$	$\alpha J - 2\Delta P_2 + \beta T$	$C_1 - \Delta P_1 - \gamma F - \beta T$
$E_9 = (x^*, y^*, z^*)$		Saddle point	

outweigh the benefits, enterprises tend not to be motivated to undertake sustainable green development.

Proposition 2. When $C_u - \alpha J<0$ and $\Delta P_1 - C_1 + \gamma F + \beta T <0$. it is the only ESS point that the government and digital consulting institutions both choose positive strategies, only enterprises choose negative ones.

It follows from Proposition 2 that digital consulting institutions will provide digital technical support if they pay less than the government's digital technology subsidy, that is, z = 1. However, if the cost of sustainable green development for enterprises is still greater than the benefit under the premise of environmental regulation by the government and digital technical support provided by digital consulting institutions, then the enterprises will not undertake sustainable green development at this time, that is, x = 0. Therefore, we can draw a second conclusion: an appropriate subsidy can make a digital consulting institution choose an aggressive strategy, but it will not necessarily make an enterprise choose an aggressive strategy as well.

Taking the two propositions together, the government will choose a positive strategy when setting $\alpha J - 2\Delta P_2 + \beta T <0$. At this point, the government gains more from the sustainable green development of the enterprise than its environmental regulation expenditure, so it will choose a positive strategy. When the government chooses to support the sustainable green development of enterprises, the benefits that enterprises get from sustainable green development must be greater than the costs they put into sustainable green development, otherwise the enterprises will not choose sustainable green development, so set $C_1 - \Delta P_1 - \gamma F - \beta T<0$. Digital consulting institutions will not take the risk of providing digital technical support to enterprises if the benefits they get from providing digital technical support are less than their own expenses, so set $C_u - \eta C_1 - \alpha T <0$. With this setting, it is the only ESS point that enterprises undertake sustainable green development, the government imposes environmental regulation, and digital consulting institutions provide digital technical support, that is, x = 1 and y = 1 and z = 1.

Simulation Analysis of Evolutionary

To verify the path of the sustainable green development of enterprises under different environmental regulations and the support of digital consulting institutions, this paper carries out a simulation based on replicated dynamic equations and constraints using the MATLAB R2022a software. The parameters α, β, γ and η are adjusted to explore the effects of various environmental regulation intensities and digital technology subsidy intensities on enterprises and digital consulting institutions. When the parameter is 0, it indicates that the government adopts the most lenient regulatory measures. When the parameter is 1, it indicates that the government is taking the most stringent regulatory measures. In order to further ensure the validity and robustness of this result, it is argued that without the help of the government and digital consulting institutions, the costs of sustainable green development undertaken by enterprises on their own are higher than the benefits in the short term, that is, $\Delta P_1 - C_2<0$. Middle managers from various enterprises, primarily from the Departments of Ecological Environmental Protection, Finance, and Planning and Investment, were interviewed to gain a deeper understanding of enterprise development. Subsequently, 15 experts from Taiyuan University of Technology, the Finance Department of the Shanxi Provincial Party Committee, the General Office of the Taiyuan Municipal Party Committee, and other relevant research institutions were interviewed to establish parameters and values for different subjects from the perspectives of academic research and government decision-making. Therefore, the parameters are initially set as follows: $\alpha = 0.5$, $\beta = 0.5$, $\gamma = 0.5$, $\eta = 0.5$, $C_1 = 40$, $C_2 = 50$, $T = 20$, $F = 30$, $J = 40$, $\Delta P_2 = 45$, $\Delta P_1 = 10$, $P_u = 10$, $C_u = 30$.

Analysis of the Effects of Different Environmental Regulation Intensity on Evolutionary Pathways

Analysis of Command-and-Control Environmental Regulation of Different Intensities

First, to make clear how command-and-control environmental management affects evolutionary pathways, γ was assigned the values $\gamma = 0.2$, 0.5, 0.9, and the simulation results for 50 evolutions over time are depicted in Fig. 3.

The three-party evolutionary path under the effect of different intensities of command-and-control environmental regulation is depicted in Fig. 3a). Fig. 3a) illustrates that enterprises will not to undertake sustainable green development when the intensity of punishment is small ($\gamma = 0.2$). When the punishment is stronger ($\gamma = 0.5$), enterprises spontaneously undertake sustainable green development. When the discipline is stronger ($\gamma = 0.9$), enterprises will still undertake sustainable green development, except that the three-party evolutionary game reaches equilibrium earlier compared to $\gamma = 0.5$. The smaller graphs in Fig. 3a) provide a more visual representation of the speed of reaching stability from a different perspective.

Fig. 3(b, c, d) show the three-party evolution paths for γ = 0.2, 0.5 and 0.9, respectively, corresponding to the three-party evolution paths under low-, middle- and high-intensity command-and-control environmental regulations, with x representing enterprises, y representing the government and z representing digital consulting institutions. Fig. 3b) shows that enterprises will not to undertake sustainable green development when low intensity command-and-control environmental regulations are implemented, and the benefits of sustainable green development are less than the costs. At this level of environmental regulation, both the government and digital consulting institutions choose to be proactive. As for the government, although the low intensity of environmental regulation does not make enterprises go green, the penalties imposed on the enterprises do generate some revenue for the government. Since digital consulting institutions are subsidized by the government, they will also be part of the positive strategy. However, this steady state is not what we want.

As can be seen in Fig. 3c) and Fig. 3d), as environmental regulations continue to be carried out at a middle intensity, the government's discipline increases and the choices of enterprises begin to change, and as environmental regulation becomes more stringent, enterprises reach a steady state of sustainable green development more quickly. The main difference between Fig. 3c) and Fig. 3d) is that as environmental regulation becomes more stringent, enterprises evolve at a faster rate and reach a stable point more quickly. There is no significant difference in the speed of stabilization between the government and digital consulting institutions.

In summary, low-intensity command-and-control environmental regulation does not create an 'innovation compensation' effect for enterprises and only increases

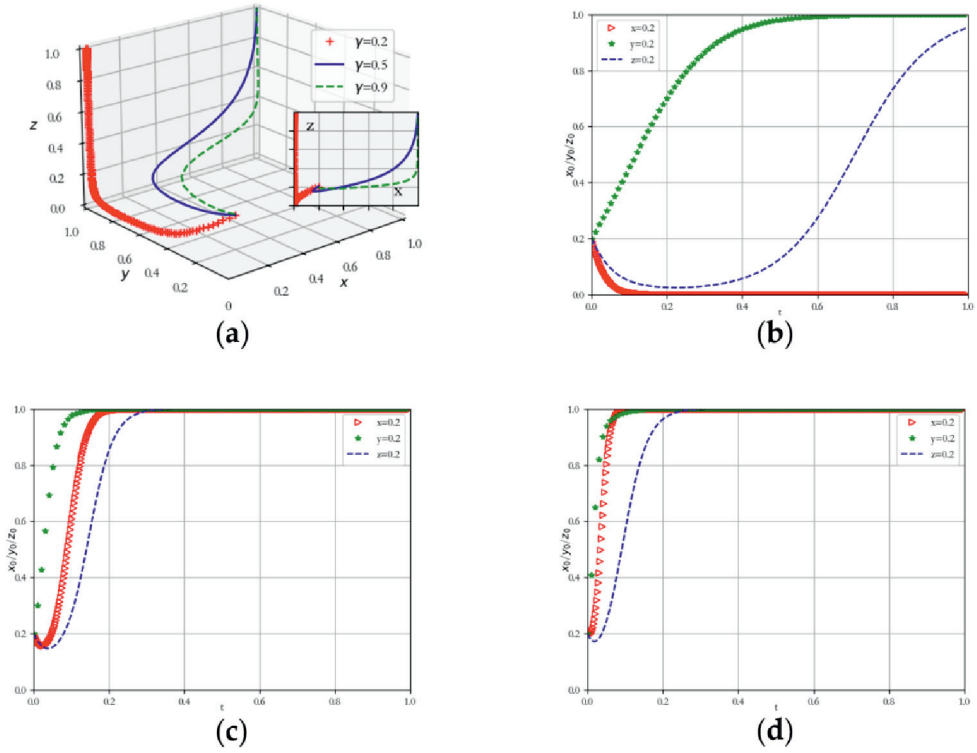

Fig. 3. a) Evolution paths for three subjects when γ changes. Evolutionary paths of three-party at $\gamma = 0.2$ b), $\gamma = 0.5$ c) and $\gamma = 0.9$ d).

social costs without improving the living environment. High or middle-intensity environmental regulation will encourage enterprises to undertake sustainable green development. And higher levels of command-and-control environmental regulation will lead enterprises to undertake sustainable green development more quickly.

Analysis of Market-Inspired Environmental Regulation of Different Intensities

To make clear how market-inspired environmental management affects evolutionary pathways, β was assigned the values β = 0.2, 0.5, 0.9, and the simulation results for 50 evolutions over time are depicted in Fig. 4.

Fig. 4a) depicts the evolutionary course of a three-party evolutionary game with various market-inspired environmental regulatory levels. And from Fig. 4a) we can know that when the incentive is small (β = 0.2), enterprises will not undertake sustainable green development, and only the government imposes environmental regulation at this time, and digital consulting institutions also do not adopt a positive strategy. When incentives are moderately strong (β = 0.5), enterprises will undertake sustainable green development, the government will impose environmental regulation, and digital consulting institutions will provide digital technical support. When the penalty is greater (β = 0.9), the government makes a change at this point and environmental regulations won't be implemented by the government. This steady state is bound to be unsustainable, even if enterprises and digital consulting institutions adopt a positive strategy, due to the government's losses.

Fig. 4(b, c, d) shows the three-party evolution path when β = 0.2, 0.5, 0.9, which corresponds to the three-party evolution path under the low, middle and high intensity market-inspired environmental regulations, respectively. The three axes x, y and z represent enterprises, government, and digital consulting institutions. Fig. 4b) demonstrates that when the implementation of low intensity only the government chooses the positive strategy, and the enterprise do not choose positive strategy because the government's incentive level cannot attract enterprises to undertake sustainable green development. At this level of environmental regulation, digital consulting institutions also choose a negative strategy. For governments, low-intensity market-inspired environmental regulations are a waste of social resources and do not serve the purpose for which they are intended and should be avoided in decision-making.

As can be seen from Fig. 4c), when the incentive intensity continues to increase to a middle intensity, enterprises begin to choose to actively pursue sustainable green development, mainly because the benefits of pursuing sustainable green development already cover the costs at this point. Fig. 4d) shows that when the incentive intensity increases to a high

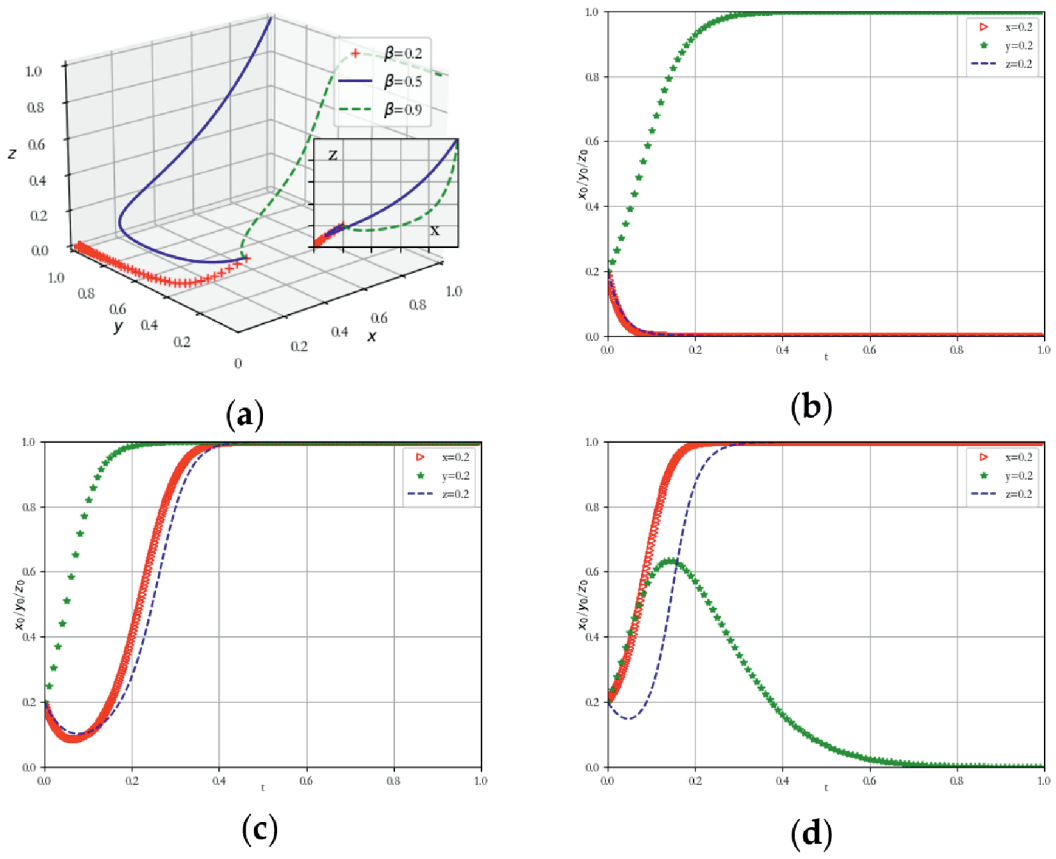

Fig. 4. a) Evolution paths for three subjects when β changes. Evolution paths of three-party at β = 0.2 b), β = 0.5 c) and β = 0.9 d).

intensity (β = 0.9), the government's incentive to implement environmental regulation is affected by the high government expenditure. If the government exits the game without providing incentives, then enterprises and digital consulting institutions will quickly fall back to their original state.

In summary, middle-intensity market-inspired provide a better incentive for enterprises to undertake sustainable green development. Low-intensity incentives will not attract enterprises to develop, while high-intensity incentives will not be sustainable and will cause them to revert back to high-pollution development patterns.

Analysis of Public Participation-Based Environmental Regulation of Different Intensities

To make clear how public participation-based environmental management affects evolutionary pathways, η was assigned η = 0.3, 0.5, 1.0 and the simulation result for 50 evolutions over time is depicted in Fig. 5.

The three-part evolutionary path of public participation-based environmental regulation at different intensities is depicted in Fig 5a). At low intensity (η = 0.3) and at middle intensity (η = 0.5) all three parties choose an active strategy. From the figure it is clear that under middle intensity parties enter the steady state more quickly. Enterprises will not, however, engage in sustainable green development at this time as environmental regulation becomes more stringent, which may be influenced by the particulars of the public participation-based form of environmental regulation instrument. As a public-oriented environmental regulation tool, it can indirectly influence the sustainable green development of enterprises. This shows that the public participation-based environmental regulation tool did not achieve the desired result.

Fig. 5(b, c, d) represent the three-party evolutionary path at η = 0.3, 0.5, 1.0, corresponding to the three-party evolutionary path under low, middle and high intensity, respectively, with x representing enterprises, y representing the government and z representing digital consulting institutions. from Fig. 5b) and Fig. 5c), it can be seen that under low intensity and the middle intensity condition, all three parties choose an active strategy. The difference is that when environmental regulation intensity is increased to middle intensity (η = 0.5), instead of entering the steady state more slowly, enterprises enter the steady state more quickly. The reason for this is that the appropriate increase in public pressure allows digital consulting institutions to provide digital technical support more quickly, and their point of entry into steady state is significantly earlier, subsequently helping enterprises to enter steady state more quickly as well, resulting in a win-win situation for both parties.

However, in Fig. 5d), further intensification of environmental regulation η = 1.0 forces enterprises out of the game and out of the sustainable green development due to fear of uncertain risks and rising costs. At this point, although the government and digital consulting institutions choose an aggressive strategy, they do not achieve their initial goal.

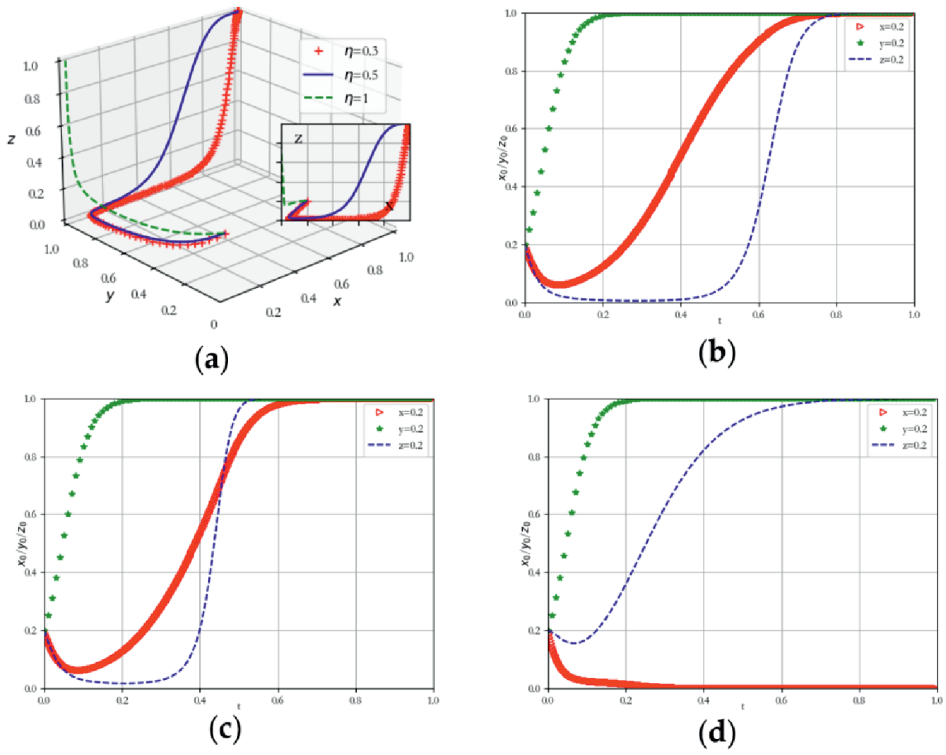

Fig. 5. a) Evolution paths for three subjects when η changes. Evolution paths of three-party at η = 0.3 b), η = 0.5 c) and η = 1.0 d).

In summary, all three parties will choose a positive strategy under low and middle-intensity conditions, but under middle-intensity conditions, enterprises and digital consulting institutions can achieve a win-win situation in favour of sustainable green development. At high intensity, however, enterprises will not to undertake sustainable green development, as the costs of sustainable green development are already much higher than the benefits.

Analysis of Government Digital Technology Subsidies of Different Intensities

To make clear how the government's digital technology subsidy for digital consulting institutions affects evolutionary pathways, α was assigned α = 0.2, 0.5, 0.9 and the results are depicted in Fig. 6 for 50 evolutions over time.

The three-party evolutionary path under various intensities of digital technology subsidies is depicted in Fig. 6a). All three parties choose an active strategy at low (α = 0.2) and middle (α = 0.5) intensities, with the difference that digital consulting institutions tend to reach a steady state at a faster rate when the government implements a middle digital technology subsidy intensity (α = 0.5), while enterprises reach a steady state at a similar time for both subsidy intensities. However, when the government chooses a high intensity subsidy (α = 0.9), there is no significant steady state between the subjects, which is in a constant cycle, and the enterprises do not choose an active strategy at this time.

Fig. 6(b, c, d) show the three-party evolutionary paths at α = 0.2, 0.5, 0.9, corresponding to the three-party evolutionary paths under low-, middle- and high-intensity digital technology subsidies, with x representing enterprises, y representing the government and z representing digital consulting institutions. Fig. 6c) shows that when digital technology subsidies are implemented at low intensities, enterprises choose to undertake sustainable green development and enter the steady state in a similar time frame, and just a little faster at middle intensities. The middle-intensity digital technology subsidy allows digital consulting institutions to provide digital technical support faster than the low-intensity digital technology subsidy, which helps enterprises to develop. However, in Fig. 6d), enterprises will not to undertake sustainable green development, and the probabilities of government and digital consulting institutions fluctuate between 0 and 1, suggesting that no definite steady state arises. and that the choice of digital consulting institutions varies with the choice of the government, suggesting that at the beginning of the game the government provides high digital technology subsidies and digital consulting institutions are happy to provide digital consulting institutions. However, as time progresses, the government's financial pressure increases and it has to choose a negative strategy, at which point digital consulting institutions follow suit and stop providing digital technical support. As a result, there is no steady state of affairs under this level of subsidy, which is not conducive to the greening of enterprises.

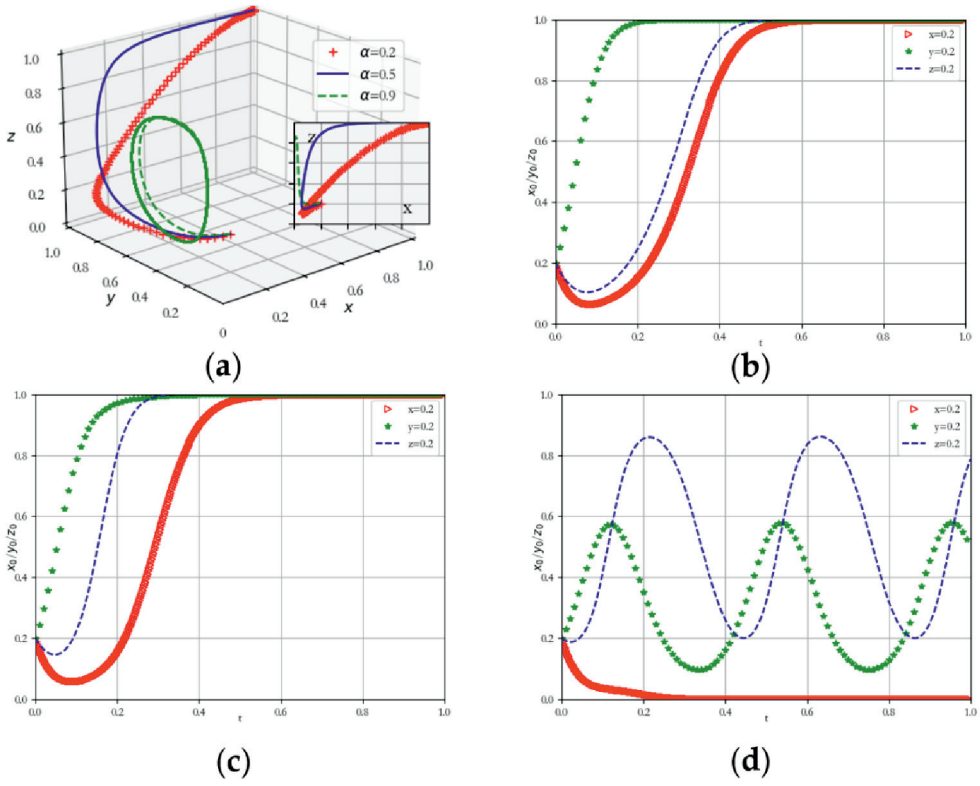

Fig. 6. a) Evolution paths for three subjects when α changes. Evolution paths of three-party at α = 0.2 b), α = 0.5 c) and α = 0.9 d).

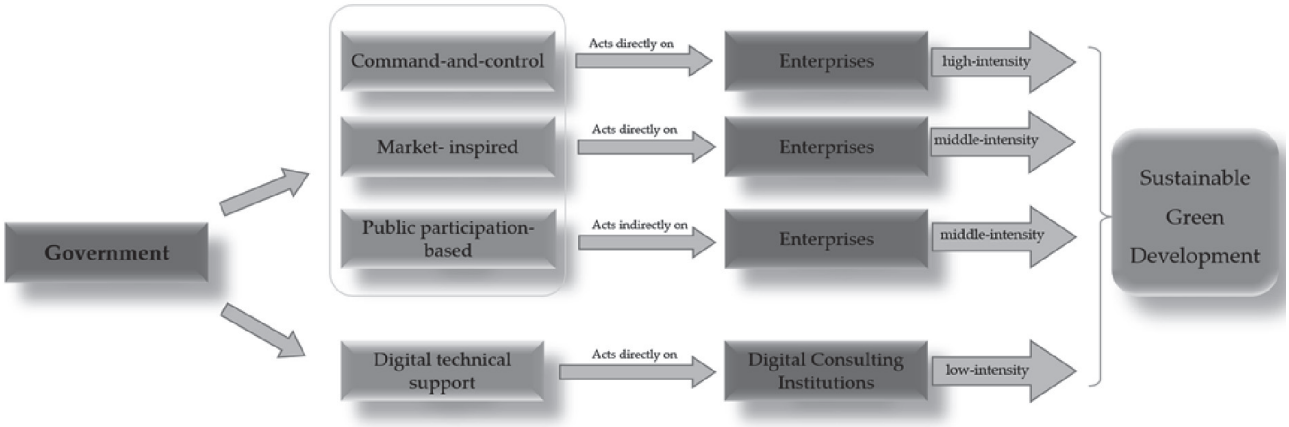

Fig. 7. Flow chart for promoting sustainable green development.

In summary, both low and middle intensity digital technology subsidies will promote the choice of sustainable green development by enterprises. The difference lies in the fact that middle intensity digital technology subsidies lead digital consulting institutions to choose aggressive strategies more quickly and do not promote enterprises as much. High intensity digital technology subsidies do not tend to stabilize because the government is not able to provide them on a permanent basis.

Summary

In summary, both different environmental regulations for enterprises and digital technology subsidies for digital consulting institutions can contribute to the sustainable green development of enterprises as long as they are implemented with appropriate intensity, as depicted in Fig. 7, this is also this paper's main goal and difficult. Combined with Figs 3-6, it is found that high-intensity command-and-control environmental regulations, middle-intensity market- inspired environmental regulations, middle-intensity public participation-based environmental regulation and low-intensity digital technology subsidies are the optimal implementation approach to encourage sustainable green development of enterprises, and the best choice to reduce social costs. In this approach, all three actors choose a proactive strategy. The role of the three environmental regulation strategies, namely 'command-and-control', 'market-inspired' and 'public participation-based', in promoting the sustainable green development of enterprises is a sequential decrease in the intensity. In contrast, digital technology subsidies for digital consulting institutions do not differ significantly between low and middle intensity for enterprises. Therefore, in this evolutionary game system, the government should priorities command-and-control environmental regulation to create a favourable policy context for enterprises, while it is also necessary to implement market-inspired environmental regulation and digital technology subsidies for digital consulting institutions to promote the sustainable green development of enterprises.

Conclusions and Suggestions

Under the dual perspectives of heterogeneous environmental regulation and digital technology subsidies, this study proposes a three-party evolutionary game model based on the supervision of information asymmetry theories and finite rationality. By analysing replicated dynamical equations, the system's evolutionary stabilization strategy is provided. Finally, three distinct environmental rules are examined for their impact on the sustainable growth of enterprises using numerical simulations.

The results of this study show that: (1) a reasonable incentive mechanism is needed for the government, enterprises, and digital consulting institutions to achieve stable evolutionary synergy. Among them, command-and-control and market-inspired environmental regulations make significant contributions to the sustainable green development of enterprises. At the same time, command-and-control environmental regulation has a more significant impact on the sustainable green development of enterprises than market-inspired environmental regulations. In contrast, public participation-based environmental regulation and the government's digital technology subsidy to the digital consulting institution were not significant for the sustainable green development of enterprises. (2) All three environmental regulation tools and digital technology subsidies can promote sustainable green development under certain conditions, but the "Porter hypothesis" can only be realized when environmental regulation is more stringent or digital technology subsidies cross a specific threshold. Among them, command-and-control environmental regulations have the most important result on the sustainable green development of enterprises, followed by market-

inspired environmental regulations. Meanwhile, public participation-based environmental regulations or digital technology subsidies need to be more vital to be maintained for a long time. (3) The government can promote the sustainable green development of enterprises more efficiently by choosing the right combination of government regulation strategies and the appropriate level of enforcement. The best strategy for government environmental regulation is to impose multiple environmental regulations, including high-intensity command-and-control environmental regulation, medium-intensity market-inspired environmental regulation, low-intensity public participation-based environmental regulation, and low-intensity digital technology subsidies.

Considering the outcomes of the aforementioned simulated analysis and the calculation of stabilization strategies, the following suggestions are made to the government in this paper: (1) Use and combine different environmental regulatory tools in a rational way. From the simulation results above, it appears that if the government only implements one environmental regulation tool, then enterprises may not choose to undertake sustainable green development. In addition, public participation-based environmental regulation tools and digital technology subsidies have limited incentive effects on enterprises. Governments should combine command-and-control and market-inspired environmental instruments or all four instruments to provide enterprises with long-term incentives to undertake sustainable green development. (2) Environmental regulation and enforcement should be moderate. The intensity of the application of different environmental regulation tools varies. If a low-intensity command-and-control or low-intensity market-inspired environmental regulation tool is implemented, enterprises are less likely to choose to go green. It is therefore essential to choose different levels of intensity for different environmental instruments. The use of command-and-control and market-inspired environmental instruments can be strengthened, and the use of public participation-based environmental regulation tools and digital technology subsidies can be weakened. (3) Motivate enterprises to engage in sustainable green development. Whether or not an enterprise goes green has much to do with its interests and costs. Firstly, the government can provide digital technology subsidies to digital consulting institutions to promote their services and maximize the sustainable green development of enterprises to reduce the costs of sustainable green development. Secondly, appropriate environmental regulations should be adopted to promote sustainable green development. Finally, through education and awareness-raising, enterprises should be made aware of the public and environmental benefits of sustainable green development. Only in this way can the sustainable green development of enterprises be long-term and enter a virtuous cycle.

The research utilizes the evolutionary game method to explore the impact of various environmental regulation tools and digital consulting organizations on the sustainable development of businesses. It aims to elucidate the concept of "optimal strategic combination" and "optimal implementation" of government-led environmental regulation, with the objective of maximizing the benefits of enterprises' sustainable green development and fostering the integration of economic, ecological, and social benefits. The findings of this study will offer valuable guidance and recommendations for promoting sustainable business development, as well as serve as a practical foundation for formulating relevant environmental and investment policies. However, it is crucial to conduct further analysis considering regional and industrial disparities in China, which will pave the way for future research endeavours.

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Conflicts of Interest

The authors declare no conflict of interest.

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