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Research on Stability of Green Transformation Strategy of Manufacturing Enterprises under Multi-dimensional Environmental Regulation

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ABSTRACT

Giving full play to the interaction of multi-dimensional environmental regulation is an important method to accelerate the green transformation of manufacturing enterprises which is a significant way to achieve carbon peaking and carbon neutrality goals. Based on the theory of evolution game, a green transformation strategy evolution game model participated by the government, consumers, and manufacturing enterprises has been constructed. Stability research is conducted based on the behavioral mode of the three parties participating subjects and the paper uses MATLAB for numerical simulation to analyze the impact of environmental regulations of different dimensions on the green transformation of enterprises. The research shows that: (1) When the government adopts a single environmental regulation of carbon emission right transaction or green consumption subsidy, it will not affect the choice of green transformation strategies of the enterprise. (2) When the government adopts a single environmental regulation of environmental protection tax, it only promotes enterprises to choose green transformation strategies under limited conditions. (3) Under the multi-dimensional environmental regulations of the government, by affecting the cost and income of enterprise green technology innovation, consumers' green consumption behavior, and the manufacturing enterprises choose green transformation as a stable strategy. Therefore, the government should give full play to the role of multi-dimensional environmental regulations in promoting consumers' green consumption and enterprises' green technology innovation to accelerate the green transformation of manufacturing enterprises.

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Multi-dimensional environmental regulation; Green consumption; Green transformation of manufacturing enterprises; Three-party evolution game

1. Introduction

As China enters a new stage of development, manufacturing enterprises must make green transformation to achieve the goal of "dual carbon" and promote high-quality economic development. Green technology innovation is the main way for enterprises to achieve green transformation. Government policies promote the development of green technology innovation (Sheng et al., 2023), but environmental supervision is increasingly strict, and traditional polluting manufacturing enterprises will face huge operational risks. In contrast, manufacturing enterprises with green advantages will have better access to environmental policy guarantees and improve market competitiveness. Therefore, government environmental regulation has become an important factor affecting the green transformation strategy of manufacturing enterprises. Sharma (2015) divides environmental strategies into reactive and forward-looking. Reactive environmental strategy means that enterprises passively carry out green production activities under environmental regulation, while forward-looking environmental strategy means that enterprises actively carry out green technology innovation and produce green products. At present, China is in the transition period of the environmental governance system, and there are uncertainties in enterprises to formulate environmental strategies (Zhou et al., 2023; Jiang et al., 2022). On the one hand, enterprises are constrained by government environmental regulation and external environmental pressure such as market green demand caused by the deepening of consumers; on the other hand, the government environmental regulation will also stimulate the green technology innovation of manufacturing enterprises and promote the green transformation of enterprises (Yin et al., 2023). In general, the choice of green transformation strategy of enterprises is not simply either - or, but the result of multi-party games between the government, consumers and manufacturing enterprises.

The game between the government and manufacturing enterprises is mainly reflected in the dual influence of government environmental regulation on the green transformation of enterprises. Existing studies have shown that different types of environmental regulation tools have different impacts on the green transformation of enterprises (Wang et al., 2019). Compared with the mandatory environmental regulation tools, the economic incentive environmental regulation tools can effectively improve the level of green technology innovation of enterprises, and then promote the green transformation of enterprises (Tian and Feng, 2022). Among them, sewage charge has both an internal incentive and external pressure on enterprise green innovation, thus forming the forcing effect, especially the stronger the enterprise resource base, the stronger the "forcing" effect, but the environmental protection subsidy will produce "crowding out" effect on enterprise green innovation, which is not conducive to enterprise green transformation (Wang et al., 2022); carbon emission trading policy can promote enterprise green innovation (Su and Fan, 2022), and the government guides enterprises to make green transformation strategy through market signals (Bai et al., 2023); environmental tax also has a dual effect on the green transformation of enterprises, including the promotion effect of environmental tax incentives and the forcing effect of the environmental tax burden (Qi et al., 2023; Wang et al., 2022). From the perspective of the evolutionary game, the cost and benefit of government environmental regulation and supervision, and the cost of green technology innovation in manufacturing enterprises are all important factors affecting the evolutionary game behavior between the government and enterprises (Wang et al., 2022).

The game between manufacturing enterprises and consumers is mainly reflected in the game between green production and green consumption (Fan et al., 2022). With green products as the link, enterprises and consumers have contradictions in pursuing the maximization of their interests (Yuan et al., 2020). For enterprises, with the improvement of consumers' environmental awareness, manufacturing enterprises produce green products to meet the needs of consumers with green preferences. Although the premium of green products will increase the profit of enterprises (Zhou, 2018), it will also lead to an increase in production costs, which may not necessarily bring higher profit to enterprises (Yu et al., 2016). For consumers, because the price of green products is often higher than that of traditional products, consumers' acceptance of green products will be affected. The interaction between enterprises and consumers cannot be separated from the support of the government. The government's green consumption subsidies can not only effectively enhance consumers' awareness of green consumption (Zhou and Duan, 2022; Wang et al., 2020), but also promote the green transformation of manufacturing enterprises from the demand side.

In recent years, the research on the tripartite game between the government, enterprises and consumers has gradually increased. Based on the interests and rights of stakeholders, Li and Gao (2022) analyzed the impact of the government's pollution tax collection and public environmental protection publicity on the green technology innovation of enterprises. Yang et al. (2023) constructed a game model of the evolution of enterprise green technology innovation system and analyzed three stable and balanced strategies: consumers buying green products, government market regulation strategy and enterprise green technology innovation strategy. Zhang and Kong (2022) used evolutionary game theory to systematically explore the impact of environmental regulation tools such as environmental protection penalties, environmental protection subsidies and green consumption subsidies on green production and green consumption. Therefore, the formulation of green transformation strategies of manufacturing enterprises is influenced by many factors such as government environmental regulation and consumer environmental awareness.

Based on the above analysis, in the study of the relationship between government and enterprises, most scholars mainly study the green transformation strategy of manufacturing enterprises based on single environmental regulation tools such as carbon emission trading and environmental protection tax, while few scholars research the green transformation of enterprises from multi-dimensional environmental regulation. At the same time, consumers are important drivers of enterprises to realize green transformation, and consumers' environmental awareness and purchasing power of green products are also one of the most important factors in the green transformation of manufacturing enterprises. In existing studies, the impact of government green consumption subsidies on the green transformation of enterprises is rarely analyzed from the perspective of consumers. The research on the stability of the green transformation strategy of manufacturing enterprises needs to comprehensively consider the multiple participants of the government, consumers and enterprises, and focus on the interactive perspective of multi-dimensional environmental regulation.

Compared with the existing studies, the possible contributions and innovations of this paper are as follows: (1) considering the influence factors such as government environmental regulation and consumer acceptance, this paper comprehensively describes the green transformation behavior of manufacturing enterprises guided by government environmental regulation and driven by consumer demand from both macro and micro perspectives. (2) this paper systematically discusses the impact of single environmental regulation and multi-dimensional environmental regulation on the green transformation of manufacturing enterprises, such as environmental protection tax, carbon emission rights trading, and green consumption subsidy. (3) according to the realistic problems of high carbon emission, high pollution and low-end in China's manufacturing enterprises, this paper adds the "green" factor into the practice process of the transformation of manufacturing enterprises, so as to expand the connotation boundary of the transformation of manufacturing enterprises. (4) this paper analyzes the influence of multi-dimensional environmental regulations, including environmental taxes, green subsidies and carbon emission rights trading, on the stability of the green transformation strategy of manufacturing enterprises in choosing green technology innovation, enriching the research on the impact of environmental regulations on the green transformation of manufacturing enterprises, and providing a theoretical basis for subsequent relevant research.

The paper is structured as follows: Chapter 2 is mainly about the construction of the tripartite evolutionary game model of the government, consumers and enterprises, and the hypothesis of relevant parameters. In Chapter 3, the stability of evolutionary game strategy is analyzed in detail, and the replication dynamic equation of game players is obtained. Chapter 4 analyzes the asymptotic stability of the equilibrium point by constructing the Jacobian matrix and draws relevant inferences. In Chapter 5, Matlab software is used to simulate and analyze the sensitivity of different environmental regulation policies under single environmental regulation and multi-dimensional environmental regulation. The last chapter is about the conclusion and suggestion, emphasizes the importance of multi-dimension environmental regulation to the green transformation of manufacturing enterprises, and puts forward the corresponding suggestion according to the conclusion of the paper.

2. Model Construction

2.1. Model assumptions and parameter settings

This paper is based on carbon emissions trading, environmental protection tax, and green consumption subsidies under the multidimensional environment regulation game between the government, manufacturing enterprises, and consumers, combined with the evolutionary game theory, involving the evolution of manufacturing enterprise green transformation strategy game model, the basic assumptions are as follows (see table 1):

H1: Without considering other constraints, the government, consumers and manufacturing enterprises form a complete information asymmetry system. The probability of governments adopting an environmental regulation strategy is $x(0 \le x \le 1)$, and the probability of adopting a deregulation strategy is $1-x$. Similarly, the probability of consumers adopting a green consumption strategy is $y(0 \le y \le 1)$, and the probability of choosing a not green consumption strategy is $1-y$. Finally, the probability of manufacturing enterprises adopting a green transformation strategy is $z(0 \le z \le 1)$, and the probability of adopting a traditional production method strategy is $1-z$.

H2: As the maker of environmental regulation, the government can choose multi-dimensional environmental regulation, single environmental regulation, or not implement an environmental regulation strategy. When the government chooses multi-dimensional environmental regulation: (1) under the carbon emission right trading system, the government issues the initial carbon emission quota to manufacturing enterprises Q; (2) under the environmental protection tax system, the government will impose a lower environmental protection tax on the enterprises undergoing green transformation, which is T1; with a higher environmental protection tax, the tax is T2; (3) under the green consumption subsidy system, the government will give green consumption subsidy to consumers D to encourage consumers to buy green products with a relatively high price. Besides, according to the research conclusions of Wang et al. (2022), we assume that the cost of government supervision of environmental regulation is Cg, including the cost related to carbon emission testing and the collection cost of environmental protection tax. The government will pay green technology innovation cost compensation G for enterprises undergoing green transformation. In addition, drawing on the research of Wang et al. (2021), we assume that under the environmental regulation of the government, enterprises choose green transformation to reduce pollution emissions, which will produce environmental effect B. When the government only adopts a single environmental regulation such as carbon emission right trading, environmental protection tax and green consumption subsidy, the government will only issue the initial carbon emission quota, levy environmental protection tax or give green consumption subsidies to consumers accordingly. When the government does not adopt any environmental regulation, the government will no longer issue carbon emission quotas and impose environmental protection taxes on enterprises, and will no longer give consumers green consumption subsidies.

H3: Manufacturing enterprises can choose two strategies: green transformation and maintaining the traditional production method. This paper assumes that enterprises will produce green products if they carry out the green transformation strategy, while ordinary products will be produced if they maintain traditional production methods. When manufacturing enterprises choose the green transformation strategy, their carbon emissions are E1 ($E1<Q$), and enterprises can sell excess carbon emission rights in the carbon market to obtain additional benefits A. As long as enterprises choose the green transformation strategy, they will be compensated for the cost of green technology innovation G by the government, and the innovation cost that needs to be paid is C. When manufacturing

enterprises choose to maintain the traditional production method, their carbon emission is E2 (E2>Q), so they need to buy the carbon emission right of (E2-Q) units in the market, and the additional expenditure is F (Chen et al., 2021).

H4: Consumers choose manufacturing products from green products and ordinary products. Assuming that all consumers can get value v from the products purchased, the consumer acceptance of green products is α, and the acceptance of ordinary products is 1-α. The perceived loss of consumers who prefer to buy ordinary products and turn over to green products is L1, while the perceived loss of consumers who prefer to buy green products and turn over to ordinary products is L2 (Li et al., 2021). When consumers with green product preferences buy green products, they will gain psychological benefits from participating in the green transformation of enterprises ηe. η(0≤η≤1) represents the sensitivity of consumers to green products, and e represents the upper limit of psychological benefits for consumers to participate in the green transformation of enterprises (Ji et al., 2017). Make p0 and p1 represent the price of green products and ordinary products, respectively (p0> p1). The calculation formula of utility U0 of green products and utility U1 of ordinary products are as follows:

$$U_0 = v + \eta e + D - p_0 \tag{1}$$

$$U_1 = v - p_1 \tag{2}$$

In addition, the utility of consumers with ordinary product preference for purchasing green products is $U_2 = \alpha(v + D - p_0 - L_1)$; that of consumers with green product preference is $U_3 = (1-\alpha)(v - p_1 - L_2)$. Of which U0, U1, U2 and U3 are greater than 0.

Table 1. Model parameters and their interpretations.

parameters	Meaning description
E_1	Carbon emissions of manufacturing enterprises choosing green transformation strategies
E_2	Manufacturing companies choose to maintain carbon emissions from traditional production
Q	Initial carbon emission allowances issued by the government to manufacturing companies
A	Additional gains for manufacturing businesses
F	Additional spending by manufacturing firms
C	The cost of innovation paid by manufacturing companies when they choose a green transformation strategy
B	The environmental benefits of the green transformation strategy chosen by manufacturing enterprises
G	Compensation for the cost of green technology innovation obtained by manufacturing companies from the government
T_1	An environmental protection tax imposed by the government on manufacturing companies that make a green transition
T_2	An environmental protection tax imposed by the government on manufacturing companies that maintain traditional production
L_1	Perceived loss of green product purchases by consumers with generic product preferences
L_2	Perceived loss of consumers with green product preferences to purchase ordinary products
C_g	The supervision cost of government environmental regulation
D	Green consumption subsidies given by the government to consumers
U_0	Utility that consumers get from buying green products
U_1	The utility that consumers get from buying common products
v	The value the consumer gets from the product
α	Consumer acceptance of green products
e	The upper limit of the psychological benefits of consumers participating in the green transformation of enterprises
η	Consumer sensitivity to green products
p_0	Green product price
p_1	Prices of common products

2.2. Construction of mixed strategy game matrix

Based on the above model assumptions and parameter setting, the mixed strategy game matrix between the government, manufacturing enterprises and consumers is established, as shown in Table 2 to Table 6.

Table 2. Mixed strategy game Matrix (x) of various participants under multi-dimensional environmental regulation adopted by the government.

Behavior		Government	Consumers	Businesses
Green Transition(z)	Green consumption(y)	T_1+B-G-D-C_g	v-p_0+η_e+D	p_0+G+A-T_1-C
	Not green consumption(1-y)	T_1+B-G-D-C_g	α(v-p_0+D-L_1)	α(p_0+G+A-T_1-C)
Traditional production method (1-z)	Green consumption(y)	T_2-C_g	(1-α)(v-p_1-L_2)	(1-α)(p_1-T_2-F)
	Not green consumption(1-y)	T_2-C_g	v-p_1	p_1-T_2-F

Table 3. Game Matrix of mixed strategies of participants under the single environmental regulation of carbon emission trading adopted by the government (x).

Behavior		Government	Consumers	Businesses
Green Transition(z)	Green consumption(y)	B-G-C_g	v-p_0+η_e	p_0+G+A-C
	Not green consumption(1-y)	B-G-C_g	α(v-p_0-L_1)	α(p_0+G+A-C)
Traditional production method (1-z)	Green consumption(y)	-C_g	(1-α)(v-p_1-L_2)	(1-α)(p_1-F)
	Not green consumption(1-y)	-C_g	v-p_1	p_1-F

Table 4. Game Matrix of mixed strategies of participants under single environmental regulation adopted by the government (x).

Behavior		Government	Consumers	Businesses
Green Transition(z)	Green consumption(y)	T_1+B-G-C_g	v-p_0+η_e	p_0+G-T_1-C
	Not green consumption(1-y)	T_1+B-G-C_g	α(v-p_0-L_1)	α(p_0+G-T_1-C)
Traditional production method (1-z)	Green consumption(y)	T_2-C_g	(1-α)(v-p_1-L_2)	(1-α)(p_1-T_2)
	Not green consumption(1-y)	T_2-C_g	v-p_1	p_1-T_2

Table 5. Game Matrix of mixed strategies of participants under single environmental regulation of green consumption tax adopted by the government (x).

Behavior		Government	Consumers	Businesses
Green Transition(z)	Green consumption(y)	B-G-D-C_g	v-p_0+η_e+D	p_0+G-C
	Not green consumption(1-y)	B-G-D-C_g	α(v+D-p_0-L_1)	α(p_0+G-C)
Traditional production method (1-z)	Green consumption(y)	-C_g	(1-α)(v-p_1-L_2)	(1-α)p_1
	Not green consumption(1-y)	-C_g	v-p_1	p_1

Table 6. Game Matrix of mixed strategies of participants without environmental regulation by the government (1-x).

Behavior		Government	Consumers	Businesses
Green Transition(z)	Green consumption(y)	B-G	v-p_0+η_e	p_0-C+G
	Not green consumption(1-y)	B-G	α(v-p_0-L_1)	α(p_0+G-C)
Traditional production method (1-z)	Green consumption(y)	0	(1-α)(v-p_1-L_2)	(1-α)p_1
	Not green consumption(1-y)	0	v-p_1	p_1

3. Evolutionary game stability strategy analysis

3.1. Stable evolution strategy under multi-dimensional environment regulation

3.1.1. Government expected income and stability analysis

When the government implements multi-dimensional environmental regulation, the expected revenue N_{e1} is:

$$N_{e1} = z\left[y\left(T_1 + B - G - D - C_g\right) + (1-y)\left(T_1 + B - G - D - C_g\right)\right] + (1-z)\left[y\left(T_2 - C_g\right) + (1-y)\left(T_2 - C_g\right)\right]$$
$$= z(T_1 + B - T_2 - D - G) + T_2 - C_g \quad (3)$$

When the government does not implement environmental regulation, the expected revenue N_{e0} is:

$$N_{e0} = z[y(B-G) + (1-y)(B-G)] = z(B-G) \quad (4)$$

The average expected revenue N_d of the government is:

$$N_d = xN_{e1} + (1-x)N_{e0} = z(B-G) + xz(T_1 - T_2 - D) + x\left(T_2 - C_g\right) \quad (5)$$

Then the replication dynamic equation of the government's multi-dimensional environmental regulation is as follows:

$$F_{d(x)} = \frac{dx}{dt} = x(N_{e1} - N_d) = x(1-x)\left[Z(T_1 - T_2 - D) + T_2 - C_g\right] \quad (6)$$

3.1.2. Consumer expected income and stability analysis

Under multi-dimensional environmental regulation, when consumers choose "green consumption" and "no green consumption", the expected income is N_{c1} and N_{c2} respectively, and the average expected return is N_{cd}.

$$N_{c1} = z(\mathrm{v} - \mathrm{p}_0 + \eta e) + xzD + (1-z)(1-\alpha)(\mathrm{v} - \mathrm{p}_1 - L_2) \quad (7)$$

$$N_{c2} = z\alpha(v - p_0 - L_1) + xz\alpha D + (1-z)(v - p_1) \quad (8)$$

$$N_{cd} = yN_{c1} + (1-y)N_{c2} \quad (9)$$

Under the multi-dimensional environmental regulation, the replication dynamic equation of consumers choosing "green consumption" is as follows:

$$F_{c1(y)} = \frac{dy}{dt} = y(N_{c1} - N_{cd})$$
$$= y(1-y)\{xz(1-\alpha)D + z[(\mathrm{v} - \mathrm{p}_0 + \eta e) - \alpha(\mathrm{v} - p_0 - L_1)] + (1-z)[(1-\alpha)(\mathrm{v} - \mathrm{p}_1 - L_2) - (\mathrm{v} - p_1)]\} \quad (10)$$

3.1.3. Expected income and stability analysis of manufacturing enterprises

Under multi-dimensional environmental regulation, the expected returns of manufacturing enterprises when they choose "green transformation" and "traditional production mode" are N_{m1} and N_{m2} respectively, and the average expected returns are N_{md}.

$$N_{\mathrm{m1}} = \alpha(p_0 + G - C) + y(1-\alpha)(p_0 + G - C) + x\alpha(A - T_1) + xy(1-\alpha)(A - T_1) \quad (11)$$

$$N_{m2} = -x(T_2 + F) - \alpha y p_1 + \alpha xy(T_2 + F) + p_1 \quad (12)$$

$$N_{md} = zN_{m1} + (1-z)N_{m2} \quad (13)$$

Then, under multi-dimensional environmental regulation, the replication dynamic equation of manufacturing enterprises choosing "green transformation" is as follows:

$$F_{\mathrm{m1}(z)} = \frac{\mathrm{dz}}{\mathrm{dt}} = \mathrm{z}(N_{\mathrm{m1}} - \mathrm{N}_{\mathrm{md}})$$
$$= \mathrm{z}\,(1 - \mathrm{z})\{x[\alpha(\mathrm{A} - \mathrm{T}_1) + T_2 + F] + y[(1-\alpha)(p_0 + G - C) + \alpha p_1] + \mathrm{xy}[(1-\alpha)(\mathrm{A} - \mathrm{T}_1) - \alpha(T_2 + F)] + \alpha(p_0 + G - C) - p_1\} \quad (14)$$

3.2. Stable evolution strategy under single environmental regulation

Based on the above analysis, the replicated dynamic equation of the game between the government, consumers and manufacturing enterprises can be obtained respectively when the government only implements single environmental regulations such as environmental protection tax, carbon emission trading and green consumption subsidies.

When the government implements single environmental regulation of environmental protection tax, the replication dynamic equation is as follows:

$$F_{t(x)} = x(1-x)\left[z(T_1 - T_2) + \left(T_2 - C_g\right)\right] \quad (15)$$

$$F_{c2(y)} = y(1-y)\{z[(\mathrm{v}-\mathrm{p}_0+\eta e)-\alpha(\mathrm{v}-p_0-L_1)]+(1-z)[(1-\alpha)(\mathrm{v}-\mathrm{p}_1-L_2)-(\mathrm{v}-p_1)]\} \quad (16)$$

$$F_{m2(z)}=\mathrm{z}\ (1\text{ - z})\{x[\alpha(-\mathrm{T}_1)+T_2]\ +y[(1-\alpha)(p_0+G-C)+\alpha p_1]+\mathrm{xy}[(1-\alpha)T_1-\alpha T_2]+\alpha(p_0+G-C)-p_1\} \quad (17)$$

When the government implements a single environmental regulation of carbon emission trading, the dynamic equation is:

$$F_{cm(x)} = \mathrm{x}\ (1\text{ - x})(-\mathrm{C}_g) \quad (18)$$

$$F_{c3(y)} = y(1-y)\{z[(\mathrm{v}-\mathrm{p}_0+\eta e)-\alpha(\mathrm{v}-p_0-L_1)]+(1-z)[(1-\alpha)(\mathrm{v}-\mathrm{p}_1-L_2)-(\mathrm{v}-p_1)]\} \quad (19)$$

$$F_{m3(z)}=\mathrm{z}\ (1\ -\mathrm{z})\{x(\alpha A+F)\ +y[(1-\alpha)(p_0+G-C)+\alpha p_1]+\mathrm{xy}[(1-\alpha)A-\alpha F]+\alpha(p_0+G-C)-p_1\} \quad (20)$$

When the government implements the single environmental regulation of green consumption subsidies, the dynamic equation of replication is:

$$F_{s(x)} = x(1-x)(-C_g-zD) \quad (21)$$

$$F_{c4(y)} = y(1-y)\{xz(1-\alpha)D+z[(\mathrm{v}-\mathrm{p}_0+\eta e)-\alpha(\mathrm{v}-p_0-L_1)]+(1-z)[(1-\alpha)(\mathrm{v}-\mathrm{p}_1-L_2)-(\mathrm{v}-p_1)]\} \quad (22)$$

$$F_{m4(z)}=\mathrm{z}\ (1\ -\mathrm{z})\{y[(1-\alpha)(p_0+G-C)+\alpha p_1]+\alpha(p_0+G-C)-p_1\} \quad (23)$$

4. Asymptotic stability analysis of equilibrium point

4.1. Analysis of the asymptotic stability of equilibrium points under the multi-dimensional environment regulation

Let $F_d(x)=F_{c1}(y)=F_{m1}(z)=0$, eight local equilibrium points can be obtained, namely: $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$ and $E_8(1,1,1)$.

In a replicated dynamic system of a tripartite evolutionary game, the strategy combinations are all pure strategy Nash equilibria, which are stable states only in this case. The Jacobian matrix for tripartite evolutionary games is shown below.

$$J=\begin{bmatrix} (1-2x)\ B_1 & 0 & x(1-x)(T_1-T_2-D) \\ y(1-y)z(1-\alpha)D & (1-2y)\ B_2 & y(1-y)B_3 \\ z(1-z)B_4 & z(1-z)B_5 & (1-2z)\ B_6 \end{bmatrix}$$

Where:

$$B_1 = z(T_1-T_2-D)+(T_2-C_g) \quad (24)$$

$$B_2 = xz(1-\alpha)D+z[(\mathrm{v}-\mathrm{p}_0+\eta e)-\alpha(\mathrm{v}-p_0-L_1)]+(1-z)[(1-\alpha)(\mathrm{v}-\mathrm{p}_1-L_2)-(\mathrm{v}-p_1)] \quad (25)$$

$$\begin{aligned} B_3 &= x(1-\alpha)D\ +(\mathrm{v}-\mathrm{p}_0+\eta e)-\alpha(\mathrm{v}-p_0-L_1)-(1-\alpha)(\mathrm{v}-\mathrm{p}_1-L_2)+(\mathrm{v}-p_1) \\ &= x(1-\alpha)D\ +\mathrm{v}-\mathrm{p}_0+\eta e+L_2+\alpha(L_1+p_0-L_2-p_1) \end{aligned} \quad (26)$$

$$B_4 = \alpha(\mathrm{A}-\mathrm{T}_1)+T_2+F+y[(1-\alpha)(\mathrm{A}-\mathrm{T}_1)-\alpha(T_2+F)] \quad (27)$$

$$B_5 = (1-\alpha)(p_0+G-C)+\alpha p_1+x[(1-\alpha)(\mathrm{A}-\mathrm{T}_1)-\alpha(T_2+F)] \quad (28)$$

$$B_6 = x[\alpha(\mathrm{A}-\mathrm{T}_1)+T_2+F]\ +y[(1-\alpha)(p_0+G-C)+\alpha p_1]+\mathrm{xy}[(1-\alpha)(\mathrm{A}-\mathrm{T}_1)-\alpha(T_2+F)]+\alpha(p_0+G-C)-p_1 \quad (29)$$

Therefore, the Jacobian of the three-way evolution game at the equilibrium point E1(0,0,0) is:

$$J_1=\begin{bmatrix} T_2-C_g & 0 & 0 \\ 0 & -[\alpha(\mathrm{v}-\mathrm{p}_1-L_2)+L_2] & 0 \\ 0 & 0 & \alpha(p_0+G-\mathrm{C})-p_1 \end{bmatrix}$$

According to Lyapunov's first law, the equilibrium point is asymptotically stable if all eigenvalues of the Jacobian matrix have negative real parts, and is unstable if the Jacobian matrix has at least one eigenvalue with positive real parts (Wang, 2022).

The eigenvalues of the matrix J1 are given as follows: $\lambda_1 = \mathrm{T}_2-\mathrm{C}_g, \lambda_2 = -[\alpha(\mathrm{v}\text{-}\mathrm{p}_1-\mathrm{L}_2)+\mathrm{L}_2]$ and $\lambda_3 = \alpha(\mathrm{p}_0+\mathrm{G}-\mathrm{C})-\mathrm{p}_1$. Because $\alpha(\mathrm{v}\text{-}\mathrm{p}_1-\mathrm{L}_2)+\mathrm{L}_2 > 0$, then $\lambda_2 < 0$.When consumers do not carry out the green consumption strategy and manufacturing enterprises do not carry out the green transformation strategy, the government's environmental regulation cost is higher than the environmental protection tax revenue, namely $T_2 < C_g$; When the government does not carry out environmental regulation and consumers choose not to carry out the green consumption strategy, the benefits of enterprises not carrying out the green transformation strategy are greater than the net benefits of enterprises maintaining traditional production methods. Immediately, $\alpha(p_0 + G - C) < p_1$, E_1 has asymptotic stability, otherwise it is an unstable equilibrium point.

The Jacobian matrix J2 at the equilibrium point $E_2(1,0,0)$ is:

$$J_2 = \begin{bmatrix} -(T_2 - C_g) & 0 & 0 \\ 0 & -[\alpha(\mathrm{v} - \mathrm{p}_1 - L_2) + L_2] & 0 \\ 0 & 0 & \alpha(p_0 + G + \mathrm{A} - \mathrm{C} - \mathrm{T}_1) + T_2 + F - p_1 \end{bmatrix}$$

The eigenvalues of the matrix J_2 are given as follows: $\lambda_1 = -(T_2 - C_g)$,$\lambda_2 = -[\alpha(\text{v-}p_1 - L_2) + L_2]$ and $\lambda_3 = \alpha(p_0 + G + A - C - T_1) + T_2 + F - p_1$. Because $\alpha(\text{v-}p_1 - L_2) + L_2 > 0$, then $\lambda_2 < 0$. In the case that consumers do not carry out the green consumption strategy and manufacturing enterprises do not carry out the green transformation strategy, the government's tax revenue is greater than the cost of environmental regulation, namely $T_2 > C_g$; In the scenario where the government chooses to carry out environmental regulation while consumers prefer ordinary products, the net income of manufacturing enterprises not to carry out green transformation is greater than the net income of carrying out green transformation. Immediately $\alpha(p_0 + G + A - C - T_1) < p_1 - F - T_2$, E_2 has asymptotic stability, otherwise it is an unstable equilibrium point.

The Jacobian matrix J_3 at the equilibrium point $E_3(0,1,0)$ is:

$$J_3 = \begin{bmatrix} T_2 - C_g & 0 & 0 \\ 0 & -[-\alpha(\mathrm{v} - \mathrm{p}_1 - L_2) - L_2] & 0 \\ 0 & 0 & p_0 + G - C - (1 - \alpha)p_1 \end{bmatrix}$$

The eigenvalues of the matrix J3 are given as follows: $\lambda_1 = T_2 - C_g$, $\lambda_2 = -[-\alpha(\text{v-}p_1 - L_2) - L_2] = \alpha(\text{v-}p_1 - L_2) + L_2$ and $\lambda_3 = p_0 + G - C - (1 - \alpha)p_1$. Because $\alpha(\text{v-}p_1 - L_2) + L_2 > 0$, then $\lambda_2 > 0$. Therefore, the equilibrium point is not asymptotically stable.

The Jacobian matrix J_4 at the equilibrium point $E_4(0,0,1)$ is:

$$J_4 = \begin{bmatrix} T_1 - D - C_g & 0 & 0 \\ 0 & (\mathrm{v} - \mathrm{p}_0 + \eta e) - \alpha(\mathrm{v} - p_0 - L_1) & 0 \\ 0 & 0 & -[\alpha(p_0 + G - C) - p_1] \end{bmatrix}$$

The eigenvalues of the matrix J4 are given as follows: $\lambda_1 = T_1 - D - C_g$,$\lambda_2 = (\text{v-}p_0 + \eta e) - \alpha(\text{v-}p_0 - L_1)$ and $\lambda_3 = -[\alpha(p_0 + G - C) - p_1]$. Because $(\text{v-}p_0 + \eta e) - \alpha(\text{v-}p_0 - L_1) > 0$, then $\lambda_2 > 0$. Therefore, the equilibrium point is not asymptotically stable.

The Jacobian matrix J_5 at the equilibrium point $E_5(1,1,0)$ is:

$$J_5 = \begin{bmatrix} -(T_2 - C_g) & 0 & 0 \\ 0 & \alpha(\mathrm{v} - \mathrm{p}_1 - L_2) + L_2 & 0 \\ 0 & 0 & A + p_0 + G - C - T_1 + (1 - \alpha)(T_2 + F - p_1) \end{bmatrix}$$

The eigenvalues of the matrix J5 are given as follows:$\lambda_1 = -(T_2 - C_g)$,$\lambda_2 = \alpha(\text{v-}p_1 - L_2) + L_2$ and $\lambda_3 = A + p_0 + G - C - T_1 + (1 - \alpha)(T_2 + F - p_1)$. Because $\alpha(\text{v-}p_1 - L_2) + L_2 > 0$, then $\lambda_2 > 0$. Therefore, the equilibrium point is not asymptotically stable.

The Jacobian matrix J_6 at the equilibrium point $E_6(1,0,1)$ is:

$$J_6 = \begin{bmatrix} -(T_1 - D - C_g) & 0 & 0 \\ 0 & D + \mathrm{v} - \mathrm{p}_0 + \eta e - \alpha(\mathrm{v} + D - p_0 - L_1) & 0 \\ 0 & 0 & -[T_2 + \mathrm{F}\ \text{-}p_1 + \alpha(p_0 + A + G - T_1 - C)] \end{bmatrix}$$

The eigenvalues of the matrix J6 are given as follows:$\lambda_1 = -(T_1 - D - C_g)$,$\lambda_2 = D + v - p_0 + \eta e - \alpha(\text{v+D-}$

$p_0 - L_1)$ and $\lambda_3 = -[T_2 + F - p_1 + \alpha(p_0 + A + G - T_1 - C)]$. Because $D + v - p_0 + \eta e - \alpha(v+D-p_0 - L_1) > 0$, then $\lambda_2 > 0$. Therefore, the equilibrium point is not asymptotically stable.

The Jacobian matrix J_7 at the equilibrium point $E_7(0,1,1)$ is:

$$J_7 = \begin{bmatrix} T_1 - C_g - D & 0 & 0 \\ 0 & -[(v - p_0 + \eta e) - \alpha(v - p_0 - L_1)] & 0 \\ 0 & 0 & -[(p_0 + G - C) - (1-\alpha)p_1] \end{bmatrix}$$

The eigenvalues of the matrix J7 are given as follows: $\lambda_1 = T_1 - C_g - D, \lambda_2 = -[(v\text{-}p_0 + \eta e) - \alpha(v\text{-}p_0 - L_1)]$ and $\lambda_3 = -[(p_0 + G - C) - (1-\alpha)p_1]$. Because $(v\text{-}p_0 + \eta e) - \alpha(v\text{-}p_0 - L_1) > 0$, then $\lambda_2 < 0$. When consumers choose green consumption and manufacturing enterprises choose green technological innovation, the sum of the government's expenditure and cost for environmental regulation is higher than the environmental protection tax collected from manufacturing enterprises, i.e. $T_1 < C_g + D$; In the case of no environmental regulation by the government and green consumption by consumers, the net income from the sale of green products by manufacturing enterprises is greater than the net income from the sale of ordinary products, even if $p_0 + G - C > (1-\alpha)p_1$, E_7 is stable, otherwise, it is an unstable equilibrium point.

The Jacobian matrix J_8 at the equilibrium point $E_8(1,1,1)$ is:

$$J_8 = \begin{bmatrix} -(T_1 - C_g - D) & 0 & 0 \\ 0 & -[v + D + \eta e - p_0 - \alpha(v + D - p_0 - L_1)] & 0 \\ 0 & 0 & -[A + p_0 + G - C - T_1 - (1-\alpha)(p_1 - F - T_2)] \end{bmatrix}$$

The eigenvalues of the matrix J7 are given as follows: $\lambda_1 = -(T_1 - C_g - D), \lambda_2 = -[D + v + \eta e - p_0 - \alpha(v+D\text{-}p_0 - L_1)]$ and $\lambda_3 = -[A + p_0 + G - C - T_1 - (1-\alpha)(p_1 - F - T_2)]$. Because $D + v - p_0 + \eta e - \alpha(v+D\text{-}p_0 - L_1) > 0$, then $\lambda_2 < 0$. In the case that consumers prefer green products and manufacturing enterprises to carry out green transformation, the government's tax revenue is higher than the sum of subsidies and regulation costs, i.e. $T_1 > C_g + D$; When the government chooses environmental regulation and consumers choose green consumption, the net income of manufacturing enterprises in green transformation is higher than the net income of traditional production. Immediately, $A + p_0 + G - C - T_1 > (1-\alpha)(p_1 - F - T_2)$. E_8 is stable, otherwise, it is an unstable equilibrium point.

Corollary 1: When $T_2<C_g$, $\alpha(p_0+G\text{-}C)<P_1$, $E_1(0,0,0)$ is the stable point of an evolutionary game system. This indicates that: when the government imposes a low environmental protection tax on enterprises that maintain traditional production mode, consumers' acceptance of green products is low, and enterprises' cost of green technology innovation is too high, the stable point of the strategy mix will be close to (no environmental regulation, no green consumption, traditional production). When $T_1<D+C_g$, $p_0+G\text{-}C>(1\text{-}\alpha)p$, $E_7(0,1,1)$ is the stable point of the ev1ol7utionary game system. This indicates that: when the government imposes a lower environmental protection tax on enterprises undergoing green transformation, the benefits of enterprises' green technology innovation are higher than the costs, and consumers' acceptance of green products is high, the evolutionary stability strategy tends to be (no environmental regulation, green consumption, green production). From the perspective of government environmental regulation, when the government adopts loose environmental regulation, as long as the cost of enterprise green technology innovation is low enough and consumers' acceptance of green products is high enough, enterprises will choose the green transformation strategy and reach a stable state.

Corollary 2: When $T_2>C_g$, $\alpha(p_0+G+A\text{-}C\text{-}T_1)<p_1\text{-}F\text{-}T_2$, $E_2(1,0,0)$ is the stable point of the evolutionary game system. This indicates that: when the government imposes higher environmental protection tax on enterprises that maintain traditional production mode, the cost of green technology innovation is too high for enterprises, and the acceptance of green products by consumers is low, the strategic stability point tends to be (environmental regulation, non-green consumption, traditional production). When $T_1>D+C_g$, $p_0+G+A\text{-}C\text{-}T_1>(1\text{-}\alpha)(p_1\text{-}F\text{-}T_2)$, E8 (1,1,1) is the stable equilibrium point of the evolutionary game system. This shows that: when the government imposes a higher environmental protection tax on enterprises, the cost of green technology innovation is lower for enterprises, and the enterprises obtain higher income through carbon emission trading, and the consumers have a high acceptance of green products, the strategic stability point tends to be (environmental regulation, green consumption, green production). From the perspective of government environmental regulation, when the government adopts strict environmental regulation and imposes a high environmental protection tax, it needs to use carbon emission trading platforms to help enterprises obtain high enough profits from green technology innovation and improve consumers' acceptance of green products through green consumption subsidies. Enterprises will choose a green transformation strategy and reach a stable state. In other words, only by adopting multi-dimensional environmental regulation can enterprises effectively promote green transformation.

Table 7. Analysis of evolutionary stability of equilibrium point under multi-dimensional environmental regulation.

Equilibrium point	Eigenvalues	Eigenvalue symbol	Stability determination and condition
$E_1(0,0,0)$	$\lambda_1=T_2-C_g$ $\lambda_2=-[\alpha(v-p_1-L_2)+L_2]$ $\lambda_3=\alpha(p_0+G-C)-p_1$	(×,-,×)	$T_2<C_g$; $\alpha(p_0+G-C)<p_1$
$E_2(1,0,0)$	$\lambda_1=-(T_2-C_g)$ $\lambda_2=-[\alpha(v-p_1-L_2)+L_2]$ $\lambda_3=\alpha(p_0+G+A-C-T_1)+T_2+F-p_1$	(×,-,×)	$T_2>C_g$; $\alpha(p_0+G+A-C-T_1)<p_1-F-T_2$
$E_3(0,1,0)$	$\lambda_1=T_2-C_g$ $\lambda_2=-[-\alpha(v-p_1-L_2)-L_2]$ $\lambda_3=p_0+G-C-(1-\alpha)p_1$	(×,+,×)	Non-asymptotically stable point
$E_4(0,0,1)$	$\lambda_1=T_1-D-C_g$ $\lambda_2=v-p_0+\eta_e-\alpha(v-p_0-L_1)$ $\lambda_3=-[\alpha(p_0+G-C)-p_1]$	(×,+,×)	Non-asymptotically stable point
$E_5(1,1,0)$	$\lambda_1=-(T_2-C_g)$ $\lambda_2=\alpha(v-p_1-L_2)+L_2$ $\lambda_3=p_0+G+A-C-T_1+(1-\alpha)(T_2+F-p_1)$	(×,+,×)	Non-asymptotically stable point
$E_6(1,0,1)$	$\lambda_1=-(T_1-D-C_g)$ $\lambda_2=v-p_0+\eta_e+D-\alpha(v+D-p_0-L_1)$ $\lambda_3=-[\alpha(p_0+A+G-T_1-C)+T_2+F-p_1]$	(×,+,×)	Non-asymptotically stable point
$E_7(0,1,1)$	$\lambda_1=T_1-D-C_g$ $\lambda_2=-[v-p_0+\eta_e-\alpha(v-p_0-L_1)]$ $\lambda_3=-[p_0+G-C-(1-\alpha)p_1]$	(×,-,×)	$T_1<D+C_g$; $p_0+G-C>(1-\alpha)p_1$
$E_8(1,1,1)$	$\lambda_1=-(T_1-D-C_g)$ $\lambda_2=-[v+D-p_0+\eta e-\alpha(v+D-p_0-L_1)]$ $\lambda_3=-[(p_0+G+A-C-T_1)-(1-\alpha)(p_1-F-T_2)]$	(×,-,×)	$T_1>D+C_g$; $p_0+G+A-C-T_1>(1-\alpha)(p_1-F-T_2)$

4.2. Analysis of asymptotic stability of equilibrium point under single environmental regulation of environmental protection tax

As in 3.1, let $F_t(x)=F_{c2}(y)=F_{m2}(z)=0$, eight local equilibrium points can be obtained, namely: $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$ and $E_8(1,1,1)$. The following table summarizes the evolutionary stability of the eight equilibrium points and their stability conditions.

Table 8. Analysis of the evolutionary stability of the equilibrium point under the single environmental regulation of environmental protection tax.

Equilibrium point	Eigenvalues	Eigenvalue symbol	Stability determination and condition
$E_1(0,0,0)$	$\lambda_1=T_2-C_g$ $\lambda_2=-[\alpha(v-p_1-L_2)+L_2]$ $\lambda_3=\alpha(p_0+G-C)-p_1$	(×,-,×)	$T_2<C_g$; $\alpha(p_0+G-C)<p_1$
$E_2(1,0,0)$	$\lambda_1=-(T_2-C_g)$ $\lambda_2=-[\alpha(v-p_1-L_2)+L_2]$ $\lambda_3=\alpha(p_0+G-C-T_1)+T_2-p_1$	(×,-,×)	$T_2>C_g$; $\alpha(p_0+G-C-T_1)<p_1-T_2$
$E_3(0,1,0)$	$\lambda_1=T_2-C_g$ $\lambda_2=-[-\alpha(v-p_1-L_2)-L_2]$ $\lambda_3=p_0+G-C-(1-\alpha)p_1$	(×,+,×)	Non-asymptotically stable point
$E_4(0,0,1)$	$\lambda_1=T_1-C_g$ $\lambda_2=v-p_0+\eta_e-\alpha(v-p_0-L_1)$ $\lambda_3=-[\alpha(p_0+G-C)-p_1]$	(×,+,+)	Non-asymptotically stable point
$E_5(1,1,0)$	$\lambda_1=-(T_2-C_g)$ $\lambda_2=\alpha(v-p_1-L_2)+L_2$ $\lambda_3=p_0+G-C-T_1+(1-\alpha)(T_2-p_1)$	(×,+,×)	Non-asymptotically stable point
$E_6(1,0,1)$	$\lambda_1=-(T_1-C_g)$ $\lambda_2=v-p_0+\eta_e-\alpha(v-p_0-L_1)$ $\lambda_3=-[\alpha(p_0+G-T_1-C)+T_2-p_1]$	(×,+,×)	Non-asymptotically stable point
$E_7(0,1,1)$	$\lambda_1=T_1-C_g$ $\lambda_2=-[v-p_0+\eta_e-\alpha(v-p_0-L_1)]$ $\lambda_3=-[p_0+G-C-(1-\alpha)p_1]$	(×,-,×)	$T_1<C_g$; $p_0+G-C>(1-\alpha)p_1$
$E_8(1,1,1)$	$\lambda_1=-(T_1-C_g)$ $\lambda_2=-[v-p_0+\eta_e-\alpha(v-p_0-L_1)]$ $\lambda_3=-[(p_0+G-T_1-C)-(1-\alpha)(p_1-T_2)]$	(×,-,×)	$T_1>C_g$; $p_0+G-T_1-C>(1-\alpha)(p_1-T_2)$

Corollary 3: When $T_2<C_{gand}$ $\alpha(p_0+G-C)<p1$, $E_1(0,0,0)$ is the stable point of the evolutionary game system, and when $T_1<C_g$ and $p0+G-C>(1-\alpha)p_1$, $E_7(0,1,1)$ is the stable point of the evolutionary game system; When $T_1>C_g$ and $p_0+G-T_1-C>(1-\alpha)(p_1-T_2)$, $E_8(1,1,1)$ is for the stability of evolutionary game points. This shows that when the government adopts the single environmental regulation of environmental protection tax, if the environmental protection tax levied by the government is low, the environmental protection tax can not affect the green transformation strategy of enterprises. If the government imposes a higher environmental protection tax, only when the cost of green technology innovation is low enough and consumers' acceptance of green products is high enough, enterprises will choose the green transformation strategy.

4.3. Analysis of the asymptotic stability of equilibrium point under the single environmental regulation of carbon emission trading

Similarly 3.1, let $F_{cm}(x)=F_{c3}(y)=F_{m3}(z)=0$, eight local equilibrium points can be obtained, namely: $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$ and $E_8(1,1,1)$. The following table summarizes the evolutionary stability of the eight equilibrium points and their stability conditions.

Table 9. Analysis of the evolutionary stability of equilibrium points under the single environmental regulation of carbon emission rights trading.

Equilibrium point	Eigenvalues	Eigenvalue symbol	Stability determination and condition
$E_1(0,0,0)$	$\lambda_1=-C_g$ $\lambda_2=-[\alpha(v-p_1-L_2)+L_2]$ $\lambda_3=\alpha(p_0+G-C)-p_1$	(-,-,×)	$\alpha(p_0+G-C)<p_1$
$E_2(1,0,0)$	$\lambda_1=C_g$ $\lambda_2=-[\alpha(v-p_1-L_2)+L_2]$ $\lambda_3=\alpha(p_0+G-C)-p_1$	(+,-,×)	Non-asymptotically stable point
$E_3(0,1,0)$	$\lambda_1=-C_g-D$ $\lambda_2=-[-\alpha(v-p_1-L_2)-L_2]$ $\lambda_3=p_0+G-C-(1-\alpha)p_1$	(×,+,×)	Non-asymptotically stable point
$E_4(0,0,1)$	$\lambda_1=-C_g$ $\lambda_2=v-p_0+\eta_e-\alpha(v-p_0-L_1)$ $\lambda_3=-[\alpha(p_0+G-C)-p_1]$	(-,+,+)	Non-asymptotically stable point
$E_5(1,1,0)$	$\lambda_1=C_g+D$ $\lambda_2=\alpha(v-p_1-L_2)+L_2$ $\lambda_3=p_0+G-C+(1-\alpha)(-p_1)$	(+,+,×)	Non-asymptotically stable point
$E_6(1,0,1)$	$\lambda_1=C_g$ $\lambda_2=v-p_0+\eta_e+D-\alpha(v+D-p_0-L_1)$ $\lambda_3=-[\alpha(p_0+G-C)-p_1]$	(+,+,×)	Non-asymptotically stable point
$E_7(0,1,1)$	$\lambda_1=-D-C_g$ $\lambda_2=-[v-p_0+\eta_e-\alpha(v-p_0-L_1)]$ $\lambda_3=-[p_0+G-C-(1-\alpha)p_1]$	(-,-,×)	$p_0+G-C>(1-\alpha)p_1$
$E_8(1,1,1)$	$\lambda_1=D+C_g$ $\lambda_2=-[v+D-p_0+\eta_e-\alpha(v+D-p_0-L_1)]$ $\lambda_3=-[(p_0+G-C)-(1-\alpha)p_1]$	(+,-,×)	Non-asymptotically stable point

Corollary 4: When $\alpha(p_0+G-C)<p1$, $E_1(0,0,0)$ is the stable point of the evolutionary game system; When $p_0+G-C>(1-\alpha)p_1$, $E_7(0,1,1)$ is the stable point of the evolutionary game system. This shows that: when the government only adopts the single environmental regulation of carbon emission trading, the environmental regulation has no impact on the choice of green transformation strategy of enterprises.

4.4. Asymptotic stability analysis of equilibrium point under single environmental regulation of green consumption subsidy

Similarly 3.1, let $F_s(x)=F_{c4}(y)=F_{m4}(z)=0$, eight local equilibrium points can be obtained, namely: $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$ and $E_8(1,1,1)$. The following table summarizes the evolutionary stability of the eight equilibrium points and their stability conditions.

Corollary 5: When $\alpha(p_0+G-C)<p_1$, $E_1(0,0,0)$ is the stable point of the evolutionary game system; When $p_0+G-C>(1-\alpha)p_1$, $E_7(0,1,1)$ is the stable point of the evolutionary game system. This shows that when the government only adopts the single environmental regulation of green consumption subsidy, the environmental regulation does not influence the green transformation strategy choice of enterprises.

Table 10. Analysis of the evolutionary stability of the equilibrium point under the single environmental regulation of green consumption subsidies.

Equilibrium point	Eigenvalues	Eigenvalue symbol	Stability determination and condition
$E_1(0,0,0)$	$\lambda_1=-C_g$ $\lambda_2=-[\alpha(v-p_1-L_2)+L_2]$ $\lambda_3=\alpha(p_0+G-C)-p_1$	(-,-,×)	$\alpha(p_0+G-C)<p_1$
$E_2(1,0,0)$	$\lambda_1=C_g$ $\lambda_2=-[\alpha(v-p_1-L_2)+L_2]$ $\lambda_3=\alpha(p_0+G+A-C)+F-p_1$	(+,-,×)	Non-asymptotically stable point
$E_3(0,1,0)$	$\lambda_1=T_2-C_g-D$ $\lambda_2=-[-\alpha(v-p_1-L_2)-L_2]$ $\lambda_3=p_0+G-C-(1-\alpha)p_1$	(×,+,×)	Non-asymptotically stable point
$E_4(0,0,1)$	$\lambda_1=-C_g$ $\lambda_2=v-p_0+\eta_e-\alpha(v-p_0-L_1)$ $\lambda_3=-[\alpha(p_0+G-C)-p_1]$	(-,+,+)	Non-asymptotically stable point
$E_5(1,1,0)$	$\lambda_1=C_g$ $\lambda_2=\alpha(v-p_1-L_2)+L_2$ $\lambda_3=p_0+G+A-C+(1-\alpha)(F-p_1)$	(+,+,×)	Non-asymptotically stable point
$E_6(1,0,1)$	$\lambda_1=C_g$ $\lambda_2=v-p_0+\eta_e-\alpha(v-p_0-L_1)$ $\lambda_3=-[\alpha(p_0+A+G-C)+F-p_1]$	(+,+,×)	Non-asymptotically stable point
$E_7(0,1,1)$	$\lambda_1=-C_g$ $\lambda_2=-[v-p_0+\eta_e-\alpha(v-p_0-L_1)]$ $\lambda_3=-[p_0+G-C-(1-\alpha)p_1]$	(-,-,×)	$p_0+G-C>(1-\alpha)p_1$
$E_8(1,1,1)$	$\lambda_1=C_g$ $\lambda_2=-[v-p_0+\eta_e-\alpha(v-p_0-L_1)]$ $\lambda_3=-[(p_0+A+G-C)-(1-\alpha)(p_1-F)]$	(+,-,×)	Non-asymptotically stable point

5. Simulation analysis

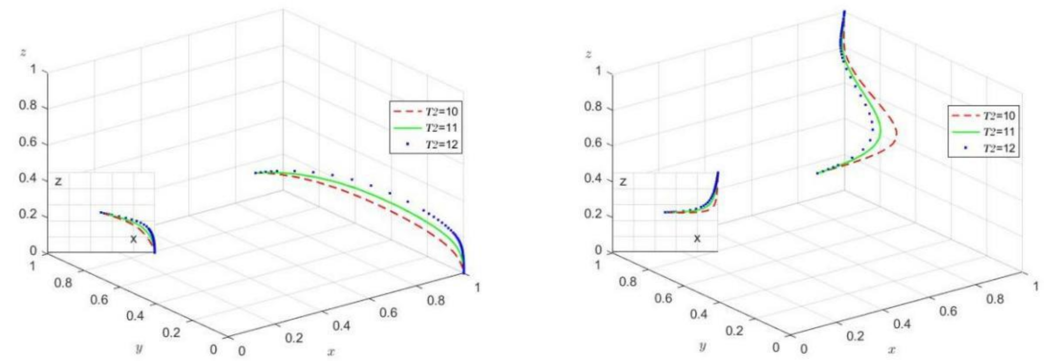
5.1. Assignment of relevant parameters

Drawing on the existing research (Bian et al., 2022; Liu and Dong, 2022), set $C:C_g:G=12:0.2:2.3$, and let $C=12$, $C_g=0.2$, $G=2.3$. to ensure the stability of the evolution results, the target variables were controlled to ensure that other variables had a small impact on the system evolution process, and the remaining relevant parameters were fitted according to the actual situation, that is, $v=100$, $e=0.8$, $\eta=0.3$. And, the simulation analysis meets the consumer utility is greater than 0, $v+\eta_e+D-p0>0$, $v-p_1>0$, $\alpha(v+D-p_0-L_1)>0$, $(1-\alpha)(v-p_1-L_1)>0$, $v+\eta_e-p_0>0$, $\alpha(v-p_0-L_1)>0$. The initial strategy possibility of the tripartite game participants is set to 0.5, that is, $x=y=z=0.5$, and numerical simulation is carried out by matlab2016b software.

5.2. Parameter sensitivity analysis

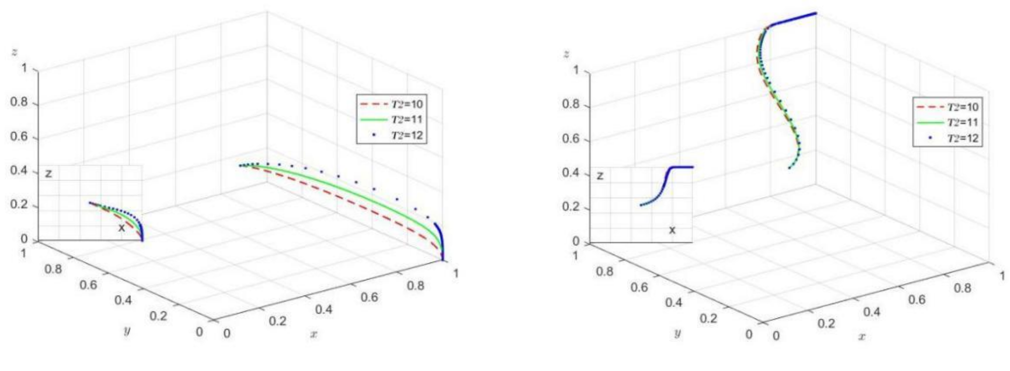
5.2.1. Sensitivity analysis of environmental protection tax

The environmental protection tax T_2 imposed by the government on manufacturing enterprises maintaining traditional production is set as 10, 11 and 12 respectively, and the sensitivity of environmental protection tax under single environmental regulation and multi-dimensional environmental regulation is explored. Taking the difference between T_2 and T_1 as the tax incentives that enterprises can enjoy for green transformation, Figure 1 (a) and Figure 2 (a) show that when the tax incentives enjoyed by enterprises for green transformation are low, no matter under the single environmental regulation of environmental protection tax or the multi-dimensional environmental regulation, with the increase of T_2, The government, consumers and enterprises respectively choose environmental regulation, non-green consumption and traditional production as the final strategies. Figure 1 (b) shows that only when environmental protection tax is adopted as a single environmental regulation, enterprises must enjoy sufficiently high tax incentives during green transformation, obtain higher compensation for green technology innovation and lower innovation cost, and at the same time, consumers have a high acceptance of green products, enterprises will choose green transformation strategy. Figure 2 (b) shows that under multi-dimensional environmental regulation, carbon emission trading can increase the profits of enterprises' green technology innovation, and green consumption subsidies can promote consumers' green consumption behavior. With the increase of T_2, the probability of consumers choosing green consumption and enterprises choosing green transformation gradually increases and approaches 1. The final stabilization strategies of the government, consumers and enterprises are environmental regulation, green consumption and green transformation, respectively.



(a) $\alpha(p_0+G-C-T_1)<p_1-T_2$ (b) $G+p_0-T_1-C>(1-\alpha)(p_1-T_2)$

Figure 1. Influence chart of the intensity of environmental protection tax collection in different degrees under single environmental regulation.

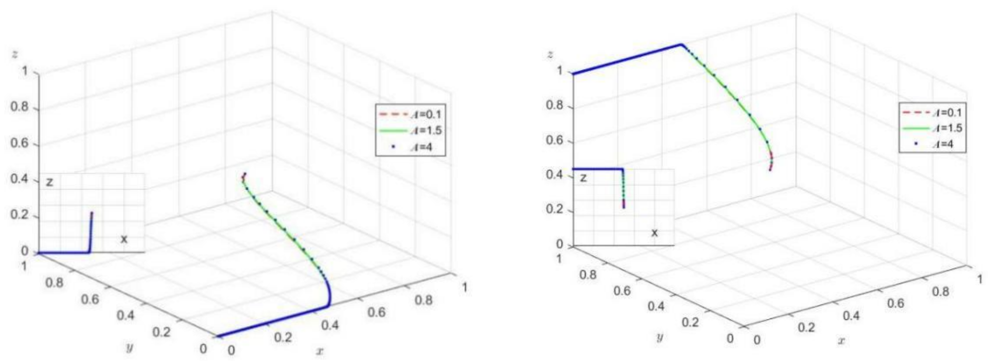


(α) $(p_0+G-C-T_1)<p_1-T_2$ (b) $G+p_0-T_1-C>(1-\alpha)(p_1-T_2)$

Figure 2. Influence of different environmental protection tax intensification under multidimensional environmental regulation.

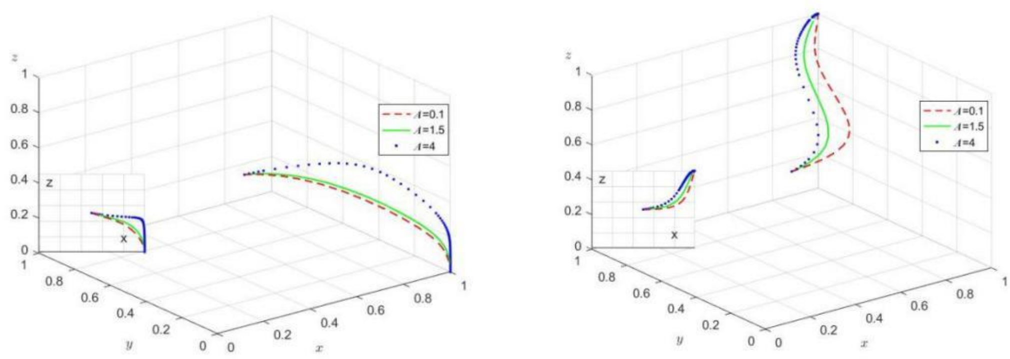
5.2.2. Sensitivity analysis of carbon emission rights trading

Set the additional income of manufacturing enterprises from the sale of excess carbon allowances as 0.1, 1.5 and 4 respectively, and explore the sensitivity of carbon emission rights trading under single environmental regulation and multi-dimensional environmental regulation. Figure 3 shows that under the single environmental regulation of carbon emission trading, with the increase of the extra income obtained from the sale of excess carbon allowances, the government's evolutionary stability strategy tends to be "no environmental regulation", and the green transformation strategy of enterprises is not affected by it. Figure 4 shows that under multi-dimensional environmental regulation, enterprises' green transformation strategy is not only affected by the additional income obtained from the sale of excess carbon allowances but also affected by environmental protection tax and consumers' acceptance of green products. Moreover, when the tax incentives that enterprises can enjoy in green transformation and the acceptance of green products by consumers are high enough, the evolution speed of corporate green transformation will accelerate with the increase of the additional revenue obtained by enterprises from selling excess carbon allowances, and the government, consumers and enterprises respectively choose environmental regulation, green consumption and green transformation as the final stable strategies, as shown in Figure 4 (b).



(a) $\alpha(p_0+G-C)<p_1$ (b) $p_0+G-C>(1-\alpha)p_1$

Figure 3. Influence of additional revenue from different carbon emission trading under single environmental regulation.

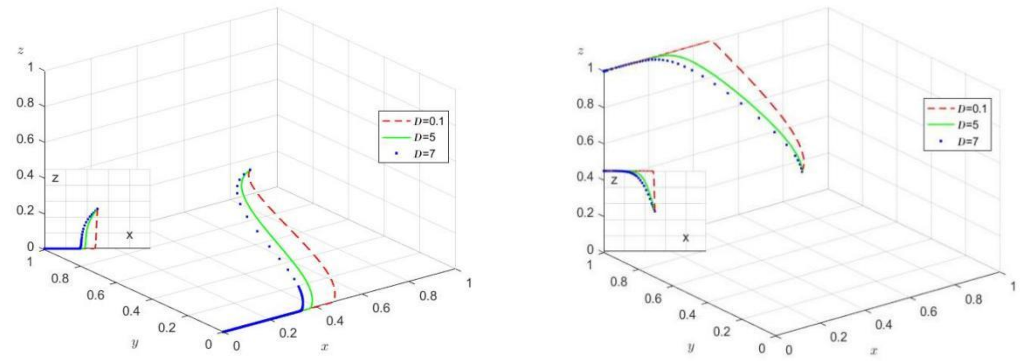


(a) $\alpha(p_0+G+A-C-T_1)<p_1-F-T_2$ (b) $p_0+G+A-C-T_1>(1-\alpha)(p_1-F-T_2)$

Figure 4. Influence of additional revenue from different carbon emission trading under multi-dimensional environmental regulations.

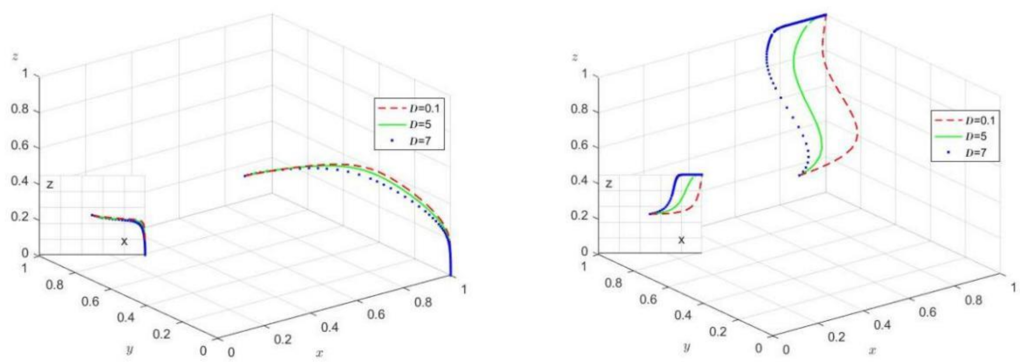
5.2.3. Sensitivity analysis of green consumption subsidies

Set the government's green consumption subsidies to consumers as 0.1, 5 and 7 respectively, and explore the sensitivity of green consumption subsidies under single environmental regulation and multi-dimensional environmental regulation. Figure 5 shows that under the single environmental regulation of green consumption subsidies, with the increase of environmental subsidies, the government's evolutionary stability strategy tends to be "non-environmental regulation", and the enterprise's green transformation strategy is not affected by it. Figure 6 shows that under multi-dimensional environmental regulation, enterprises' green transformation strategies are not only affected by green consumption subsidies but also by carbon emission rights trading and environmental protection tax. Moreover, when the additional income and tax incentives obtained by enterprises from selling excess carbon allowances are high enough, the probability of enterprises carrying out green transformation increases with the increase of consumption subsidies and the government, consumers and enterprises respectively choose environmental regulation, green consumption and green transformation as the final stable strategies, as shown in Figure 6 (b).



(a) $\alpha(p_0+G-C)<p_1$ (b) $p_0+G-C>(1-\alpha)p_1$

Figure 5. Influence of different levels of green consumption subsidies under a single environmental regulation.



(a) $\alpha(p_0+G+A-C-T_1)<p_1-F-T_2$ (b) $p_0+G+A-C-T_1>(1-\alpha)(p_1-F-T_2)$

Figure 6. Influence of different levels of green consumption subsidies under multi-dimensional environmental regulation.

According to the above numerical simulation analysis, it can be seen that when the government adopts the single environmental regulation of carbon emission rights trading or green consumption subsidies, the green transformation strategy of enterprises will not be affected. The reason may be: there is a certain heterogeneity in government environmental regulation tools, and different dimensions of environmental regulation have different impacts on enterprises' environmental behavior. The government's environmental regulation is dominated by command-and-control policies, supplemented by market-incentive policies. Different from mandatory constraints of command-and-control environmental regulation, market-incentive environmental regulation does not rely on environmental control standards issued by the government, but guides enterprises' environmental behavior through market information (Yin et al., 2023). The effective implementation of the single environmental regulation of carbon emission trading and green consumption subsidy as market-incentive policies requires the use of the market or the establishment of a new market, which has many uncertainties (Pizer, 2002). Therefore, in the case of market uncertainty, the implementation of single environmental regulation of carbon emission trading or green consumption subsidy by the government will not affect the choice of green transformation strategy of enterprises. In addition, previous studies have shown that the incentive effect of environmental regulation policy combination is often better than that of a single environmental regulation policy. Only in-depth coordination and cooperation between different types of environmental regulations within their respective regulatory scope can more effectively promote the sustainable development of enterprises (Xie et al., 2022). In addition, information asymmetry leads to the unsatisfactory effect of government environmental regulation in the process of transmitting corporate green behavior, resulting in incoordination between policy formulation and response, resulting in the phenomenon of "government failure"(Cong et al., 2023). In the case of information asymmetry between the government and enterprises, government environmental regulation policies have no impact on enterprises' green transformation behavior.

6. Conclusions and Suggestions

6.1. Research Conclusions

This paper comprehensively considers the impact of environmental protection tax, carbon emission trading and green consumption subsidy multidimensional environmental regulations on the green transformation strategies of manufacturing enterprises, constructs a tripartite evolutionary game model of government, consumers and enterprises, and draws the following conclusions: (1) The choice of green transformation strategy of manufacturing enterprises is also affected by government environmental regulation, consumer demand, enterprise green technology innovation and other aspects. When the government adopts single environmental regulation of carbon emission trading or green consumption subsidies, the green transformation strategy of enterprises will not be affected; (2) When the government adopts the single environmental regulation of environmental protection tax, enterprises will be promoted to choose the green transformation strategy only when the tax incentives are high enough, the cost of enterprise green technology innovation is low and the acceptance of green products by consumers is high; (3) Under multi-dimensional environmental regulation by the government, the government, consumers and enterprises can finally choose environmental regulation, green consumption and green transformation as a stable strategy by influencing the cost and income of enterprises' green technology innovation and consumers' green consumption behavior.

6.2. Policy Suggestions

The research conclusions of this paper have certain reference significance for the current government to promote the green transformation of manufacturing enterprises and accelerate the realization of the "dual carbon" goal. When formulating environmental regulations, the government should not only consider the number of policies but also consider the synergy between different environmental regulations, which can stimulate the enthusiasm of enterprises in green transformation from the perspective of enterprises' green technology innovation.

(1) At the government level, multi-dimensional environmental regulation can help consumers and enterprises choose green consumption and green transformation as stable strategies respectively. Since technological innovation often has externalities and high risks, the government's multi-dimensional environmental regulation has become a key starting point to promote enterprises' green technological innovation and accelerate green transformation. The synergy between multi-dimensional environmental regulations is crucial, that is, through the back-forcing effect of environmental protection tax, the incentive effect of carbon emission trading and the pulling effect of green consumption subsidies, we can jointly promote the green technology innovation of manufacturing enterprises from multiple dimensions and promote the green transformation of enterprises.

(2) At the level of manufacturing enterprises, the tax incentives of environmental protection tax, the income from the sale of excess carbon emission rights and the premium of green products are all important factors affecting the choice of enterprises' green transformation strategy. Therefore, under the multi-dimensional environmental regulation, enterprises should not only feel the rising costs brought by green transformation but also be able to predict the benefits obtained after green transformation, so as to encourage enterprises to increase investment in green technology innovation, accelerate green transformation, and better meet the needs of the green consumer market.

(3) At the consumer level, the government's green consumption subsidies and consumers' acceptance of green products will affect consumers' choice of green consumption strategy. Therefore, the government and enterprises can enhance consumers' green consumption concept and promote consumers' green consumption from different angles. On the one hand, through green consumption subsidies, the government can make up for the green premium of green products and enhance consumers' acceptance of green products from the perspective of product price; On the other hand, by encouraging enterprises to innovate in green technology, the government can improve the unique value of green products and enhance consumers' acceptance of green products from the perspective of product value.

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Conflict of interest

The authors claim that the manuscript is completely original. The authors also declare no conflict of interest.

Author contributions

Conceptualization: Jiang Haiyong, Chen Zhenyu; Funding acquisition:Jiang Haiyong; Methodology: Chen Zhenyu,Ma Chuanlong; Formal analysis: Li Sufeng; Writing – original draft: QinYan; Writing – review & editing: Li Sufeng ,Qin Yan.

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