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Original Research

Evolutionary Game Analysis of Stakeholders' Decision-Making Behaviors Based on Constraints of "Dual Carbon" Goal

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Abstract

The government, enterprises, and consumers play an important role in the realization of the "dual carbon" goal. However, the relationship between consumer behavior and this goal has not received sufficient attention. Based on theories related to green consumption, this paper analyzes the internal psychological factors of consumers and external influencing factors and constructs a tripartite evolutionary game model involving the government, enterprises, and consumers. The findings are as follows: (1) If the consumer's price sensitivity coefficient is either too high or too low, it does not favor the evolution of consumer behavior towards green consumption, nor does it encourage enterprises to adopt green production practices. In such scenarios, government regulation and the provision of green subsidies to consumers and enterprises might be more effective. (2) The larger the green preference coefficient of consumers, the more likely they are to opt for green consumption, which in turn accelerates the shift of enterprises towards green production. In this situation, a robust supply and demand market for green products can effectively alleviate the pressure of environmental regulation. (3) The government's "dual carbon" policy publicity prompts consumers to choose green consumption and enterprises to choose green production. (4) Government subsidies to enterprises and to consumers both encourage enterprises to choose green production and consumers to choose green consumption. The results of this study provide enlightenment on the development of the green product market and the achievement of the "dual carbon" goal.

Keywords: green consumption; green production; environmental regulation; "dual carbon" goal; evolutionary game

Introduction

Since the Industrial Revolution, the emission of greenhouse gases such as carbon dioxide has increased year by year, intensifying the greenhouse effect. Consequently, addressing climate change has become a focal and urgent issue in global sustainable development [1]. The Paris Agreement of 2015 highlighted the need to limit global temperature rise to within 2°C above pre-industrial levels, ideally keeping it below 1.5°C, to prevent further climate deterioration [2]. To fulfill such an ambitious goal, more than 110 countries are determined to achieve carbon neutrality by 2050 [3]. China also places a high priority on tackling climate change and has enacted

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a national strategy for proactive response. On September 22, 2020, at the 75th session of the United Nations General Assembly, China announced its ambition to peak carbon dioxide emissions before 2030 and to strive to achieve carbon neutrality before 2060. "Carbon peaking" refers to the point where carbon emission in a certain area starts to decline after reaching a peak, while "carbon neutrality" means reducing net carbon emission to zero through measures such as emission reduction and carbon sequestration. These two objectives are collectively known as the "dual carbon" goal [4].

Numerous practical studies have shown that green consumption, an important part of sustainable development, can effectively reduce carbon emissions [5-7]. However, most existing studies on green consumption have primarily focused on empirical methods to explore its influencing factors [8, 9] and the gap between green consumption attitudes, intentions, and behaviors [10, 11]. In game research related to green development, more attention has been paid to the interaction between the government's environmental regulation and enterprises' green production and green technology innovation [12-14], thereby ignoring the consumer-driven "demand" factor, which is crucial for the diffusion of green products [15-17]. Furthermore, although existing game studies do include green consumers as decision-makers, they often oversimplify consumer assumptions, typically considering only the costs and expected benefits of green versus non-green consumption [18], thus ignoring the psychology of consumers and the behavioral changes caused by psychological factors. A series of environmental psychology theories suggest that attitudes, norms, and perceived behavior control are vital in the decision-making process of individual consumption and energy use [19]. Therefore, understanding human behavior is key to proposing more targeted and effective policy measures to promote behavioral change and mitigate climate change [20].

To understand the consumer decision-making mechanism in green consumption, this study considers the pull effect of green demand [21], and integrates external uncertainties and consumer psychology within a single framework. Utilizing bounded rationality as a basis, it analyzes consumers' internal and external factors and constructs a tripartite evolutionary game model involving the government, enterprises, and consumers. This model aims to refine green decision-making practices and support the achievement of "dual carbon" goals. The main work of this article has the following aspects. Firstly, existing research studies the development of the green product market from the perspectives of government environmental regulation as well as corporate green technological innovation and production. However, this paper focuses more on consumers, thereby enriching the research on the consumption side in the development of the green product market. Secondly, although existing research includes consumers in the game model, it rarely considers the impact of consumer psychology and behavioral characteristics. This paper takes consumer psychology as the basis for decision-making, studying its impact on consumer behavior, and offers insights for achieving low-carbon development from consumption. Thirdly, different from the static analysis approach in empirical research, this paper uses evolutionary game theory and numerical simulation methods to dynamically analyze the evolution of consumer decision-making under different scenarios.

Literature Review

Green Consumption and Its Influencing Factors

In 1987, Elkington proposed the concept of "green consumption" in the book *Green Consumer Guide*. He believed that green consumption does not consume products harmful to health and does not use excessive energy and cause environmental pollution [22]. Then, many scholars further define the connotations of green consumption. Moraes et al. [23] summarized that green consumption, also known as environmental-friendly consumption, refers to the consumption behaviors driven by a conscious awareness of environmental protection. Wang, H.Y. et al. [24] argued that green consumption is different from general consumption. On the one hand, it needs to satisfy consumers' use demands. On the other hand, as a carrier to convey green values, it meets consumers' ethical demands. Policarpo and Aguiar [25] believed that the motivation behind green consumption behavior is the desire of consumers to demonstrate their pro-social behavior. Existing research mostly explores the influencing factors of green consumption from the perspectives of society, markets, and consumers themselves. Zhong et al. [26] concluded that consumer attitudes, government policies, social norms, and the quality and price of products are significant factors. Some researchers believe that consumption behavior is the result of the interaction of individuals, culture, society, and environment [9, 27, 28]. Moreover, Tilikidou [29] argued that the education level of consumers has an impact on green consumption behaviors. More specifically, individuals can figure out hazards of overconsumption through learning, so that they know how to protect the environment effectively and consume greenly [30].

The theory of planned behavior proposed by Ajzen is the most common theory to analyze green consumption behavior and its antecedents [31]. Based on the theory, intention is the most direct factor affecting behavior, while intention is influenced by attitudes, subjective norms, and perceived behavioral control [32]. The study of Lao and Wang [33] showed that attitudes, subjective norms, and perceived behavioral control can positively influence green consumption behaviors. Yadav and Pathak [34] demonstrated that green consumption attitudes, subjective norms, and perceived behavioral control positively influenced green consumption behaviors by positively influencing green consumption intentions. In accordance with a questionnaire survey in Hanoi, Van Tran and Nguyen [35] revealed that subjective norms and social norms have the greatest positive impact on the green consumption of households. Perceived behavioral control and product availability also have positive impacts, but product price has a negative impact. Xie et al. [36] found that environmental cognition positively affected attitudes, subjective norms, and perceived behavioral control of consumers, thereby reinforcing their intentions and behaviors of green consumption. In conclusion, consumers' attitude, subjective norms, and perceived behavioral control jointly affect green consumption behaviors [37].

Attitude refers to an individual's stable preference towards an object, encompassing the evaluations and opinions formed through interaction with it. This process influences individuals to adopt specific responses towards the object [35]. Research indicates that consumer attitudes towards green products significantly affect their purchase intentions [38], with individuals who hold positive attitudes towards green products being more likely to engage in green consumption [39]. The cognitive and emotional preferences of consumers reflect their attitudes towards green products, positively impacting their intentions and behaviors toward green consumption [40]. Furthermore, the demand for green products is influenced by consumer preferences [41]. In this study, the level of cognitive and affective preferences is termed the green preference coefficient, which is specifically reflected in its impact on the demand for green products and is incorporated into the tripartite evolutionary game model.

Subjective norm is the social pressure that individuals perceive when deciding whether to take a certain action, and it is the judgment of social rules. Some studies found that subjective norms are the social pressure perceived by consumers when they consider whether and how to engage in green consumption, especially the influence of others or groups, including governments, media, experts, and international organizations [37, 39]. The "dual carbon" goal aims to cultivate the awareness of the whole society to control carbon emission, and urges the formation of a consensus among various economic entities on green development [42]. The government propagates the goals and policies of "dual carbon". Not only can consumers feel the pressure of green consumption and energy savings imposed by the government [43], but it also increases the knowledge of green consumption. As a result, consumers generate corresponding behaviors. So, this paper will study the influence of the government's "dual carbon" policy publicity on green consumption behavior.

Perceived behavioral control is the perception of the difficulty of achieving a certain behavior [44]. It has been widely applied in the field of prediction of environmentally friendly behaviors, such as energy-saving behaviors, green consumption behaviors, and other sustainable consumption behaviors [27, 45, 46]. According to the theory of planned behavior, when consumers believe that they have more resources and opportunities to purchase products and there are no or fewer perceived barriers during the purchase process, their perceived behavioral control will be stronger, and their possibility of green consumption will be greater [47]. Van Tran and Nguyen [35] defined perceived behavioral control as consumers' evaluation of the products' availability, and the availability can be reflected in the price of the products. Price changes perceived by consumers will affect their purchase behavior [48], thus affecting the market demand for products. Therefore, the research focuses on the influence of consumers' price sensitivity on green consumption behaviors.

Game Study on Green Product Market

Since Veblen's research on conspicuous consumption, sociologists have noticed that consumption is not merely a simple economic behavior, but is embedded in the macro environment. Like other behaviors, it is affected by values, norms, and social situations, and has profound significance. Although green consumption still belongs to the category of individual consumption and follows the law of cost-benefit comparison under the framework of rational choice, it has been regarded as an important part of sustainable development. This is because it is committed to reducing environmental externalities, with strong altruism and sociality [49]. Therefore, although existing research on green consumption usually focuses on the fields of economics and psychology and emphasizes the influence of individual rationality and psychological factors, the embeddedness of green consumption behavior in the social structure cannot be ignored. Further, the low-carbon society mode should be explored to realize multiple interactions among the government, enterprises, and consumers.

At present, some scholars have proposed a two-party game model concerning green products. Ren et al. [50] studied the game between the government and enterprises and developed a two-stage dynamic game model to analyze the influence of different government subsidies on demand, product price, manufacturer profits, consumer surplus, and social welfare. Considering the preferences of consumers and the greenness of products, Sun and Yu [41] developed a two-stage game model under two different subsidy policies: subsidies for producers and subsidies for consumers. They further analyzed the distinct impacts of these subsidy policies through numerical simulation. Zhang et al. [51] studied the equilibrium conditions of the game between manufacturers and retailers and found that the evolutionary stability strategy is related to the sensitivity coefficient of carbon emission reduction, sensitivity coefficient of marketing effort, carbon transaction price, low carbon subsidy, and carbon tax ratio. Huang et al. [52] established an evolutionary game model of green industry between enterprises and consumers, and discussed the evolutionary and stable strategies to promote the development of green industry. Xia et al. [53] discussed how consumers' willingness to pay for green products affects the decisions of manufacturers and retailers in the green supply chain. In addition, Liu et al. [54] applied the evolutionary game model to a two-level green supply chain composed of green suppliers and green manufacturers and used numerical simulation to explore the behavior trends of participants.

Furthermore, some scholars constructed a tripartite game model among government, enterprises, and consumers. Zheng et al. [55] studied the mechanism of energy-saving subsidy policies by establishing a three-stage game model of "government-enterprise-consumer". Dong [56] developed a tripartite game model of government, enterprises, and consumers to study the optimization of government subsidies and regulatory strategies in low-carbon diffusion. Considering the incentives, penalties, regulatory costs of government, and green technology innovation costs of enterprise, Ma and Xia [57] constructed a tripartite evolutionary game model among enterprises, governments, and consumers in the green product market and studied the main influencing factors of green technology innovation. Chen et al. [58] established a game model involving the government, consumers, and enterprises, discussing how government reward and punishment and consumer supervision affect low-carbon technology innovation of enterprise. Wang et al. [59]}} developed an evolutionary game model involving local governments, enterprises, and consumers. They explored the effects of subsidy coefficients, market supervision intensity, and enterprise brand benefits on the implementation of green technology innovation strategies by enterprises. Yang et al. [15] proposed a tripartite evolutionary game model that includes the government, manufacturers, and consumers, simulating the impact of government regulation on green product diffusion in complex networks. Gong and Dai [18] focused on a market-oriented green technology innovation system that requires the joint effort of the government, enterprises, and consumers. They built the tripartite evolutionary game model and discussed the strategy's evolution trend. It is found that government subsidies for enterprises and consumers, the benefits of enterprise speculation, and green consumption costs affect the enterprise decisions of green innovation.

Summary

The literature review reveals that existing research on green consumption, particularly in relation to environmental regulation and green production, has provided valuable theoretical insights and practical references. In terms of green consumption, existing studies have used a questionnaire survey method to empirically examine the influence of green consumption attitudes, subjective norms, and perceived behavioral control on green consumption behavior based on the theory of planned behavior [35, 39]. With regard to game models in the green product market, some studies only analyzed the two-party game among the government, enterprises, and consumers [53, 60]. Some researchers built a dynamic evolutionary game model involving the government, consumers, and manufacturing enterprises to study the impact of consumer behavior on the green transformation decisions of enterprises under government supervision. However, there is a lack of numerical simulation under different conditions, making it difficult to demonstrate the evolution trajectories of each subject [61]; When some hypotheses are proposed and models are designed, only the influence of green consumption cost and green preference of consumers is considered [18, 21]. There are few studies that comprehensively consider the impact of external and internal factors of consumers on green consumption behaviors, from aspects of green consumption attitudes, subjective norms, and perceived behavior control, and then explore the behavioral evolution path of the government, enterprises, and consumers.

However, to deepen understanding of the evolution of consumer behavior, two major issues still need to be further explored. Firstly, it's essential to consider how consumers' psychological and behavioral traits influence their decision-making. This aspect has often been overlooked in previous game studies. Secondly, this study employs evolutionary games and numerical simulations, offering a dynamic and in-depth analysis of consumer decision-making in various scenarios. This approach provides new insights into understanding and promoting green product markets. Therefore, building on existing research, this paper posits that attitudes towards green consumption, subjective norms, and perceived behavioral control impact green consumption behavior. And this influence is evident in consumers' green preferences, response to the government's "dual carbon" policy, and price sensitivity. Additionally, the consumer – the micro subject – is placed in the context of the interplay between enterprises and the government, and a tripartite evolutionary game model involving these three parties is constructed. Through numerical simulations, this study explores the behavioral evolution paths of each party, focusing especially on consumers. This research offers insights into the development of the green product market and achieving the dual carbon targets.

Research Model

Basic Assumptions and Model Construction

Problem Description

Achieving the "dual carbon" goal is a systematic project that involves comprehensive changes in production and lifestyle [62]. Producing and consuming green products is considered a key path to achieving this goal [63]. However, green products have not yet been widely used in all aspects of Chinese daily lives, and their scale benefits have not been fully realized [64]. This suggests that, while the importance of green products is recognized, their promotion and application still face many challenges.

In the development of the green product market, consumers, enterprises, and the government are the three main stakeholders, each playing different but interrelated roles. Firstly, consumers' growing low-carbon awareness and green preference drive the demand for green products, but are constrained by the high prices and information asymmetry of green products, so consumers sometimes turn to traditional products [64]. Secondly, in the pursuit of government subsidies and social support, enterprises face the double pressure of green production: not only to meet market demands for green products but also to assume social responsibilities. However, the high costs of green technology innovation often delay short-term economic benefits, leading to challenges in green production. In this case, the role of the government is particularly important. The government needs to promote the market's green transition through a series of measures, such as environmental regulation, improving laws and regulations, tax breaks, and subsidies for green production and consumption. This includes encouraging consumers to buy green products and prompting enterprises to engage in green technological innovation and production [57, 65]. In addition, the government can also implement pollution control by imposing taxes and fines on high energy-consuming and high-polluting products [66, 67]. Such multifaceted strategies and cooperation are key to achieving a green low-carbon transition and the "dual carbon" goal. Fig. 1 shows a logical framework diagram to visually represent the relationships between the government, enterprises, and consumers in the context of the "dual carbon" goal.

Evolutionary Game Model

Assumption 1 The government, enterprises, and consumers are regarded as a system in which the participants all exhibit bounded rationality. They adjust their strategies through this game to pursue the optimal decision that maximizes their own interests.

Assumption 2 Suppose that consumers' green consumption refers to the purchase of green products, and the change of consumption behavior is reflected in product demand. Similarly, green production is defined as the production of green products. It is noteworthy that there is a slight imbalance between the production and sales of products, with supply marginally exceeding demand. For model simplification, it is assumed that potential inventory costs and product loss are negligible [68]. In the context of the "dual carbon" goal, consumer choices are influenced by attitudes, subjective norms, perceived behavioral control, and government subsidies. They have two options: purchasing green products (x) or purchasing traditional products (1-x). Enterprises, considering factors like government environmental regulation, corporate social responsibility, market demand, and the costs and revenues associated with green production, can choose between green production (y) and traditional

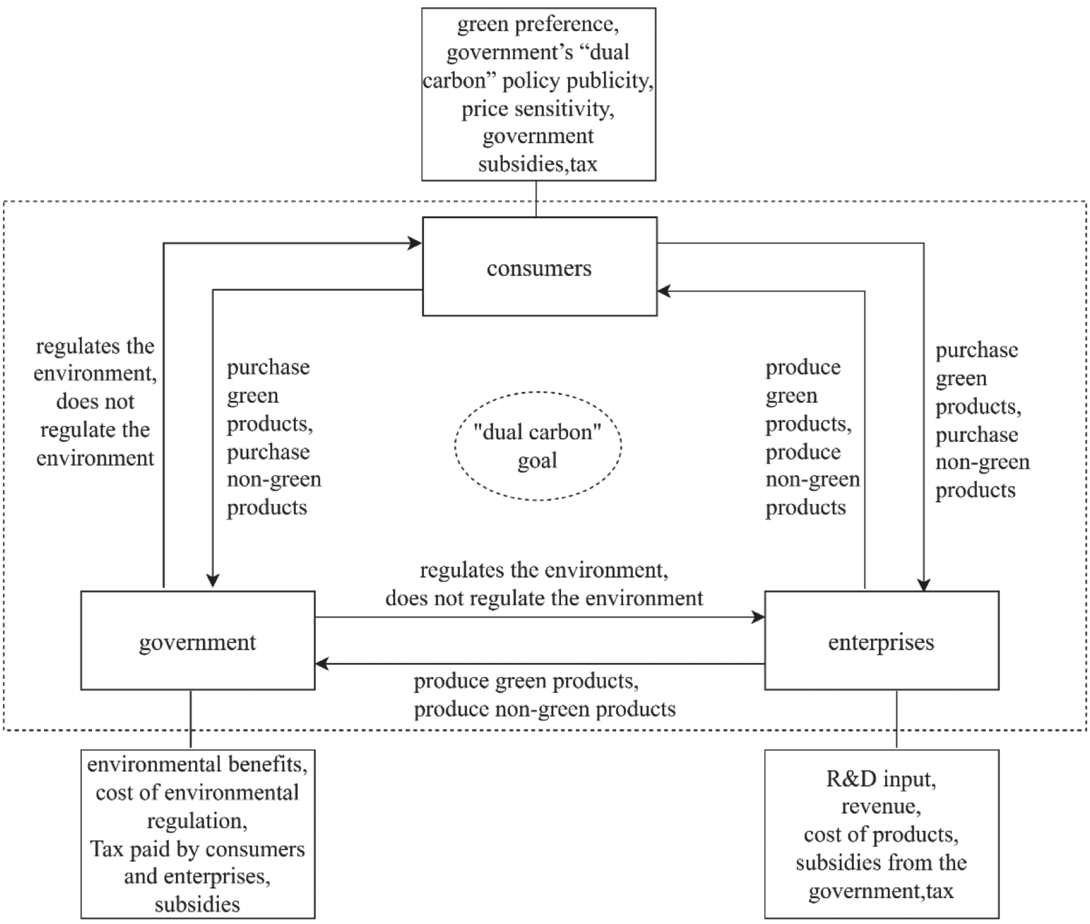

Fig. 1. Conceptual relationship diagram between the three parties of the game

production (1-y). To foster a low-carbon economy and achieve the "dual carbon" goal, the government evaluates the benefits and costs of environmental regulation. The available strategies include implementing environmental regulation (z) or not (1-z). Where x, y, z, ∈ [0,1] are time-dependent functions.

Assumption 3 Consumers' demand has uncertainty when consumers choose traditional products, the demand function is: $D_t=d_t-\theta P_t$ [69, 70], where d_t is the market size of the traditional products, θ is the price sensitivity coefficient, $d_t>0$, $\theta>0$.

Assumption 4 According to the Theory of Planned Behavior, attitudes, subjective norms, and perceived behavioral control influence behavioral intentions, which in turn directly affect behavior [71]. This theory is effective in predicting both behavioral intentions and actual behavior [72]. As discussed in the literature review, green consumption behavior can be expressed as a function of green consumption attitude, subjective norm, and perceived behavioral control. Therefore, the demand for green products, which primarily reflects consumers' green consumption behavior, can be modeled as a function of these three factors: green consumption attitude, subjective norm, and perceived behavioral control.

Specifically, consumers' cognitive and emotional preferences reflect their attitudes toward green products. These attitudes positively affect their intentions toward green products, which in turn influences their actual green consumption behaviors [40]. It is assumed that consumers' green consumption attitude has a positive impact on green consumption behavior, which is expressed by the green preference coefficient γ.

Subjective norms, especially those influenced by external information on green products and consumption, significantly impact individual behavior. As the comprehensiveness and influence of this information increase, consumers are correspondingly more likely to make green choices [73]. The government's "dual carbon" policy not only encourages consumers to be aware of the necessity of green consumption, energy saving, and low-carbon practices [43] but also enhances their knowledge about green consumption. This leads to an increase in corresponding green consumer behaviors. Such a shift in consumer behavior is quantified by the influence factor *k* in the context of the government's "dual carbon" policy publicity, indicating a positive effect on green consumer behavior.

Perceived behavioral control is reflected in consumers' own assessments of the difficulty involved in purchasing green products, with factors like product pricing playing a crucial role [35]. Changes in prices, as perceived by consumers, can influence their purchasing decisions [48], thereby impacting the market demand for these products. This paper explores the impact of perceived behavioral control on green consumption behavior, focusing specifically on the aspect of price perception. It posits that perceived behavioral control negatively affects green consumption behavior, a relationship quantified by the price sensitivity coefficient θ.

In conclusion, the extension of the green product demand function for $D_g=f(P_g, \gamma, \theta, k)$, namely $D_g=d_g-\theta P_g+\gamma e+kC_p+\varepsilon$. Among them, d_g represents the market size of green products, P_g denotes the selling price of green products, *e* is the greenness of products [74], C_p is the government's "dual carbon" policy publicity efforts, and ε represents the random error term. To sum up, the consumer demand function is:

$$D=\begin{cases} d_t-\theta P_t \ , & \text{if consumer chooses traditional products.} \\ d_g-\theta P_g+\gamma e+kC_p+\varepsilon \ , & \text{if consumer chooses green products.} \end{cases} \quad (1)$$

Table 1. Influencing factors of green consumption behavior

Influencing Factors	Dimension	Symbol
Attitudes	Green preference coefficient	γ
Subjective norms	The influence factor of the government's "dual carbon" policy publicity	*k*
Perceived behavioral control	Price sensitivity coefficient	θ

Assumption 5 Referring to Song Yan et al. [66], the utility obtained by consumers from purchasing green products is expressed as $U_1 = U_0 + \gamma \ln D_g + \beta D_g$, where U_0 represents the utility derived from purchasing traditional products. βD_g signifies the positive externality benefit obtained by consumers from the consumption of green products, and β represents the marginal utility. In summary, the consumer's utility function can be articulated as follows:

$$U=\begin{cases} U_0 \ , & \text{if consumer chooses traditional products.} \\ U_0+\gamma \ln D_g+\beta D_g \ , & \text{if consumer chooses green products.} \end{cases} \quad (2)$$

Assumption 6 Generally, green production in enterprises encompasses green product design and green supply chain management, culminating in the creation of green products. Hence, this paper posits that green production refers to the manufacturing of green products, whereas traditional production pertains to the creation of conventional products. In traditional production, the output is denoted as d_t, with a unit cost of C_t. Additionally, enterprises pay an environmental tax T_2 to the government and bear a welfare loss due to environmental pollution quantified as *a*. In contrast, when an enterprise engages in green production, the output is d_g, with a unit cost of C_g. The investment in R&D is represented as $\eta e^2/2$ [41, 75], where η is the R&D input cost coefficient. And a government subsidy S_1 is provided, where S_1 is less than C_g.

Assumption 7 Consider carbon trading between corporate entities, where the "right to emit carbon dioxide" is bought and sold as a commodity. Prior to trading, a competent authority allocates carbon emission allowances to corporate entities for a specified period. This paper assumes that if an enterprise engages in green production, its actual carbon emissions will be lower than its quota, and the "surplus" quota can be sold in the market. The gain from this sale is recorded as h_1. Conversely, if an enterprise engages in traditional production, it may need to buy quotas from other units at the market price to offset its excess carbon emissions, with the cost recorded as h_2.

Assumption 8 When enterprises engage in green production, the government's green environmental benefit is R_1. When enterprises engage in traditional production, the cost of environmental regulation paid by the government is *L*. When the public practices green consumption, the government's green environmental benefit is R_2. When the government actively regulates the environment, the increase in public welfare is denoted as *b*. The relevant parameters and their meanings are shown in Table 2.

Table 2. Parameters and description.

Parameters	Description
U_0	Basic utility that consumers obtain from traditional products.
d_g	Supply of green products.
d_t	Supply of traditional products.
β	External marginal utility that consumers obtain from green products.
θ	Absolute value of the price sensitivity coefficient of consumers.
γ	Green preference coefficient of consumers.
k	Strength of the government's "dual carbon" policy publicity.
P_t	Selling price of traditional products.
P_g	Selling price of green products.
e	Greenness of product.
T_1	Tax paid by consumers when they purchase traditional products.
T_2	Tax paid by enterprises when they produce traditional products.
C_t	Unit cost of traditional products.
C_g	Unit cost of green products.
η	Coefficient of R&D input.
S_1	Government subsidies obtained by enterprises for green production.
S_2	Government subsidies obtained by consumers for green consumption.
a	The welfare loss of consumers when enterprises produce traditional products.
b	The increased welfare of consumers when the government regulates the environment.
h_1	Revenue from selling surplus carbon emission quotas when enterprises engage in green production.
h_2	Cost for purchasing additional carbon emission quotas when enterprises engage in traditional production.
R_1	The government's environmental benefits when enterprises produce green products.
R_2	The government's environmental benefits when consumers purchase green products.
L	The cost of environmental regulation that the government needs to pay when enterprises produce traditional products.
C_p	The publicity cost of the government's "dual carbon" policy.
ε	The random error term of green product demand function.

Based on the above assumptions and analysis, the profit and loss values of consumers, enterprises, and the government under different strategy choices can be obtained, as shown in Table 3.

Table 3. Payoff matrix of tripartite evolutionary game.

Game participant	The government regulates the environment (z)		The government does not regulate the environment (1-z)	
	The enterprises produce green products ((y))	The enterprises produce non-green products (1-y)	The enterprises produce green products (y)	The enterprises produce non-green products (1-y)
The consumers purchase green products (x)	$U_0+\gamma*ln(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)+\beta*(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)-P_g*(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)+S_2+b+a$	$-a+b$	$U_0+\gamma*ln(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)+\beta*(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)-P_g*(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)+a$	$-a-b$
	$P_g*(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)-d_gC_g-\eta e^2/2+S_1+h_1$	$-T_2-d_tC_t-h_2$	$P_g*(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)-d_gC_g-\eta e^2/2+h_1$	$-d_tC_t-h_2$
	$R_1-S_2+R_2-C_p-S_1$	$R_2-L-C_p+T_2$	$R_1+R_2-C_p$	R_2-C_p

The consumers purchase non-green products (1-x)	$a+b$	$U_0-P_t*(d_t-\theta P_t)-a+b-T_1$	$a-b$	$U_0-P_t*(d_t-\theta P_t)-a-b$
	$-d_gC_g-\eta e^2/2+S_1+h_1$	$P_t*(d_t-\theta P_t)-d_tC_t-T_2-h_2$	$-d_gC_g-\eta e^2/2+h_1$	$P_t*(d_t-\theta P_t)-d_tC_t-h_2$
	$R_1-C_p-S_1$	$T_2-L-C_p+T_1$	R_1-C_p	$-C_p$

According to the payoff matrix in Table 3, E_1, E_2, and E_3 are selected to represent the expected benefits of consumers, enterprises, and the government, respectively.

It can be seen from Table 3 that the expected income E_{11} of consumers buying green products and the expected income E_{12} of consumers buying traditional products are as follows:

$$E_{11}=yz[U_0+\gamma ln(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)+\beta(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)-P_g(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)+S2+b+a]+(1-y)z(-a+b)+y(1-z)[U_0+\gamma ln(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)+\beta(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)-P_g(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)+a]+(1-y)(1-z)(-a-b) \quad (3)$$

$$E_{12}=yz(a+b)+(1-y)z[U_0-P_t(d_t-\theta P_t)-a+b-T_1]+y(1-z)(a-b)+(1-y)(1-z)[U_0-P_t*(d_t-\theta P_t)-a-b] \quad (4)$$

The expected benefits of consumers are:

$$E_1=xE_{11}+(1-x)E_{12} \quad (5)$$

The consumers' replication dynamic equation is:

$$F(x)=dx/dt=x(E_{11}-E_1)=x(1-x)(E_{11}-E_{12}) \quad (6)$$

The expected income E_{21} of green production and the expected income E_{22} of traditional production are as follows:

$$E_{21}=xz[P_g(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)-d_gC_g-\eta e^2/2+S_1+h_1]+(1-x)z(-d_gC_g-\eta e^2/2+S_1+h_1)+x(1-z)[P_g(d_g-\theta P_g+\gamma e+kC_p+\varepsilon)-d_gC_g-\eta e^2/2+h_1]+(1-x)(1-z)(-d_gC_g-\eta e^2/2+h_1) \quad (7)$$

$$E_{22}=xz(-T_2-d_tC_t-h_2)+(1-x)z(P_td_t-\theta P_t-d_tC_t-T_2-h_2)+x(1-z)(-d_tC_t-h_2)+(1-x)(1-z)[P_t(d_t-\theta P_t)-d_tC_t-h_2] \quad (8)$$

The expected benefits of enterprises are:

$$E_2=yE_{21}+(1-y)E_{22} \quad (9)$$

The enterprises' replication dynamic equation is:

$$F(y)=dy/dt=y(E_{21}-E_2)=y(1-y)(E_{21}-E_{22}) \quad (10)$$

The expected income E_{31} of government implementing environmental regulation and the expected income E_{32} of government not implementing environmental regulation are as follows:

$$E_{31}=xy(R_1-S_2+R_2-C_p-S_1)+(1-x)y(R_1-C_p-S_1)+x(1-y)(R_2-L-C_p+T_2)+(1-x)(1-y)(T_2-L-C_p+T_1) \quad (11)$$

$$E_{32}=xy(R_1+R_2-C_p)+(1-x)y(R_1-C_p)+x(1-y)(R_2-C_p)+(1-x)(1-y)(-C_p) \quad (12)$$

The expected benefits of the government are:

$$E_3=zE_{31}+(1-z)E_{32} \quad (13)$$

The government's replication dynamic equation is:

$$F(z)=dz/dt=z(E_{31}-E_3)=z(1-z)(E_{31}-E_{32}) \quad (14)$$

Equations (6), (10) and (14) constitute the replicative dynamic system of consumers, enterprises, and the government.

Evolutionary Stability Analysis of Consumers, Enterprises and the Government

When Formulas (6), (10), and (14) are all equal to zero, nine equilibrium points can be obtained: $E_1(0, 0, 0)$, $E_2(0, 0, 1)$, $E_3(0, 1, 0)$, $E_4(0, 1, 1)$, $E_5(1, 0, 0)$, $E_6(1, 0, 1)$, $E_7(1,1,0)$, $E_8(1,1,1)$, and $E_9(x^*, y^*, z^*)$. Where $E_9(x^*, y^*, z^*)$ is the equilibrium point and needs to satisfy the following equations:

$$\begin{cases} P_td_t-U_0+2yU_0+zT_1+by-Pt^2\theta+\gamma yln(\varepsilon+d_g+C_pk-P_g\theta+e\gamma)+\beta\varepsilon y-\varepsilon yP_g+\beta yd_g-yP_gd_g-yP_td_t+yzS_2-yzT_1-byz+P_g^2\theta y+P_t^2\theta y+\beta C_pky-C_pP_gky-\beta P_g\theta y+\beta e\gamma y-P_ge\gamma y=0 \\ C_td_t-C_gd_g-P_td_t+zS_1+zT_2+P_t^2\theta-e^2\eta/2+\varepsilon xP_g+xP_gd_g+xP_td_t-P_g^2\theta x-Pt^2\theta x+C_pP_gkx+P_ge\gamma x+h_1+h_2=0 \\ L-T_1-T_2-Ly+S_1y+T_1x+T_1y+yT_2+xyS_2-xyT_1=0 \end{cases} \quad (15)$$

Evolutionary Stability Analysis of Consumers

Let F(x)=0 and solve the equation to obtain x=0, x=1 and $y=(\theta P_t^2-d_tP_t+U_0-zT_1)/[2U_0+b+\beta d_g-P_gd_g-P_td_t+zS_2-zT_1-bz+P_g^2\theta+P_t^2\theta+\gamma ln(\varepsilon+d_g+C_pk-P_g\theta+e\gamma)+\beta\varepsilon-\varepsilon P_g+\beta C_pk-C_pP_gk-\beta P_g\theta+\beta e\gamma-P_ge\gamma]$. And $F'(x)=(1-2x)[P_td_t-U_0+2yU_0+zT_1+by-P_t^2\theta+\gamma y ln(\varepsilon+d_g+C_pk-P_g\theta+e\gamma)+\beta\varepsilon y-\varepsilon P_gy+\beta d_gy-P_gd_gy-P_td_ty+S_2yz-T_1yz-byz+P_g^2\theta y+P_t^2\theta y+\beta C_pky-C_pP_gky-\beta P_g\theta y+\beta e\gamma y-P_ge\gamma y]$.

According to the stability theorem of the replication dynamics equation, when F(x)=0 and F'(x)<0, it means that x no longer changes with time, and the choice of consumers is the optimal strategy.

(1) When $y=(\theta P_t^2-d_tP_t+U_0-zT_1)/[2U_0+b+\beta d_g-P_gd_g-P_td_t+zS_2-zT_1-bz+P_g^2\theta+P_t^2\theta+\gamma ln(\varepsilon+d_g+C_pk-P_g\theta+e\gamma)+\beta\varepsilon-\varepsilon P_g+\beta C_pk-C_pP_gk-\beta P_g\theta+\beta e\gamma-P_ge\gamma]$, then F(x)≡0. It shows that consumers purchasing green products and non-green products both have the same benefits. All values of x are evolutionary stable, and the consumers' strategy does not change with time.

(2) When $y\neq(\theta P_t^2-d_tP_t+U_0-zT_1)/[2U_0+b+\beta d_g-P_gd_g-P_td_t+zS_2-zT_1-bz+P_g^2\theta+P_t^2\theta+\gamma ln(\varepsilon+d_g+C_pk-P_g\theta+e\gamma)+\beta\varepsilon-\varepsilon P_g+\beta C_pk-C_pP_gk-\beta P_g\theta+\beta e\gamma-P_ge\gamma]$, the following two cases are discussed:

① When $0<y<(\theta P_t^2-d_tP_t+U_0-zT_1)/[2U_0+b+\beta d_g-P_gd_g-P_td_t+zS_2-zT_1-bz+P_g^2\theta+P_t^2\theta+\gamma ln(\varepsilon+d_g+C_pk-P_g\theta+e\gamma)+\beta\varepsilon-\varepsilon P_g+\beta C_pk-C_pP_gk-\beta P_g\theta+\beta e\gamma-P_ge\gamma]$, then $\left.\frac{dF(x)}{dx}\right|_{x=0}<0$, $\left.\frac{dF(x)}{dx}\right|_{x=1}>0$, it can be inferred that x = 0 is the evolutionary stable point of consumers. It shows that when the probability of enterprises choosing green production is lower than $(\theta P_t^2-d_tP_t+U_0-zT_1)/[2U_0+b+\beta d_g-P_gd_g-P_td_t+zS_2-zT_1-bz+P_g^2\theta+P_t^2\theta+\gamma ln(\varepsilon+d_g+C_pk-P_g\theta+e\gamma)+\beta\varepsilon-\varepsilon P_g+\beta C_pk-C_pP_gk-\beta P_g\theta+\beta e\gamma-P_ge\gamma]$, consumers will purchase traditional products.

②When $y>(\theta P_t^2-d_tP_t+U_0-zT_1)/[2U_0+b+\beta d_g-P_gd_g-P_td_t+zS_2-zT_1-bz+P_g^2\theta+P_t^2\theta+\gamma ln(\varepsilon+d_g+C_pk-P_g\theta+e\gamma)+\beta\varepsilon-\varepsilon P_g+\beta C_pk-C_pP_gk-\beta P_g\theta+\beta e\gamma-P_ge\gamma]$, then $\left.\frac{dF(x)}{dx}\right|_{x=0}>0$, $\left.\frac{dF(x)}{dx}\right|_{x=1}<0$, it can be inferred that x = 1 is the evolutionary stable point of consumers. It shows that when the probability of enterprises choosing green production is higher than $(\theta P_t^2-d_tP_t+U_0-zT_1)/[2U_0+b+\beta d_g-P_gd_g-P_td_t+zS_2-zT_1-bz+P_g^2\theta+P_t^2\theta+\gamma ln(\varepsilon+d_g+C_pk-P_g\theta+e\gamma)+\beta\varepsilon-\varepsilon P_g+\beta C_pk-C_pP_gk-\beta P_g\theta+\beta e\gamma-P_ge\gamma]$, consumers will purchase green products.

Evolutionary Stability Analysis of Enterprises

Let F(y)=0 and solve the equation to obtain y=0, y=1 and $z=-[h_1+h_2+C_td_t-C_gd_g-P_td_t+P_t^2\theta-(e^2\eta)/2+\varepsilon P_gx+P_gd_gx+P_td_tx-P_g^2\theta x-P_t^2\theta x+C_pP_gkx+P_ge\gamma x]/(S_1+T_2)$. And $F'(y)=(1-2y)(C_td_t-C_gd_g-P_td_t+S_1z+T_2z+P_t^2\theta-e^2\eta/2+\varepsilon P_gx+P_gd_gx+P_td_tx-P_g^2\theta x-P_t^2\theta x+C_pP_gkx+P_ge\gamma x+h_1+h_2)$.

According to the stability theorem of the replication dynamics equation, when F(y)=0 and F'(y)<0, it means that y no longer changes with time, and the choice of enterprises is the optimal strategy.

(1) When $z=-[h_1+h_2+C_td_t-C_gd_g-P_td_t+P_t^2\theta-(e^2\eta)/2+\varepsilon P_gx+P_gd_gx+P_td_tx-P_g^2\theta x-P_t^2\theta x+C_pP_gkx+P_ge\gamma x]/(S_1+T_2)]$, then F(y)≡0. It shows that the enterprises producing green products and non-green products both have the same benefits. All values of y are evolutionary stable, and the enterprise's strategy does not change with time.

(2) When $z\neq-[h_1+h_2+C_td_t-C_gd_g-P_td_t+P_t^2\theta-(e^2\eta)/2+\varepsilon P_gx+P_gd_gx+P_td_tx-P_g^2\theta x-P_t^2\theta x+C_pP_gkx+P_ge\gamma x]/(S_1+T_2)$, the following two cases are discussed:

① When $0<z<-[h_1+h_2+C_td_t-C_gd_g-P_td_t+P_t^2\theta-(e^2\eta)/2+\varepsilon P_gx+P_gd_gx+P_td_tx-P_g^2\theta x-P_t^2\theta x+C_pP_gkx+P_ge\gamma x]/(S_1+T_2)$, then $\left.\frac{dF(y)}{dy}\right|_{y=0}<0$, $\left.\frac{dF(y)}{dy}\right|_{y=1}>0$, it can be inferred that y = 0 is the evolutionary stable point of the enterprises. It shows that when the probability of government regulating environment is lower than $-[h_1+h_2+C_td_t-C_gd_g-P_td_t+P_t^2\theta-(e^2\eta)/2+\varepsilon P_gx+P_gd_gx+P_td_tx-P_g^2\theta x-P_t^2\theta x+C_pP_gkx+P_ge\gamma x]/(S_1+T_2)$, enterprises will produce traditional products.

②When $z>-[h_1+h_2+C_td_t-C_gd_g-P_td_t+P_t^2\theta-(e^2\eta)/2+\varepsilon P_gx+P_gd_gx+P_td_tx-P_g^2\theta x-P_t^2\theta x+C_pP_gkx+P_ge\gamma x]/(S_1+T_2)$, then $\left.\frac{dF(y)}{dy}\right|_{y=0}>0$, $\left.\frac{dF(y)}{dy}\right|_{y=1}<0$, it can be inferred that y = 1 is the evolutionary stable point of the enterprises. It shows that when the probability of government regulating environment is higher than $-[h_1+h_2+C_td_t-C_gd_g-P_td_t+P_t^2\theta-(e^2\eta)/2+\varepsilon P_gx+P_gd_gx+P_td_tx-P_g^2\theta x-P_t^2\theta x+C_pP_gkx+P_ge\gamma x]/(S_1+T_2)$, enterprises will produce green products.

Evolutionary Stability Analysis of the Government

Let F(z)=0 and solve the equation to obtain z=0, z=1 and $x=(T_1+T_2+Ly-L-S_1y-T_1y-T_2y)/(T_1+S_2y-T_1y)$. And $F'(z)=(1-2z)(T_1-L+T_2+Ly-S_1y-T_1x-T_1y-T_2y-S_2xy+T_1xy)$.

According to the stability theorem of the replication dynamics equation, when F(z)=0 and F'(z)<0, it means that z no longer changes with time, and the choice of government is the optimal strategy.

(1) When $x = (T_1 + T_2 + Ly - L - S_1y - T_1y - T_2y)/(T_1 + S_2y - T_1y)$, then F(z)≡0. It shows that the government regulates environment or not to have the same benefits. All values of z are evolutionary stable, and the government's strategy does not change with time.

(2) When $x \neq (T_1 + T_2 + Ly - L - S_1y - T_1y - T_2y)/(T_1 + S_2y - T_1y)$, the following two cases are discussed:

① When $0 < x < (T_1 + T_2 + Ly - L - S_1y - T_1y - T_2y)/(T_1 + S_2y - T_1y)$, then $\left.\frac{dF(z)}{dz}\right|_{z=0}>0$, $\left.\frac{dF(z)}{dz}\right|_{z=1}<0$, it can be inferred that $z = 0$ is the evolutionary stable point of the enterprises. It shows that when the probability of consumers purchasing green products is lower than $(T_1 + T_2 + Ly - L - S_1y - T_1y - T_2y)/(T_1 + S_2y - T_1y)$, the government will regulate the environment.

②When $x > (T_1 + T_2 + Ly - L - S_1y - T_1y - T_2y)/(T_1 + S_2y - T_1y)$, then $\left.\frac{dF(z)}{dz}\right|_{z=0}<0$, $\left.\frac{dF(z)}{dz}\right|_{z=1}>0$, it can be inferred that $z = 1$ is the evolutionary stable point of the enterprises. It shows that when the probability of consumers purchasing green products is higher than , the government will not regulate the environment.

Evolutionary Stability Analysis of the System

Jacobian matrix can be used as the basis for determining the stability of evolution [76]. In this paper, it can be obtained from Equation (15) as follows:

$$J_0=\begin{pmatrix} (1-2x)(P_td_t - U_0 + 2U_0y + T_1z + by - P_t^2\theta + \gamma y ln(\varepsilon + d_g + C_pk - P_g\theta + e\gamma) + \beta\varepsilon y - \varepsilon P_gy + \beta d_gy - P_gd_gy - P_td_ty + S_2yz - T_1yz - byz + P_g^2\theta y + P_t^2\theta y + \beta C_pky - C_pP_gky - \beta P_g\theta y + \beta e\gamma y - P_ge\gamma y) & x(1-x)(2U_0 + b + \beta d_g - P_gd_g - P_td_t + S_2z - T_1z - bz + P_g^2\theta + P_t^2\theta + \gamma ln(\varepsilon + d_g + C_pk - P_g\theta + e\gamma) + \beta\varepsilon - \varepsilon P_g + \beta C_pk - C_pP_gk - \beta P_g\theta + \beta e\gamma - P_ge\gamma) & x(1-x)(T_1 + S_2y - T_1y - by) \\ y(1-y)(P_gd_g + P_td_t - P_g^2\theta - P_t^2\theta + \varepsilon P_g + C_pP_gk + P_ge\gamma) & (1-2y)(C_td_t - C_gd_g - P_td_t + S_1z + T_2z + P_t^2\theta - e^2\eta/2 + \varepsilon P_gx + P_gd_gx + P_td_tx - P_g^2\theta x - P_t^2\theta x + C_pP_gkx + P_ge\gamma x + h_1 + h_2) & y(y-1)(S_1 + T_2) \\ z(1-z)(T_1y - T_1 - S_2y) & z(1-z)(L - S_1 - T_1 - T_2 - S_2x + T_1x) & (1-2z)(T_1 + T_2 + Ly - S_1y - T_1x - T_1y - T_2y - S_2xy + T_1xy - L) \end{pmatrix}$$

According to the Lyapunov discriminant, at an equilibrium point, if the eigenvalues of the Jacobian matrix are all negative, the equilibrium point is the evolutionary stability point; If the eigenvalues of the Jacobian matrix are all greater than 0, it is an unstable point; If one or two of the eigenvalues of the Jacobian matrix are greater than 0, it is a saddle point. In the asymmetric evolutionary game, only the stability of pure strategy equilibrium can be considered [77], so it is only necessary to discuss the stability of these eight equilibrium points: $E_1(0,0,0)$, $E_2(0,0,1)$, $E_3(0,1,0)$, $E_4(0,1,1)$, $E_5(1,0,0)$, $E_6(1,0,1)$, $E_7(1,1,0)$, $E_8(1,1, 1)$. When the eight equilibrium points are substituted into the Jacobian matrix, the eigenvalues of the Jacobian matrix are shown in Table 4.

Table 4. The eigenvalues of the Jacobian matrix.

Equilibrium point	Jacobian matrix eigenvalues		
	λ_1	λ_2	λ_3
E_1(0，0，0)	$P_t(d_t - \theta P_t) - U_0$	$-P_t(d_t - \theta P_t) + C_td_t - C_gd_g - (e^2\eta)/2 + h_1 + h_2$	$T_1 - L + T_2$
E_2(0，0，1)	$P_t(d_t - \theta P_t) + T_1 - U_0$	$-P_t(d_t - \theta P_t) + S_1 + T_2 - C_gd_g + C_td_t - (e^2\eta)/2 + h_1 + h_2$	$L - T_1 - T_2$
E_3(0，1，0)	$U_0 + b - P_g(d_g - \theta P_g + kC_p + \gamma e + \varepsilon) + \gamma ln(\varepsilon + d_g + C_pk - P_g\theta + e\gamma) + \beta(d_g - \theta P_g + kC_p + \gamma e + \varepsilon)$	$P_t(d_t - \theta P_t) + (e^2\eta)/2 + C_gd_g - C_td_t - h_1 - h_2$	$-S_1$

E4(0，1，1)	$S_2 + U_0 - P_g(d_g - \theta P_g + kC_p + \gamma e + \varepsilon) + \gamma ln(\varepsilon + d_g + C_p k - P_g\theta + e\gamma) + \beta(d_g - \theta P_g + kC_p + \gamma e + \varepsilon)$	$P_t(d_t - \theta P_t) + (\eta e^2)/2 - S_1 - T_2 + C_g d_g - C_t d_t - h_1 - h_2$	S_1
E5(1，0，0)	$-P_t(d_t - \theta P_t) + U_0$	$C_t d_t - C_g d_g - (e^2\eta)/2 + P_g(d_g - \theta P_g + kC_p + \gamma e + \varepsilon) + h_1 + h_2$	$T_2 - L$
E6(1，0，1)	$-P_t(d_t - \theta P_t) - T_1 + U_0$	$S_1 + T_2 - C_g d_g + C_t d_t - (e^2\eta)/2 + P_g(d_g - \theta P_g + kC_p + \gamma e + \varepsilon) + h_1 + h_2$	$L - T_2$
E7(1，1，0)	$-b - U_0 + P_g(d_g - \theta P_g + kC_p + \gamma e + \varepsilon) - \gamma ln(\varepsilon + d_g + C_p k - P_g\theta + e\gamma) - \beta(d_g - \theta P_g + kC_p + \gamma e + \varepsilon)$	$C_g d_g - C_t d_t + (e^2\eta)/2 - P_g(d_g - \theta P_g + kC_p + \gamma e + \varepsilon) - h_1 - h_2$	$-S_1 - S_2$
E8(1，1，1)	$-U_0 - S_2 - \gamma ln(\varepsilon + d_g + C_p k - P_g\theta + e\gamma) + P_g(d_g - \theta P_g + kC_p + \gamma e + \varepsilon) - \beta(d_g - \theta P_g + kC_p + \gamma e + \varepsilon)$	$C_g d_g - T_2 - S_1 - C_t d_t + (e^2\eta)/2 - P_g(d_g - \theta P_g + kC_p + \gamma e + \varepsilon) - h_1 - h_2$	$S_1 + S_2$

For simplicity, the paper assumes $-P_t(d_t - \theta P_t) + U_0 > 0$，$U_0 + \gamma ln(\varepsilon + d_g + C_p k - P_g\theta + e\gamma) + \beta(d_g - \theta P_g + kC_p + \gamma e + \varepsilon) - P_g(d_g - \theta P_g + kC_p + \gamma e + \varepsilon) > 0$, and $-P_t(d_t - \theta P_t) + C_t d_t - C_g d_g - (e^2\eta)/2 + h_1 + h_2 < 0$. Four possible evolutionary stability scenarios are discussed as follows.

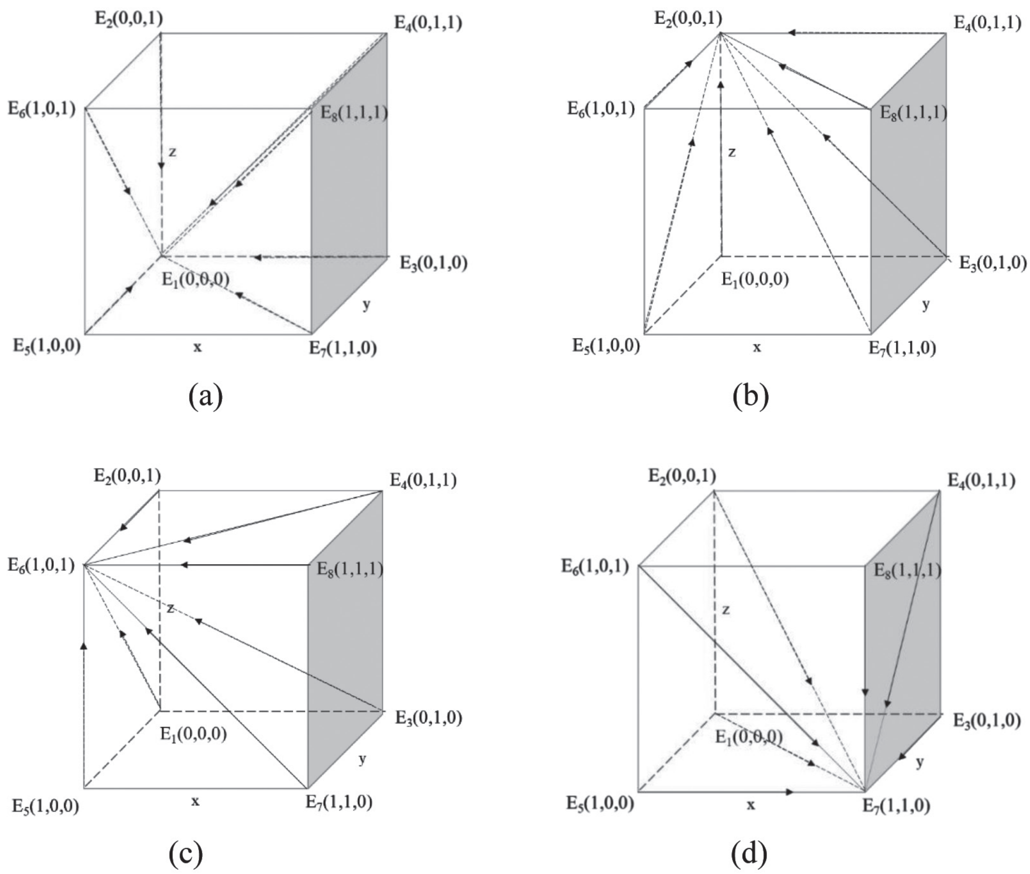

Fig. 2(a). The phase diagram when T1-L+T2 < 0.
Fig. 2(b). The phase diagram when $P_t(d_t - \theta P_t) + T_1 - U_0 < 0$，$-P_t(d_t - \theta P_t) + S_1 + T_2 - C_g d_g + C_t d_t - (e^2 * \eta)/2 + h_1 + h_2 < 0$ and $L - T_1 - T_2 < 0$.
Fig. 2(c). The phase diagram when $-P_t(d_t - \theta P_t) - T_1 + U_0 < 0$，$S_1 + T_2 - C_g d_g + C_t d_t - (e^2\eta)/2 + P_g(d_g - \theta P_g + kC_p + \gamma e + \varepsilon) + h_1 + h_2 < 0$ and $L - T_2 < 0$
Fig. 2(d). The phase diagram when $C_g d_g - C_t d_t + (e^2\eta)/2 - P_g(d_g -.\theta P_g + kC_p + \gamma e + \varepsilon) - h_1 - h_2 < 0$.

Proposition 1. When $T_1 - L + T_2 < 0$, that is, the sum of tax paid by enterprises for traditional production and tax paid by consumers for traditional consumption is less than the cost of environmental regulation paid by government, it can be seen from Table 4 that the Jacobian matrix eigenvalues corresponding to $E_1(0, 0, 0)$ are negative, so $E_1(0, 0, 0)$ is the equilibrium point, (traditional consumption and traditional production, without environmental regulation) is an evolutionary stable strategy. The phase diagram of the evolutionary game model is shown in Figure 2(a).

Proposition 2. When $P_t(d_t - \theta P_t) + T_1 - U_0 < 0$, $-P_t(d_t - \theta P_t) + S_1 + T_2 - C_g d_g + C_t d_t - (e^2 * \eta)/2 + h_1 +$ and $L - T_1 - T_2 < 0$, that is, the sum of consumption expenditure and tax paid by consumers is less than the utility obtained by consumers when they purchase traditional products; The sum of government subsidies given to enterprises when they produce green products, the income obtained by enterprises for selling surplus carbon emission allowances, the cost paid by enterprises for purchasing excess carbon emission allowances, and tax and production cost paid by enterprises when they produce traditional products is less than the sum of consumers' expenditure when they buy traditional products, and the production cost and R&D input cost of enterprises when they produce green products; The sum of the tax paid by enterprises for traditional production and the tax paid by consumers for non-green consumption is greater than the cost of environmental regulation paid by the government when enterprises produce traditional products. It can be seen from Table 3 that the Jacobian matrix eigenvalues corresponding to $E_2(0, 0, 1)$ are negative, so $E_2(0, 0, 1)$ is the equilibrium point, so (traditional consumption, traditional production, environmental regulation) is an evolutionarily stable strategy. The phase diagram of the evolutionary game model is shown in Figure 2(b).

Proposition 3. When $-P_t(d_t - \theta P_t) - T_1 + U_0 < 0$, $S_1 + T_2 - C_g d_g + C_t d_t - (e^2\eta)/2 + P_g(d_g - \theta P_g + kC_p + \gamma e + \varepsilon) + h_1 + h_2 < 0$, and $L - T_2 < 0 < 0$, that is, the difference between the utility and expenditure obtained by consumers is less than the tax paid by consumers when they purchase traditional products; The sum of the expenditure of consumers on green consumption, the cost and tax paid by enterprises in traditional production, the income obtained by enterprises from selling surplus carbon emission allowances, the cost paid by enterprises in purchasing excess carbon emission allowances and the subsidies received by enterprises in green production is less than the sum of the cost paid by enterprises in green production and the cost of R&D input; the tax paid by enterprises in traditional production is greater than the environmental regulation costs paid by the government. It can be seen from Table 4 that the Jacobian matrix eigenvalues corresponding to $E_6(1, 0, 1)$ are negative, so $E_6(1, 0, 1)$ is the equilibrium point, so (green consumption, traditional production, environmental regulation) is an evolutionarily stable strategy. The phase diagram of the evolutionary game model is shown in Figure 2(c).

Proposition 4. When $C_g d_g - C_t d_t + (e^2\eta)/2 - P_g(d_g - \theta P_g + kC_p + \gamma e + \varepsilon) - h_1 - h_2 < 0$, that is, the sum of the enterprise's green production cost and R&D input cost is less than the sum of the consumer's green consumption expenditure, the enterprise's income from selling surplus carbon emission allowances, the enterprise's cost of purchasing excess carbon emission allowances, and the enterprise's cost of traditional production. It can be seen from Table 4 that the eigenvalues of the Jacobian matrix corresponding to $E_7(1, 1, 0)$ are negative, so $E_7(1, 1, 0)$ is the equilibrium point, so (green consumption, green production, without environmental regulation) is an evolutionarily stable strategy. The phase diagram of the evolutionary game model is shown in Figure 2(d).

Results and Discussion

Referring to the research of Wang Lu et al. [78]and Jin et al. [64], taking mid-range vehicles as an example, the price of traditional fuel vehicles is 200,000 yuan, The cost of each vehicle is 180,000 yuan, while the price of new energy vehicles is 250,000 yuan, and the cost of each vehicle is 230,000 yuan. Related parameters are set as follows: U_0=12, d_t=10, d_g=6, β=0.5, P_t=20, P_g=25, e=0.5, T_1=3, T_2=4, C_t=18, C_g=23, η=1, a=5, b=5, R_1=10, R_2=10, L=8, C_p=2, h_1=2, h_2=2, ε=0.5. θ, γ, k, S_1, S_2 are randomized test data [12], θ, γ, k are 0,0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, respectively. S_1 and S_2 are respectively 0,0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0. Assume that at the beginning, the probability of consumers, enterprises, and the government choosing different strategies is 0.5.

Impact of Consumer Price Sensitivity

When the price sensitivity coefficient θ is taken at different values, the simulation results of the evolutionary game are shown in Figure 3. Under different values of θ, the evolution trajectories of the tripartite game are shown in Figure 3(a). The trend of behavioral evolution of consumers and enterprises is not steady with the change of θ. While the evolutionary trajectory of the government tends to be that there is no environmental regulation regardless of the value of the price sensitivity coefficient.

The strategy evolution of consumers is shown in Figure 3(b). When θ is less than 0.5, the evolutionary path of consumers is an oscillatory process, making it difficult to reach an equilibrium point. When θ gradually increases and its value lies between 0.5 and 0.8, consumer behavior evolves towards green consumption over time. When θ is between 0.9 and 1, consumers tend to purchase traditional products. The possible reason is that when θ is less than 0.5, in order to meet a certain utility, consumers have greater randomness in the purchase of the two kinds of products, the price change of them will not significantly affect consumers' purchase intention, and the evolution path of consumer behavior is difficult to reach an equilibrium point. When θ increases, ranging from 0.5 to 0.8, although the change in price will cause a change in consumer demand, due to the publicity of the government's "dual carbon"

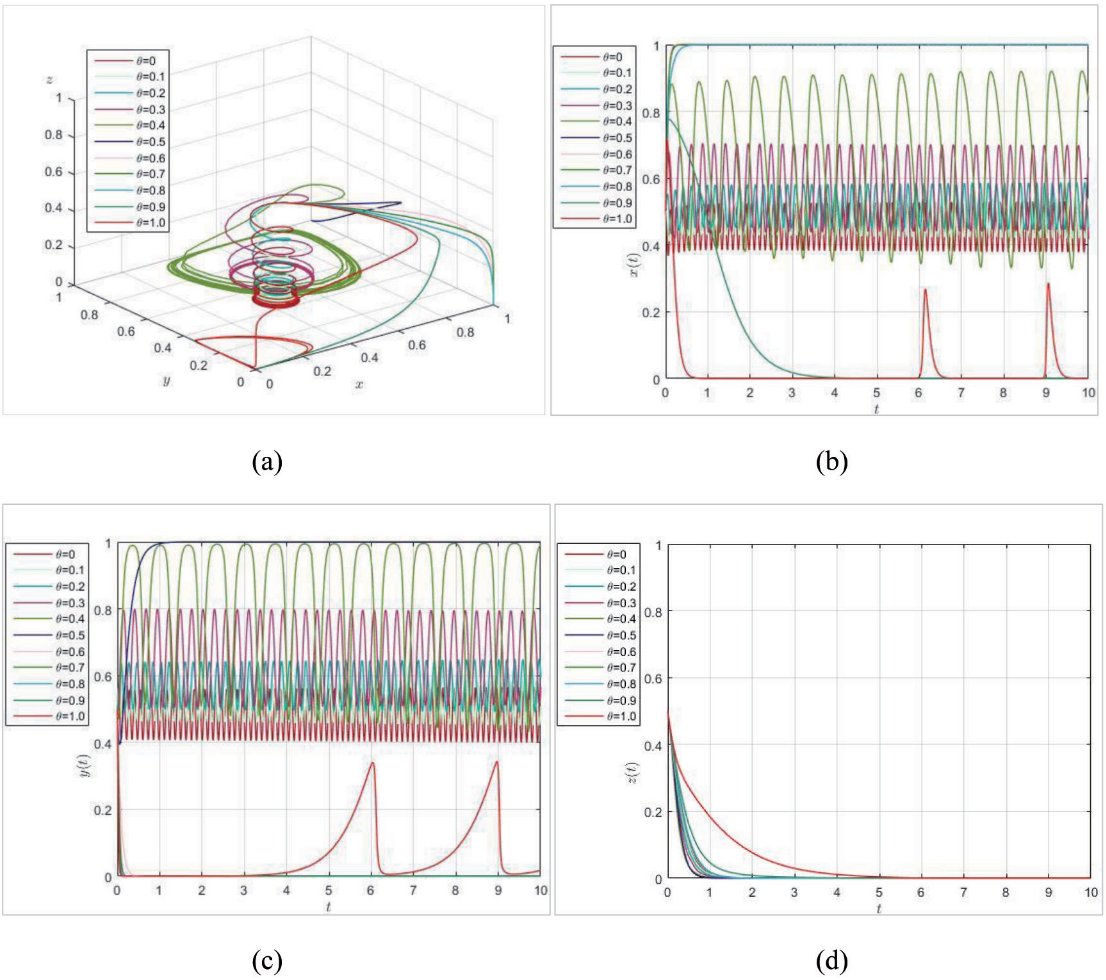

Fig. 3. Evolution trajectories of consumers, enterprises and the government under different price sensitivity coefficients.

policy, consumers will change their consumption concept, pay more attention to energy conservation, environmental protection, low carbon emissions, and believe that green products are of better quality and can obtain greater psychological utility, so they choose green consumption. When θ exceeds 0.8, as the price of green products is generally higher than that of traditional products, when the price of green products is too high and the same utility can be obtained by purchasing traditional products, consumers' willingness to purchase green products decreases, and they choose traditional consumption instead. At this point, it may be more effective for the government to regulate the environment and provide green subsidies to consumers.

The change of enterprises' strategy choices over time is shown in Figure 3(c). When θ equals 0.5, enterprises tend to choose green production. When θ is between 0 and 0.4, there is no clear behavioral tendency. When θ is greater than 0.5, enterprises choose traditional production. The possible reason is that when θ is between 0 and 0.4, due to the lack of clear purchasing tendencies of consumers towards traditional and green products, it is difficult for enterprises to formulate corresponding production plans. Therefore, the evolution path of enterprises is also a fluctuating process. When θ equals 0.5, consumers tend to purchase green products, and in order to meet consumers' demand, enterprises choose green production. When θ is greater than 0.5, considering the price sensitivity of consumers and market demand, as well as the absence of environmental regulation, and that enterprises do not need to pay taxes on traditional production; as a result, enterprises can obtain greater net profits when they produce traditional products. So enterprises choose traditional production.

The change of government strategy over time is shown in Figure 3(d). At any value of θ between 0 and 1, the government chooses not to regulate the environment. The possible reason is that when θ is between 0 and 0.4, consumers choose green consumption, enterprises' behavior does not reach the equilibrium point, and the government's environmental benefits are far less than the costs that need to be paid, so the government chooses not to regulate the environment. When θ equals 0.5, consumers choose green consumption, enterprises choose green production, and the green product market reaches equilibrium state. The government does not need to carry out environmental regulation. When θ is greater than 0.5, consumers choose green consumption, and the government needs to provide higher subsidies to them. While enterprises prefer traditional production and the tax paid by enterprises is lower than the green subsidies paid by the government, resulting in a decrease of government benefits, the government choose not to implement environmental regulation.

Impact of Consumers' Green Preferences

When the green preference coefficient γ takes different values, the simulation results of the evolutionary game are shown in Figure 4. The evolution trajectory of the tripartite game under different values of γ is depicted in Figure 4(a). Consumers tend to purchase green products, and the evolution path of the government tends not to regulate the environment. The greater the consumers' green preference is, the faster enterprises tend to choose green production.

The change of the consumers' strategy over time is demonstrated in Figure 4(b). The green preference coefficient ranges from 0 to 1, and consumers choose green consumption. The preference for green consumption is manifested in cognitive preference and emotional preference for green products. According to the theory of planned behavior, consumers' green consumption attitude affects their green consumption intention and thus their green consumption behavior [37]. Therefore, with the increase of green preference, consumers tend to favor green consumption. At the same time, in order to meet consumers' green preference, enterprises expand the production of green products and provide a broader supply market, so they also promote consumers' green consumption.

The change of the enterprises' strategy over time is shown in Figure 4(c). When the consumer green preference coefficient is between 0-1, the enterprise behavior tends towards green production. The larger the coefficient, the faster the enterprise tends towards green production. The reason is that when the green preference level of consumers is low, the market demand for green products is small. Then, with the increase of consumers' green preference, considering greater profit and sustainable development [79], enterprises constantly update their technology and carry out green production in order to meet consumer demand.

The change of government strategy over time is shown in Figure 4(d). When γ ranges from 0 to 1, the government chooses not to regulate the environment. The possible reason is that although the government obtains environmental benefits when consumers choose green consumption and enterprises select green production, it needs to provide relatively high subsidies. When the environmental benefits the government obtains are far lower than the subsidies it provides to consumers and enterprises, the government will not engage in environmental regulation. Alternatively, the green

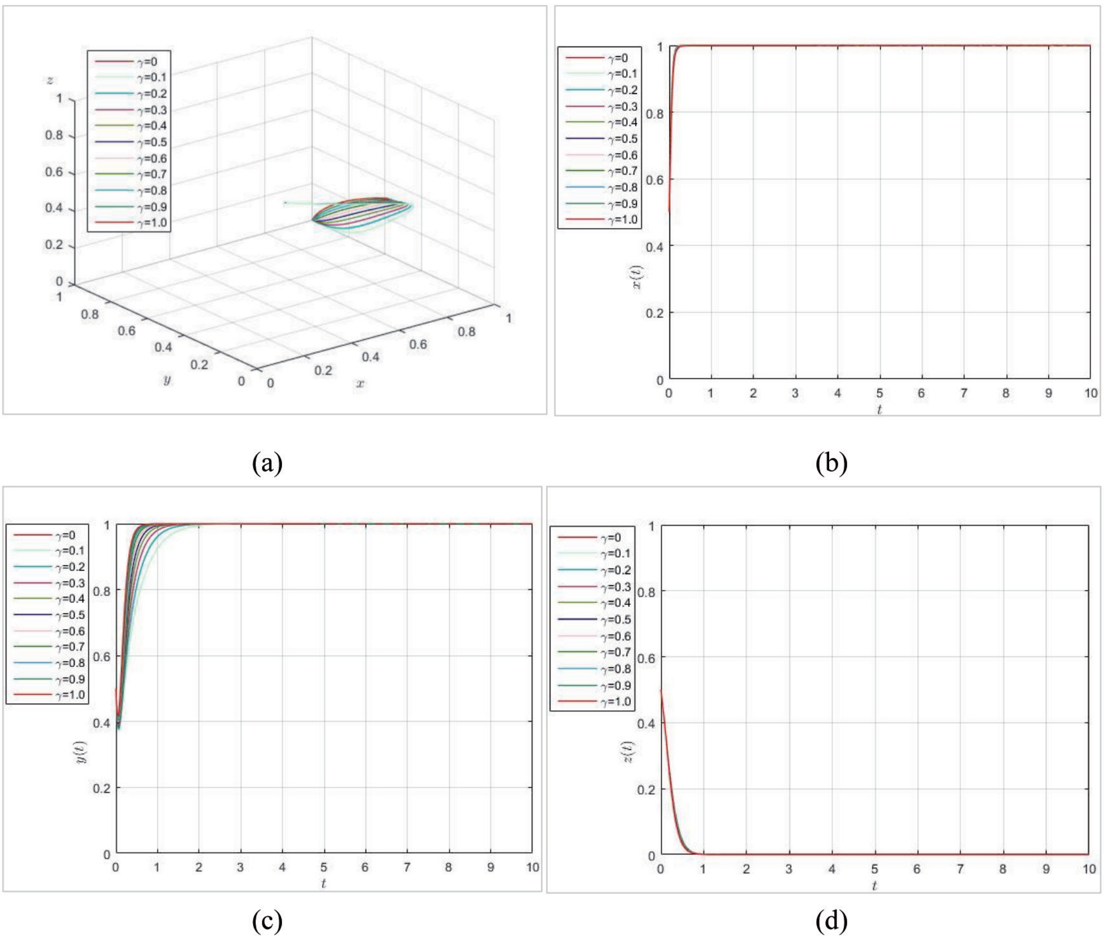

Fig. 4. Evolution trajectories of consumers, enterprises and the government under different green preference coefficients.

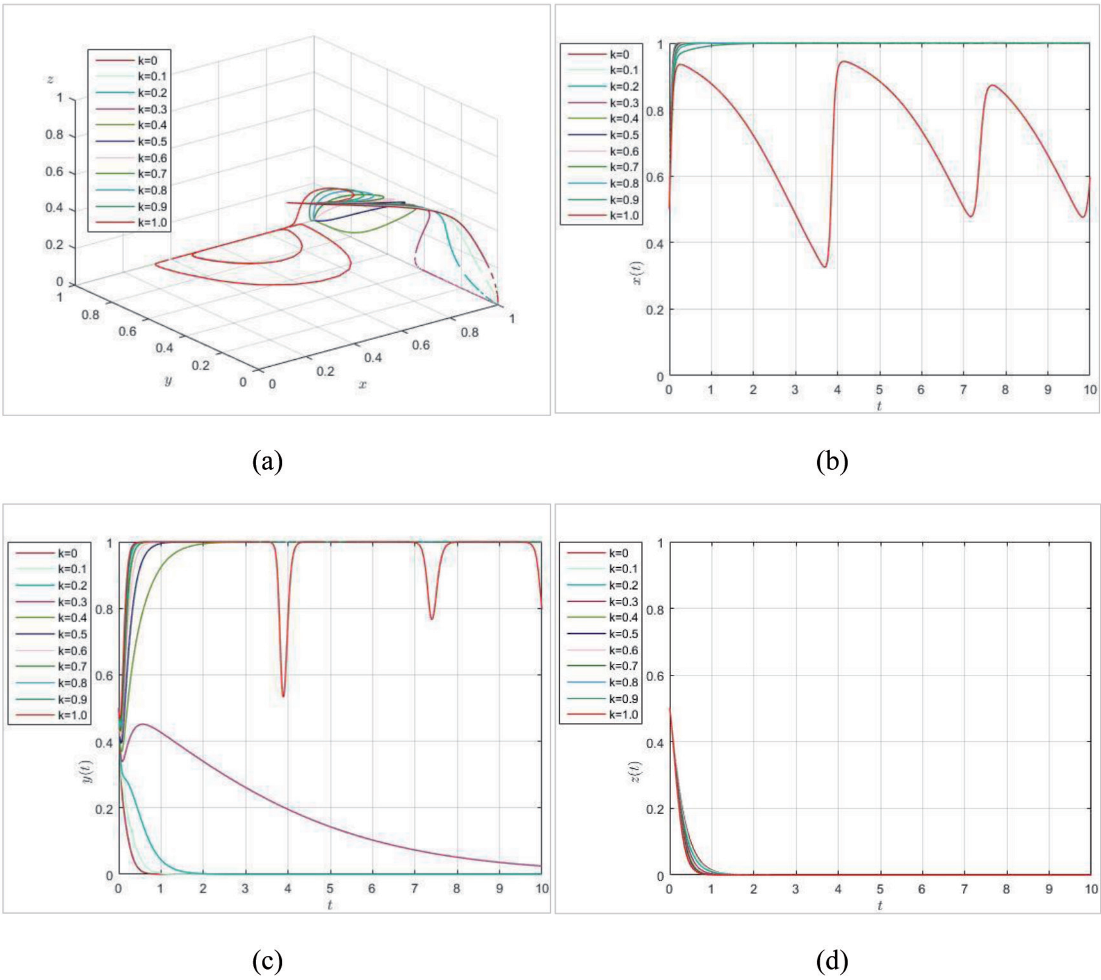

Fig. 5. Evolution trajectories of consumers, enterprises and the government under different degree of government's "dual carbon" policy publicity.

preference of consumers increases the demand for green products, which in turn pulls the development of the supply market of green products. In this way, a good supply and demand market of green products does not require the government's environmental regulation.

Impact of Government Subsidies

The simulation results of the evolutionary game are shown in Figure 5 when the government's "dual carbon" policy publicity *k* takes different values. The evolutionary trajectory of the system under different values of *k* is shown in Figure 5(a). The evolutionary path of government behavior tends not to regulate the environment, while the behavior of consumers and enterprises changes with the values of k.

The change of consumers' strategies over time are shown in Figure 5(b). The impact factor *k* is between 0 and 0.9, and consumers always choose green consumption. When *k* is set to 1, although the evolution path of consumer behavior is an oscillating process, it can be seen that the value of *x* gradually tends to 1, indicating a higher probability of consumers choosing green consumption. The possible reason is that the government's "dual carbon" policy guides consumers to transform their consumption concept, pay attention to low carbon, and save resources and energy. At the same time, enterprises provide better green products, which increases consumers' trust of green products and stimulates their demand for green consumption [59]. Therefore, the behavior of consumers evolves toward green consumption.

The strategy selection of enterprises is shown in Figure 5(c). When *k* ranges from 0 to 0.4, enterprises choose traditional production. When *k* is greater than 0.4, enterprises' behavior evolves towards green production, and a higher degree of "dual carbon" policy publicity accelerates it to reach a stable state [80]. The possible reason is that when the impact of the government's "dual carbon" policy publicity is large enough, enterprises receive the signal of green consumption to increase R&D investment and produce green products. Simultaneously, consumers are inclined toward green consumption, which expands the demand market for green products. And in order to meet the demand of consumers and obtain more profits, enterprises' behavior evolves towards green production.

The change of government strategy over time is shown in Figure 5(d). At any value of *k* between 0 and 1, the government chooses not to regulate the environment. The possible reason is that when consumers purchase green products and enterprises produce green products, although the government gains environmental benefits, it needs to provide higher subsidies. And when the environmental benefits and taxes the government obtains are far lower than the subsidies it provides to consumers and enterprises, the government chooses not to carry out environmental regulation.

Impact of Consumer Price Sensitivity

Government Subsidies to Enterprises

The government subsidies to enterprises is denoted as S_1. When S_1 takes different values, the simulation results of the evolutionary game are shown in Figure 6. As demonstrated in Figure 6(a), the behavioral evolution paths of consumers, enterprises, and the government tend to be green consumption, green production, and no environmental regulation, respectively.

The change of consumers' strategy over time is shown in Figure 6(b). When government subsidies to enterprises range from 0 to 5, and consumers all tend to choose green consumption. The possible reasons for this are the financial incentives, which make enterprises increase production and effective supply, promote green consumption products, improve consumer satisfaction, and thus encourage consumers to choose green consumption.

The variation of the enterprises' strategy is shown in Figure 6(c). When S_1 ranges from 0 to 5, enterprises tend to produce green products. The possible reason is that government subsidies provide enterprises with funds to increase R&D investment and implement green technology innovation. Consumers' demand for green products is increasing, and the benefits of producing green products outweigh the costs; therefore, enterprises choose green production.

The change of government strategy over time is shown in Figure 6(d). When S_1 ranges from 0 to 5, the government chooses not to regulate the environment. The possible reason is that initially, green subsidies given by the government encourage enterprises to increase investment in research and development, improve the performance of green products, and stabilize the price of green products, thus expanding the demand of consumers for green products and gradually forming a good supply and demand market for green products. At this time, the government does not need to impose environmental regulation.

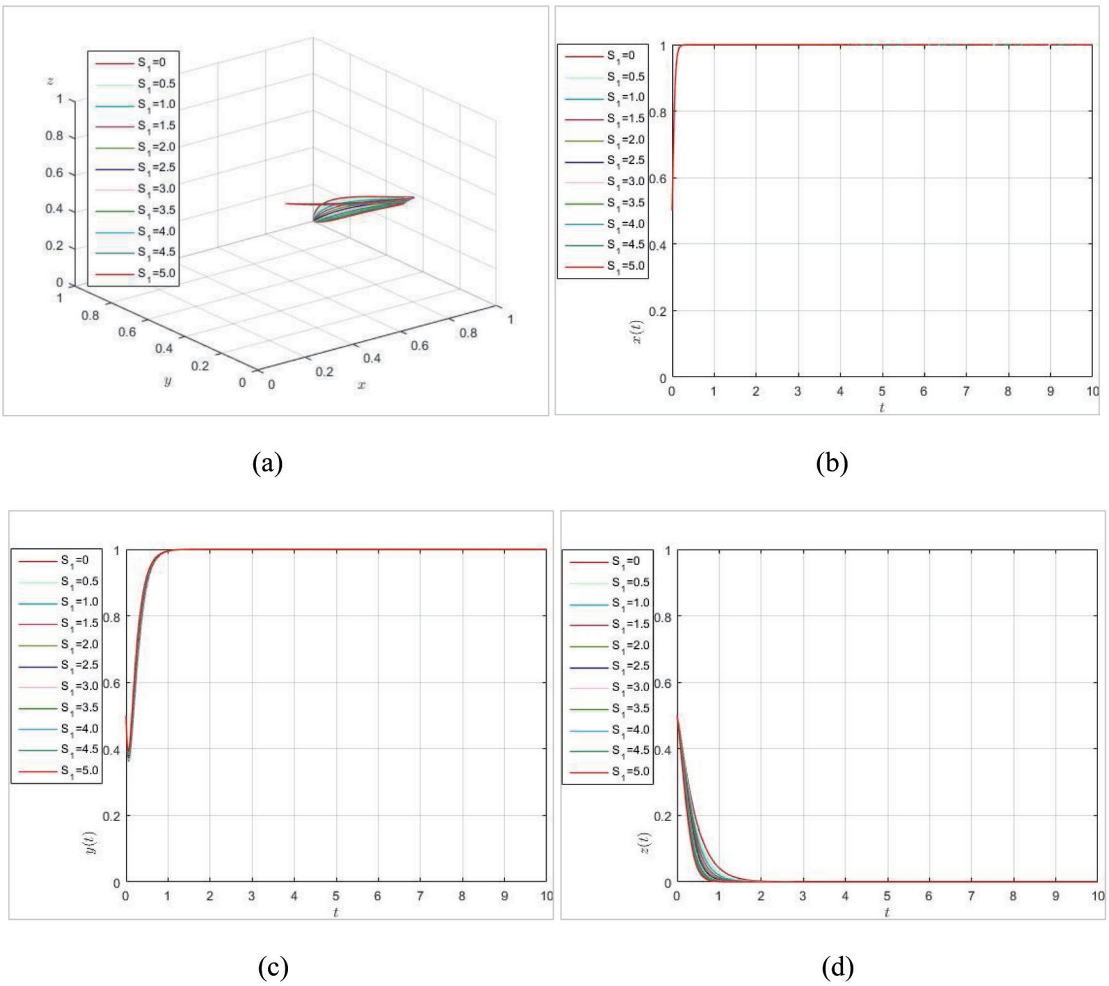

Fig. 6. Evolution trajectories of consumers, enterprises and the government under different government subsidies to enterprises.

Government Subsidies to Consumers

The government subsidies to consumers is denoted as S_2. When S_2 takes different values, the simulation results of the evolutionary game are shown in Figure 7. The evolution trajectory of the system under different subsidies is shown in Figure 7(a), and the behavioral evolution paths of consumers, enterprises, and the government tend to be green consumption, green production, and no environmental regulation, respectively.

The change of the consumers' strategy over time is shown in Figure 7(b). When the subsidies given by the government range from 0 to 5, consumers always choose green consumption. The possible reason is that the government's economic incentives allow consumers to actually obtain the benefits of green products. Moreover, the green production of enterprises promotes the development of the green product market. And green products are constantly popularized, which improves consumers' trust in green products and increases the demand for them. Therefore, consumers tend to choose green consumption.

Enterprises' strategy changes over time, as shown in Figure 7(c). When S_2 ranges from 0 to 5, enterprises select green production. The possible reason is that the government subsides consumers to expand the demand market of green products, and in order to meet consumers' demand, enterprises constantly update technology and increase the R&D investment of green production. As a result, the profits exceed the costs, so enterprises choose green production.

The change of government's strategy over time is shown in Figure 7(d). When S_2 ranges from 0 to 5, the willingness of the government to regulate environment is reduced, and it tends not to regulate the environment, which is consistent with the research results of Tian et al. [76]. The possible reason is that at the beginning, green subsidies to consumers prompt consumers to purchase green products, and demand drives production, so enterprises produce green products. After forming a good supply and demand market for green products, the government gradually tends to be free of environmental regulation.

Conclusions and Policy Implications

Conclusions

In order to accelerate the development of the green product market and achieve the goal of "dual carbon", this paper constructs a tripartite evolutionary game

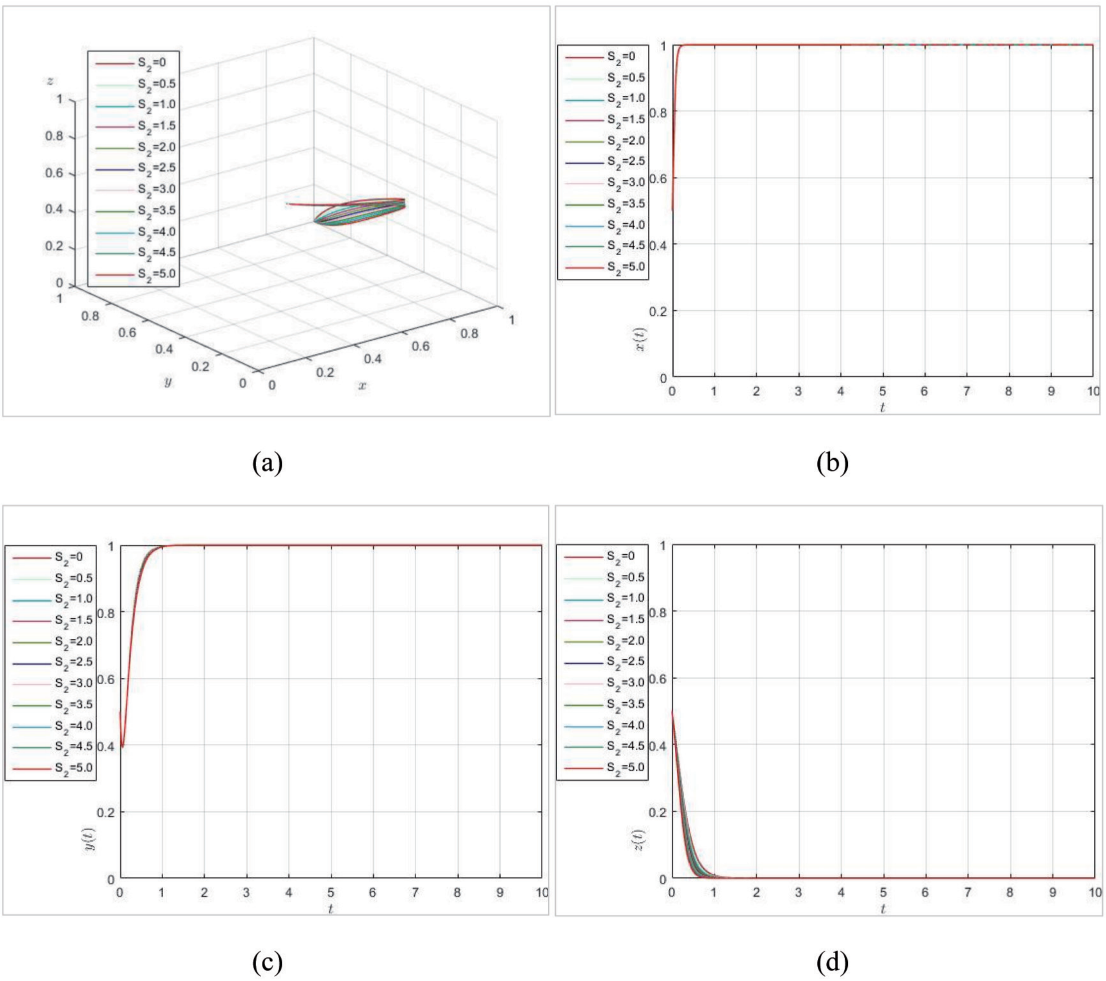

Fig. 7. Evolution trajectories of consumers, enterprises, and the government under different government subsidies to consumers.

model composed of consumers, enterprises, and the government and analyzes the evolution process of the system equilibrium strategy in different scenarios. Then, combining numerical simulation, the paper explores the factors that influence the system equilibrium and the strategy choices of the game players.

The results show that: (1) Among all possible equilibrium strategies in the evolutionary game system, there are only four stable equilibrium strategies under certain conditions, that is, (traditional consumption, traditional production, without environmental regulation), (traditional consumption, traditional production, environmental regulation), (green consumption, traditional production, environmental regulation), and (green consumption, green production, without environmental regulation). And the last strategy represents the optimal ideal situation that this study hoped to obtain [81].

(2) Consumers' cognitive and emotional preferences reflect their attitudes towards green products, which positively influence their intentions to consume green products, subsequently leading to actual green consumption behaviors [40]. This paper posits that consumers' attitudes towards green consumption positively impact the demand for green products, an effect quantified by the green preference coefficient. Simulation results indicate that a higher green preference coefficient correlates with a stronger inclination among consumers towards green consumption, and a quicker shift in enterprise behavior towards green production. This finding aligns with the research of Cao Zhongqiu et al. [82], who argue that a certain level of green preference among consumers can effectively encourage manufacturers to adopt green production and marketing strategies. At this point, a well-balanced supply and demand market for green products can significantly alleviate the pressure of government environmental regulation.

(3) Subjective norms are defined as the influence of external, positive information about green products and behaviors on individual decision-making. According to Zhang et al. [73], the more extensive and impactful this green consumption information is, the more it sways consumers towards making eco-friendly decisions. The government's "dual carbon" policy serves a dual purpose: it not only heightens consumer awareness for green consumption, energy saving, and low-carbon practices [43], but it also elevates their understanding of these concepts, encouraging the adoption of green behaviors. This paper posits that subjective norms, influenced by the government's "dual carbon" policy publicity, positively affect green consumption behavior, an impact quantifiable by a specific influence factor. System simulation results suggest that effective publicity of the government's "dual carbon" policy not only fosters a shift in consumer behavior towards green consumption but also steers enterprise behavior towards green production. This synergy between consumer and enterprise behavior organically develops the market for green products and lessens the pressure of environmental regulation by the government. In promoting the "dual carbon" policy, the government should strategically utilize the framing effect and highlight the positive emotion and social contribution of green consumption to more effectively motivate eco-friendly consumer behaviors [83].

(4) Perceived behavioral control reflects consumers' assessment of the difficulty of purchasing green products, such as the influence of product pricing [35]. And consumers' perception of price significantly affects their purchasing behavior, thereby impacting market demand for these products. This paper explores the impact of perceived behavioral control on green consumption behavior from the perspective of price perception. It posits that perceived behavioral control negatively influences green consumption behavior, an effect measured by the price sensitivity coefficient. Studies by Zhong Yunyun et al. [26] and VanTran [35] indicate that product pricing negatively affects green consumption behavior, and our research findings reveal that an excessively high or low consumer price sensitivity coefficient impedes the shift towards green consumption behavior. This is also true for the transition of corporate behavior towards green production. The rationale is that when the consumer price sensitivity coefficient is low, consumers exhibit greater randomness in choosing between green and traditional products, as price changes do not significantly alter their purchasing intention. Conversely, when the price sensitivity coefficient is high, the increased cost of green products can deter consumers, leading them to opt for traditional consumption as they weigh utility against loss. This behavior also influences enterprise strategies based on market demand. In such scenarios, government interventions through environmental regulations and the provision of green subsidies to consumers might be more effective.

(5) Additionally, through system simulation, this study examines the evolutionary paths of consumers, enterprises, and the government under various levels of government green subsidies to both enterprises and consumers. The findings reveal that subsidies directed at enterprises and consumers positively influence the shift in enterprise behavior towards green production and consumer behavior towards green consumption. This observation aligns with the findings of Tian et al. [76], Gong et al. [18], and Ning Xin et al. [84]. The use of incentives and subsidies is a crucial strategy to address the economic externalities associated with green products. Implementing such measures can effectively motivate enterprises to invest in technological innovation and encourage consumers to recognize the benefits, thereby guiding them towards making greener choices [84].

Policy Implications

The government is the subject of environmental regulation. Enterprises, as the production end, are the source and main guarantor of green consumption. Consumers are the main force and implementers of green consumption [27]. Only with the joint efforts of the tripartites can the market of green products be effectively promoted and the "dual carbon" goal be achieved.

At the level of government, it should guide enterprises to impose green technological innovation and produce green products and encourage consumers to make green purchases by offering subsidies, tax cuts, and fee reductions in areas such as food, clothing, housing, and transportation. In addition, the government should pay attention to strengthening the public's environmental education and popularizing the policies related to the "dual carbon" through social media to raise the level of public environmental literacy. As a result, it can encourage the public to participate in environmental co-governance and form the concept of green consumption and lifestyle.

At the level of enterprise, on the one hand, green consumption can enhance the social reputation of enterprises, whereas on the other hand, it can meet consumers' demand for green consumption and improve the competitive advantages of enterprises in the supply market [85]. Enterprises should actively respond to the "dual carbon" policy, expand the supply of green products, develop and apply green technologies, decrease production costs, and thus reduce the price of green products. Furthermore, enterprises should provide consumers with sufficient information of green products through relevant labels and establish communication channels with consumers to increase the acceptance and trust of the public on green products. Also, enterprises can implement precision marketing for different consumer groups.

At the level of the consumer, green consumption can be realized in the aspects of clothing, food, housing, and transportation. Specifically, it can be reflected in the purchase of clothes with environmental protection materials, green food, green household appliances, and new energy vehicles, etc. Moreover, it can be reflected in choosing public transportation, riding bicycles, and walking. In summary, on the basis of the government's environmental education and enterprises' efforts to realize green reform, consumers should take the initiative to focus on environmental issues, improve their environmental knowledge, and gradually form environmental responsibility to engage in green consumption in various ways.

The paper focuses solely on the evolution of green products market under conditions of incomplete information and bounded rationality. It overlooks the heterogeneity of income and consumers knowledge levels, as well as considerations of product design and circulation. Therefore, it will be our next research direction to incorporate the above influencing factors, construct a dynamic and repetitive game model of the government, enterprises, and consumers; under the perfectly competitive and imperfectly competitive markets. Meanwhile, the research will combine specific industries and collect real data for simulation, and explore enlightening suggestions to achieve the goal of "dual carbon".

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Conflict of Interest

The authors declare no conflict of interest.

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