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Research article

Navigating the personal carbon inclusion scheme: An evolutionary game theory approach to low-carbon behaviors among socio-economic groups

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ABSTRACT

In response to the challenges posed by climate change, China has launched the Personal Carbon Inclusion (PCI) scheme to encourage individuals to transition towards low-carbon lifestyles. This study investigates the behaviors of participants within the PCI scheme using a tripartite evolutionary game model, encompassing high-income and low-income individuals, as well as the PCI platform itself. The research analyzes participants' strategies, examines the evolutionary stability of different strategies, and assesses the robustness of equilibrium points within the game dynamics. Key findings reveal: (1) High-income participants tend to be less willing to adopt low-carbon behaviors compared to low-income participants. (2) The PCI platform displays limited proactive engagement in promoting low-carbon policies. (3) Factors, particularly the cost and pricing mechanisms of low-carbon actions, significantly impact the evolutionary progression of the system. Moreover, practical recommendations are provided to enhance the effectiveness of PCI schemes.

1. Introduction

Climate change, a global crisis underscored by the recording of July 2023 as the hottest month ever [1], has precipitated a cascade of challenges, from intensified extreme weather events to the proliferation of infectious diseases, posing a substantial threat to human survival and progression. The urgency of this situation has been encapsulated by UN Secretary-General Guterres, who declared, "The era of global warming has ended; the era of global boiling has arrived", emphasizing the imperative for nations to expedite efforts towards achieving net-zero emissions and fortifying responses to climate extremities [2].

The Paris Agreement, enacted in 2016, symbolizes a unified global commitment towards mitigating climate change and propelling low-carbon development [3]. However, while collective efforts like carbon trading mechanisms have been pivotal in reducing global carbon emissions [4,5], the role and impact of individual participation, particularly at the household level, have often been overshadowed [3]. For example, home heating, appliance usage, and personal transportation contribute to roughly 42 % of the UK's emissions [6], whereas in China, household carbon emissions constitute about 30 % of the country's total emissions [7]. Therefore, addressing household energy consumption emerges as a vital step towards effective climate change mitigation.

In this context, the Personal Carbon Trading (PCT) scheme has been explored as a mechanism to incentivize low-carbon lifestyles

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among individuals [8,9]. Various studies have examined its effectiveness in altering public behavior and reducing carbon emissions [10–12], factors influencing its implementation [13–17], and have analyzed its underlying mechanisms [3,7,10,18]. However, despite the potential advantages of PCT scheme, its implementation has been limited, primarily because of economic challenges faced by low-income households and concerns about the fairness of carbon emission reduction efforts [19,20].

In China, various personal low-carbon initiatives, such as the China Certified Emission Reduction (CCER), Carbon Account 4.0, and Ant Forest [7], have been instituted to augment public environmental awareness. However, their effectiveness is limited, likely due to modest incentives. For instance, the low carbon living incentive from Ant Forest, offering naming rights for a tree, may not effectively encourage widespread low carbon consumption habits [7]. The Personal Carbon Inclusion (PCI) scheme, also known as "Tan Pu Hui," represents a specific type of PCT and has seen broad adoption [21]. Deviating from traditional mandatory PCT schemes [22], the PCI scheme embodies a government-led, incentive-oriented, and voluntary initiative, assigning value to individual energy conservation and emission reduction efforts through a dedicated trading platform. The PCI scheme has received limited attention in research, particularly in terms of its application scenarios [23], system design [24,25] and policy effectiveness [26]. The research of the PCI scheme is still in its infancy, and it is unclear whether the PCI scheme can sustainably promote individuals to reduce carbon emissions. At the same time, little literature has examined the differences in the impact of the PCI scheme on the low-carbon behavioral decision-making of different socio-economic groups, and clarifying these issues is a prerequisite for advancing the PCI scheme.

To address these gaps, this study introduces a tripartite evolutionary game model, comprising three principal actors: high-income individuals, low-income individuals, and the PCI platform, within the context of the PCI scheme. Our primary objectives are to: (1) elucidate the evolutionary trajectory of low-carbon behaviors among different income groups and discern the low-carbon strategies employed by the PCI platform, and (2) explore how factors, such as the cost of individual low-carbon behaviors and the price of inclusive goods, influence the decision-making of the three key participants.

Therefore, there are three innovations in this study: (1) we delve into examining individual low carbon action within the PCI scheme, offering an exploration of the interactive dynamics among participants. (2) we establish a correlation between low-carbon behavior and various socio-economic groups, thereby discussing the disparities in low-carbon behaviors across these distinct socio-economic segments. (3) we thoroughly examine the pivotal factors influencing participants' low-carbon practices within the PCI scheme, furnishing insights valuable for policy formulation and effective implementation of the PCI scheme.

This paper is structured as follows: Section 2 reviews studies related to the PCT scheme. In Section 3, "Process Analysis," explores participants' carbon decision-making within the PCI scheme. Section 4 provides a simulated analysis. Section 5, "Discussion," covers both theoretical and policy implications. Section 6 offers the Conclusion, and Section 7 delves into limitations and provides suggestions for future research.

2. Literature review

The PCI scheme, a voluntary form of the PCT scheme, has been explored in several studies focusing on its effectiveness and operational mechanisms. For instance, Li et al. [27] delved into the motivational aspects of the PCI system, and Rui et al. [28] analyzed its impact on carbon emission reductions in both societal and household contexts. Despite the scarcity of research specifically targeting the PCI scheme, there exists a broad body of literature on the overarching PCT scheme. This paper concentrates on three critical areas of this extensive research.

2.1. Research on the effectiveness of PCT scheme

One primary aim of the PCT scheme is emission reduction. Described as a "radical approach to reducing emissions from energy use in the residential sector" [10], PCT schemes have demonstrated their effectiveness in altering public behavior. By offering tangible incentives for adopting a low-carbon lifestyle, these schemes have successfully reduced carbon emissions [11,12]. Simulations by Li et al. [29] showed that a well-calibrated PCT quota price for carbon emissions can significantly sway individuals' decisions towards adopting Battery Electric Vehicles, promoting their broader adoption. Kothe et al. [30] also noted that increased personal trading allowance prices and a higher percentage of buying households contribute to further carbon emission reductions.

In addition to emission reduction, PCT schemes can also enhance income distribution. The PCT scheme is known for its fairness, effectiveness, and efficiency [10,31], and is designed to reward low emitters at the expense of high emitters [32,33]. PCT schemes offer a potential solution to this challenge by generating additional revenue that could improve income distribution [34]. Poorer consumers are mostly "winners" within PCT scheme as their carbon emissions are generally lower [35]. Yet, it's crucial to consider the potential drawbacks of PCT schemes. For instance, UK research in the early 2000s revealed that 71 % of low-income households benefited, 55 % of high-income households were negatively affected, particularly those in rural areas [36]. Simulations by Burgess and Whitehead [6] further showed that one-third of poor families could face higher fuel costs or reduced usage, raising moral and political concerns.

When comparing PCT schemes with other low-carbon policies such as carbon tax and carbon subsidies, distinct differences emerge. Fan et al. [37] found that, despite energy price fluctuations, a PCT scheme can ensure emission reduction certainty, making it more effective than carbon taxes. This was particularly apparent in the private transportation sector, where PCT schemes was more successful than a carbon tax in encouraging households to purchase clean energy vehicles. However, the PCT scheme's emission reduction incentives might be less compelling than government subsidies [29]. Raux et al. [38] believes that there is no significant difference in the effectiveness of carbon tax and PCT, both of which can change individual travel behaviors and reduce carbon emissions of personal transportation.

2.2. Research on factors influencing the implementation of PCT scheme

Several studies highlight the factors affecting the implementation of the Personal Carbon Trading (PCT) scheme, with public attitude being the primary concern. Surveys suggest that individual acceptance and participation are crucial, showing potential support for PCT in the UK at around 80 % [39].

However, the acceptance of PCT is complicated by challenges like differing environmental awareness levels [40], privacy concerns [36], and perceptions of the scheme's value [41], leading to its characterization as a radical approach [8].

The cost associated with PCT implementation emerges as the second vital factor. The management expenses for PCT significantly exceed those for carbon trading on the production side [15], posing implementation challenges. Research by Lane et al. [42] indicates that initiating PCT in the UK could require an initial outlay of £700 million to £2 billion, alongside annual operating expenses ranging from £1 to £2 billion. Consequently, Francesco [43]argues for the crucial need to substantially reduce PCA costs to ensure economic viability.

Technology serves as the third influencing factor. According to Fuso & Francesco [22], the technology required for managing carbon accounts and facilitating trading under PCT is not yet mature. Nevertheless, the successful deployment of mobile apps for COVID-19 tracking demonstrates the potential for technological advancements to significantly enhance the PCT framework. Moreover, Tan et al. [44]found that in Guangdong Province's PCI project, institutional technology, perceived usefulness, and risk perceptions are key determinants of public willingness to participate.

Finally, policy considerations are integral to the discussion. Studies suggest that existing climate and energy policies might affect the implementation of the PCA mechanism. Specifically, since the PCA scheme aims to reduce emissions at the consumer end, it could overlap with the EU ETS measures targeting production-end reduction. This overlap raises concerns about the potential for double pricing of carbon emissions [11,15].

2.3. Research on the exploration of PCT scheme mechanisms

Scholars have deeply investigated the intricate mechanisms that guide participant behavior within the PCT scheme. For instance, Parag et al. [10,10] pinpointed economic, cognitive, and social mechanisms as the primary drivers prompting behavioral shifts related to carbon emissions under the PCA scheme. In a distinct approach, Guo et al. [3] applied the expected utility rank dependence theory and game models to assess the influence of varied emotions from the government and individuals on the PCT scheme's execution and equilibrium strategy. Their analysis revealed that emotions might not impact the pure strategy equilibrium but notably affect the mixed strategy equilibrium. Zhao et al. [7] introduced an innovative Public-Private Partnership for personal carbon accounts (PPP-PCAs), aiming to gauge the interplay of government and market mechanisms on reducing household energy consumption emissions. Their findings underscored that when private entities such as financial institutions, corporations, and carbon platforms enter the fray, the market mechanism robustly facilitates the PCA's wholesome and accelerated growth. In contrast, government initiatives, like subsidies and carbon taxation, seem to wield minimal sway over consumers' eco-friendly choices. Further, Al-Guthmy and Yan [18]. undertook a comprehensive study of the PCT scheme's fairness. Their evaluation of PCT's quota allocation strategies, rooted in equality per capita and equality per vehicle, revealed that these methods predominantly benefit vulnerable demographics. In a related vein, Kothe et al. [30] harnessed an Agent-Based Model to mimic the workings of the PCT scheme. They concluded that a surge in carbon emission goals resonates with escalating allowance prices and an upswing in the fraction of purchasing households.

Although research on the PCT scheme has advanced considerably, notable gaps persist, especially in the emphasis on mandatory schemes rather than the voluntary PCI scheme. Additionally, much of the existing literature is descriptive, lacking detailed analysis of participant behavior within these schemes. Moreover, there's an oversight of the complex relationship between income inequality and climate change in PCT studies. As Wan et al. [20] noted, "income inequality and climate change present intertwined challenges to global sustainable development." This study aims to address these shortcomings by leveraging the Evolutionary Game Theory (EGT) framework to examine decision-making processes and interactions among different socio-economic groups within the PCT scheme. By introducing a tripartite evolutionary game model that encompasses high-income and low-income individuals, as well as the PCI

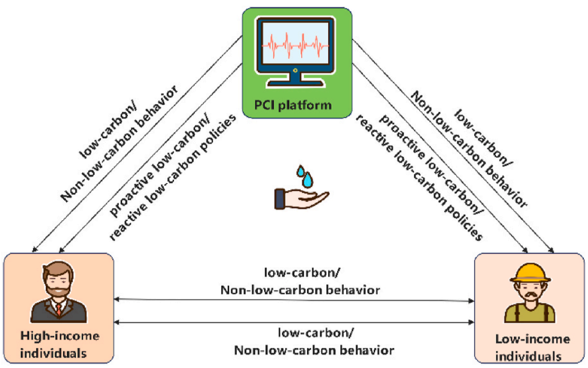

Fig. 1. Logical relationship of tripartite evolutionary game model.

platform, we aspire to shed light on ways to enhance the PCI scheme's effectiveness through insightful analysis and recommendations.

3. Process analysis

3.1. Game model based on the PCI scheme

This study introduces the tripartite evolutionary game model of low-carbon behavior, depicting the logical interplay among different entities as demonstrated in Fig. 1. The PCI platform adjusts its game strategies to maximize ecological benefits, encompassing both proactive and reactive low-carbon policies. Similarly, both high-income and low-income individuals modify their game strategies with the objective of utility maximization, with choices centered on either low-carbon or non-low-carbon behavior.

To simplify the game model construction and facilitate the analysis of strategy stability, equilibrium points, and the interplay of different factors, we adopt the subsequent assumptions.

Assumption 1. The evolutionary game model is built on three distinct population segments:

- Player 1 represents high-income individuals;
- Player 2 signifies low-income individuals;
- Player 3 stands for the PCI platform.

Each player must choose between two strategies designed to maximize their own utility. Throughout the game, players operate without external influences, making independent decisions.

Assumption 2. The strategy spaces for the players in the evolutionary game are detailed as follows:

Player 1 (High-Income Individuals): Their strategy space, α, consists of α1 (low-carbon behavior) and α2 (non-low-carbon behavior). They choose α1 with a probability x and α2 with the probability (1-x), where x is between 0 and 1.

Player 2 (Low-Income Individuals): Their strategy space, β, includes β1 (low-carbon behavior) and β2 (non-low-carbon behavior). They select β1 with a probability y and β2 with the probability (1-y). y is defined between 0 and 1.

Player 3 (PCI Platform): Their strategy space, γ, comprises γ1 (proactive low-carbon policy) and γ2 (reactive low-carbon policy). The platform adopts γ1 with a probability z and γ2 with the probability (1-z), where z lies between 0 and 1.

Throughout this game, players exhibit bounded rationality. Their strategic decisions evolve until they determine the optimal strategy set.

Table 1
Variables and their Descriptions in the Models.

Variables	Definition
E1	Carbon inclusive benefits (i.e., carbon coins) to the public when the platform implements proactive low-carbon policies
E2	Carbon inclusive benefits to the public when the platform does not implement proactive low-carbon policies
C1	The cost incurred by the public for low-carbon behavior
Cf	The cost incurred by the public for non-low-carbon behavior
Cp1	Cost to the platform for PCI projects paid to the public when both the platform implements proactive low-carbon policies and the public engages in low-carbon behavior
Cp2	Cost to the platform for PCI projects paid to the public when the platform does not implement proactive low-carbon policies but the public engages in low-carbon behavior
Cm	Fixed costs to the platform when the platform implements proactive low-carbon policies but the public does not engage in low-carbon behavior
Cn	Fixed costs to the platform when the platform does not implement proactive low-carbon policies and the public does not engage in low-carbon behavior
U11	Utility of low-carbon behavior for high-income individuals when the platform implements proactive low-carbon policies and both the high-income and low-income individuals engage in low-carbon behavior
U12	Utility of low-carbon behavior for low-income individuals when the platform implements proactive low-carbon policies and both the high-income and low-income individuals engage in low-carbon behavior
Ux1	Utility of low-carbon behavior for high-income individuals when the platform implements proactive low-carbon policies, the high-income individuals engage in low-carbon behavior, and the low-income individuals do not engage in low-carbon behavior
Ux2	Utility of low-carbon behavior for low-income individuals when the platform implements proactive low-carbon policies, the low-income individuals engage in low-carbon behavior, and the high-income individuals do not engage in low-carbon behavior
U21	Utility of low-carbon behavior for high-income individuals when the platform does not implement proactive low-carbon policies, but both the high-income and low-income individuals engage in low-carbon behavior
U22	Utility of low-carbon behavior for low-income individuals when the platform does not implement proactive low-carbon policies, but both the high-income and low-income individuals engage in low-carbon behavior
Uy1	Utility of low-carbon behavior for high-income individuals when the platform does not implement proactive low-carbon policies, the high-income individuals engage in low-carbon behavior, and the low-income individuals do not engage in low-carbon behavior
Uy2	Utility of low-carbon behavior for low-income individuals when the platform does not implement proactive low-carbon policies, the low-income individuals engage in low-carbon behavior, and the high-income individuals do not engage in low-carbon behavior
Uf1	General utility of the high-income individuals when they do not engage in proactive low-carbon behavior
Uf2	General utility of the low-income individuals when they do not engage in proactive low-carbon behavior
Up	The ecological economic utility of the platform when the public engages in proactive low-carbon behavior

Assumption 3. The composition of the utility function is:

Public Engagement in Low-Carbon Behavior: The utility function integrates direct carbon inclusive benefits, indirect societal benefits (which include political, social, and reputational values as highlighted by Ref. [45]), and costs associated with adopting a low-carbon lifestyle.

Public Non-Low-Carbon Behavior: This utility encompasses general utility from non-low-carbon activities and common behavioral costs.

PCI Platform: The profit function comprises ecological utility, determined by the number of individuals opting for low-carbon behavior, and operating costs. Notably, proactive low-carbon policy costs (Cp1 or *Cm*) exceed those of reactive policies (Cp2 or Cn), i.e., $Cp1 > Cp2$ and $Cm > Cn$.

Assumption 4. The utility derived from low-carbon behavior for high-income individuals (i.e. U11), is assumed to be less than that for low-income individuals(U12) i.e., $U11 < U12$. Additionally, during interactions between the two income groups, if either abstains from a low-carbon behavior, the utility for high-income individuals (either Ux1 or Uy1) is always less than the utility for the low-income counterparts (either Ux2 or Uy2), i.e., $Ux1 < Ux2$ and $Uy1 < Uy2$.

Assumption 5. The PCI platform offers a limited range of inclusive products. When either high-income or low-income individuals refrain from engaging in low-carbon behavior, the utility of such behavior for the opposing party escalates: $Ux1 > U11$, $Ux2 > U12$, $Uy1 > U21$, and $Uy2 > U22$. The variables and their descriptions in the models as illustrated in Table 1.

3.2. The payoff of participators in games

In line with the assumptions mentioned in previous section, the mixed strategy game matrix for high-income individuals, low-income individuals, and the PCI platform is illustrated in Table 2.

3.3. Model analysis

3.3.1. Stability analysis of strategies for the high-income individuals

The expected payoffs for the high-income individuals when they choose low-carbon behavior (M11) and non-low-carbon behavior (M12), alongside their average expected payoff (M1), as indicated in Equations (1)–(3):

$$M11 = (-C1 + E2 + Uy1)(1-y)(1-z) + (-C1 + E2 + U21)y(1-z) + (-C1 + E1 + Ux1)(1-y)z + (-C1 + E1 + U11)yz \tag{1}$$

$$M12 = (-Cf + Uf1)(1-y)(1-z) + (-Cf + Uf1)y(1-z) + (-Cf + Uf1)(1-y)z + (-Cf + Uf1)yz \tag{2}$$

$$M1 = -Cf + Uf1 + x(-C1 + Cf + E2 - Uf1 + Uy1 + U21y - Uy1y + E1z - E2z + Ux1z - Uy1z + U11yz - U21yz - Ux1yz + Uy1yz) \tag{3}$$

The replicator dynamics equation [7] for the strategy selection of the high-income individuals is as indicated in Equation (4):

Table 2

Payoff matrix for the tripartite evolutionary game.

				The high-income individuals	
				Low-carbon behavior (x)	Non-low-carbon behavior (1-x)
The PCI platform	Proactive low-carbon policies (z)	The low-income individuals	Low-carbon behavior (y)	$-C1 + E1 + U11$; $-C1 + E1 + U12$; $-Cm - 2Cp1 + Up$	$-Cf + Uf1$; $-C1 + E1 + Ux2$; $-Cm - Cp1 + \frac{1}{2}Up$
			Non-low-carbon behavior (1-y)	$-C1 + E1 + Ux1$; $-Cf + Uf2$; $-Cm - Cp1 + \frac{1}{2}Up$	$-Cf + Uf1$; $-Cf + Uf2$; $-Cm$
	Reactive low-carbon policies (1-z)		Low-carbon behavior (y)	$-C1 + E2 + U21$; $-C1 + E2 + U22$; $-Cn - 2Cp2 + Up$	$-Cf + Uf1$; $-C1 + E2 + Uy2$; $-Cn - Cp2 + \frac{1}{2}Up$
			Non-low-carbon behavior (1-y)	$-C1 + E2 + Uy1$; $-Cf + Uf2$; $-Cn - Cp2 + \frac{1}{2}Up$	$-Cf + Uf1$; $-Cf + Uf2$; $-Cn$

$$F(x) = dx/dt = x(M11 - M1) = (-1 + x)x(C1 - Cf - E2 + Uf1 - Uy1 - U21y + Uy1y - E1z + E2z - Ux1z + Uy1z - U11yz + U21yz + Ux1yz - Uy1yz) \tag{4}$$

Take the derivative of F(x) with respect to x,we can get Equation (5)

$$d(F(x))/dx = (-1 + 2x)(C1 - Cf - E2 + Uf1 - Uy1 - U21y + Uy1y - E1z + E2z - Ux1z + Uy1z - U11yz + U21yz + Ux1yz - Uy1yz) \tag{5}$$

For calculation convenience, assuming Equation (6):

$$G(y) = C1 - Cf - E2 + Uf1 - Uy1 - U21y + Uy1y - E1z + E2z - Ux1z + Uy1z - U11yz + U21yz + Ux1yz - Uy1yz \tag{6}$$

Given the conditions $y(-U21 + Uy1) > 0$ and $yz(U21 - Uy1) < 0$, it follows that $y(-U21 + Uy1) + yz(U21 - Uy1) > 0$. Furthermore, with the condition $-U11yz + Ux1yz > 0$, G(y) is an increasing function with respect to y.

The stability theorem of the replication dynamics equation determines that when $F(x) = 0$ and $dF(x)/dx < 0$, the high-income individuals' selection of the low-carbon behavior strategy is in a stable state. If $y* = \frac{C1-Cf-E2+Uf1-Uy1-E1z+E2z-Ux1z+Uy1z}{U21-Uy1+U11z-U21z-Ux1z+Uy1z}$,then $G(y) \equiv 0$. If $y > y^*$, then $G(y) > 0$, this indicates that $d(F(x))/dx|x = 0 < 0$, implying that $x = 0$ is the evolutionarily stable strategy (ESS) for the high-income individuals. Conversely, if $y < y^*$, then $G(y) < 0$, suggesting that $d(F(x))/dx|x = 1 < 0$. In this case, $x = 1$ is the ESS for the high-income individuals. The dynamic phase diagram is depicted in Fig. 2 below:

The three diagrams in Fig. 2 depict the dynamic phase diagrams under three conditions respectively: (a) when $y = y^*$, (b) when $y < y^*$, and (c) when $y > y^*$.

The stable probability of the high-income individuals practicing low-carbon behavior is denoted as VA1, while the stable probability of the high-income individuals practicing non-low-carbon behavior is denoted as VA2. As indicated in Equations (7) and (8):

$$VA1 = \int_0^1 \int_0^1 y * dzdx = 1 \Big/ [(U11 - U21 - Ux1 + Uy1)]^2((E1 - E2 + Ux1 - Uy1)(-U11 + U21 + Ux1 - Uy1) + (-CfU11 - E2U11 + CfU21 + E1U21 + U11Uf1 - U21Uf1 + CfUx1 + E2Ux1 + U21Ux1 - Uf1Ux1 - (Cf + E1 + U11 - Uf1)Uy1 + C1(U11 - U21 - Ux1 + Uy1))Log[(U11 - Ux1) / (U21 - Uy1)]) \tag{7}$$

$$VA2 = 1\text{-}VA1 \tag{8}$$

Proposition 1. *The probability (VA1) of high-income individuals consistently practicing low-carbon Behavior is a decreasing function with respect to variable C1 and an increasing function with respect to variable Cf.*

Please refer to Appendix 1 for the proof.

Proposition 2. *The probability (VA1) of high-income individuals consistently practicing low-carbon Behavior is an increasing function with respect to variables E1 and E2.*

Please refer to Appendix 2 for the proof.

3.3.2. Stability analysis of low-carbon strategies for the low-income individuals

The expected payoffs for the low-income individuals when they choose low-carbon behavior (N11) and non-low-carbon behavior (N12), alongside their average expected payoff (N1), as indicated in Equations (9)–(11):

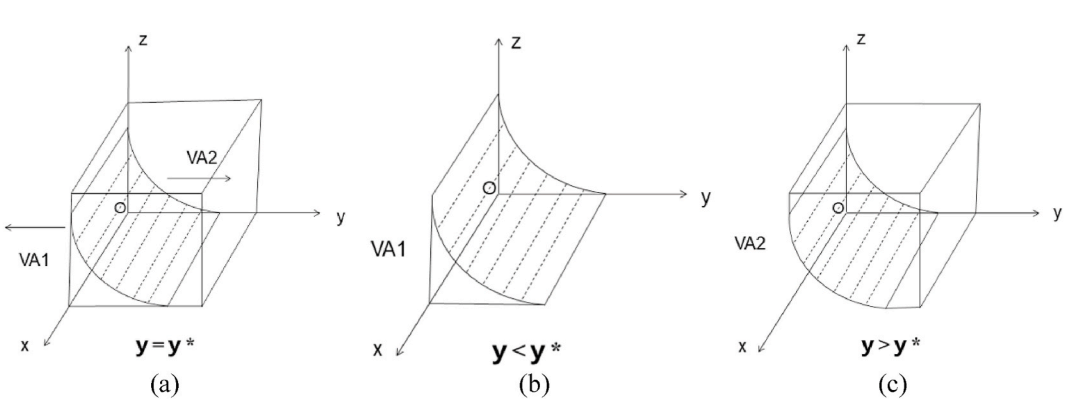

Fig. 2. Replicator dynamic phase diagram of high-income individuals.

$$N11 = (-C1 + E2 + Uy2)(1-x)(1-z) + (-C1 + E2 + U22)x(1-z) + (-C1 + E1 + Ux2)(1-x)z + (-C1 + E1 + U12)xz \tag{9}$$

$$N12 = (-Cf + Uf2)(1-x)(1-z) + (-Cf + Uf2)x(1-z) + (-Cf + Uf2)(1-x)z + (-Cf + Uf2)xz \tag{10}$$

$$N1 = -Cf + Uf2 + y(-C1 + Cf + E2 - Uf2 + Uy2 + U22x - Uy2x + E1z - E2z + Ux2z - Uy2z + U12xz - U22xz - Ux2xz + Uy2xz) \tag{11}$$

The replicator dynamics equation for strategy selection of the low-income individuals is as indicated in Equations (12) and (13):

$$F(y) = (-1 + y)y(C1 - Cf - E2 + Uf2 - Uy2 - U22x + Uy2x - E1z + E2z - Ux2z + Uy2z - U12xz + U22xz + Ux2xz - Uy2xz) \tag{12}$$

$$dF(y)/dy = (-1 + 2y)(C1 - Cf - E2 + Uf2 - Uy2 - U22x + Uy2x - E1z + E2z - Ux2z + Uy2z - U12xz + U22xz + Ux2xz - Uy2xz) \tag{13}$$

Assuming Equation (14):

$$G2(x) = C1 - Cf - E2 + Uf2 - Uy2 - U22x + Uy2x - E1z + E2z - Ux2z + Uy2z - U12xz + U22xz + Ux2xz - Uy2xz \tag{14}$$

Given that $-U22x + Uy2x + U22xz - Uy2xz > 0$, $-U12xz + Ux2xz > 0$.Therefore, G2(x) is a monotonically increasing function with respect to x.

If $x* = \frac{C1 - Cf - E2 + Uf2 - Uy2 - E1z + E2z - Ux2z + Uy2z}{U22 - Uy2 + U12z - U22z - Ux2z + Uy2z}$,then $G2(x) = 0$. If $x > x*$, then $G2(x) > 0$. In this case, $d(F(y))/dy|y = 0 < 0$, indicating that $y = 0$ is the evolutionarily stable strategy (ESS) of the low-income individuals; Conversely, $y = 1$ serves as the ESS for the low-income individuals. The dynamic phase diagram is depicted in Fig. 3 below:

The three diagrams in Fig. 3 depict the dynamic phase diagrams under three conditions respectively: (a) when $x = x^*$, (b) when $x < x^*$, and (c) when $x > x^*$.

The stable probability of the low-income individuals practicing low-carbon behavior is denoted as VB1, while the stable probability of the low-income individuals practicing non-low-carbon behavior is denoted as VB2. As indicated in Equations (15) and (16):

$$VB1 = \int_0^1 \int_0^1 x * dzdx = 1 \Big/ (U12 - U22 - Ux2 + Uy2)^2 ((E1 - E2 + Ux2 - Uy2)(-U12 + U22 + Ux2 - Uy2) + (-Cf * U12 - E2 * U12 + Cf * U22 + E1 * U22 + U12 * Uf2 - U22 * Uf2 + Cf * Ux2 + E2 * Ux2 + U22 * Ux2 - Uf2 * Ux2 - (Cf + E1 + U12 - Uf2) * Uy2 + C1(U12 - U22 - Ux2 + Uy2)) Log[(U12 - Ux2)/(U22 - Uy2)]) \tag{15}$$

$$VB2 = 1 - VB1 \tag{16}$$

Proposition 3. *The probability (VB1) of the low-income individuals stably adopting low-carbon behavior is a decreasing function of C1 and an increasing function of Cf.*

Please refer to Appendix 3 for the proof.

Proposition 4. *The probability (VB1) of low-income individuals consistently adopting low-carbon behavior is an increasing function with respect to E1 and E2.*

Please refer to Appendix 4 for the proof.

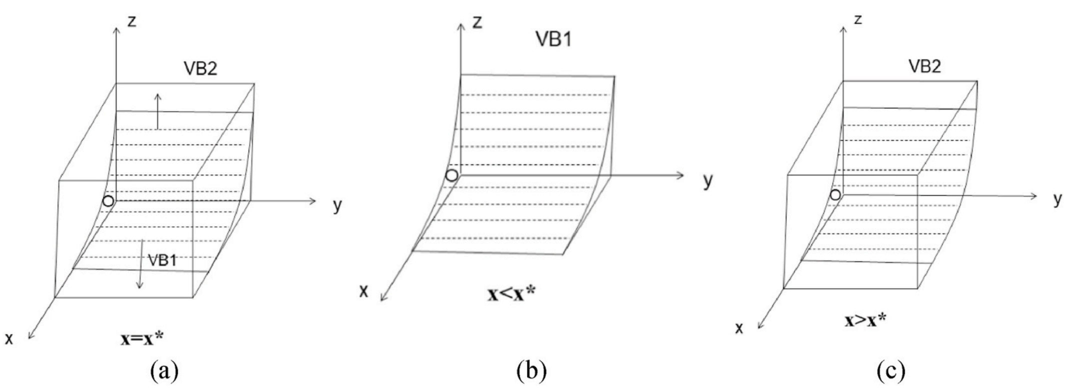

Fig. 3. The evolutionary phase diagram for the low-income individuals.

3.3.3. Stability analysis of the PCI platform's strategies

The expected benefits for the platform when they choose proactive low-carbon policy (R11) and non-proactive low-carbon policy (R12), alongside their average expected benefits(R1), as indicated in Equations (17)–(19):

$$R11 = (-Cm - 2Cp1 + Up)xy + (-Cm - Cp1 + 1/2Up)(1-x)y + (-Cm - Cp1 + 1/2Up)x(1-y) - Cm(1-x)(1-y) \tag{17}$$

$$R12 = (-Cm - 2Cp2 + Up)xy + (-Cn - Cp2 + 1/2Up)(1-x)y + (-Cn - Cp2 + 1/2Up)x(1-y) - Cn(1-x)(1-y) \tag{18}$$

$$R1 = R12(1-z) + R11z = \frac{1}{2Up(x+y)} + Cn(-1+z) + Cp2(x+y)(-1+z) - (Cm + Cp1(x+y))z \tag{19}$$

The replicator dynamics equation for strategy selection of the PCI platform is as indicated in Equations (20) and (21):

$$F(z) = z(H11 - H1) = (Cm - Cn + (Cp1 - Cp2)(x+y))(-1+z)z \tag{20}$$

$$dF(z)/dz = (Cm - Cn + (Cp1 - Cp2)(x+y))(-1+2z) \tag{21}$$

Assuming $R(x) = (Cm - Cn + (Cp1 - Cp2)(x+y))$,the coefficient of x in R(x) is (Cp1 – Cp2). Because Cp1>Cp2, hence, R(x) is an increasing function with respect to x.

If $x^{**} = \frac{-Cm+Cn-Cp1y+Cp2y}{Cp1-Cp2}$, $R(x) = 0$. If $x > x^{**}$, $R(x) > 0$, and $d(F(z))/dz|z = 0 < 0$. Hence, $z = 0$ is the platform's ESS. Conversely, when $x > x^{**}$, $z = 1$ is the platform's ESS. The dynamic phase diagram is depicted in Fig. 4 as follows:

The three diagrams in Fig. 4 depict the dynamic phase diagrams under three conditions respectively: (a) when $x = x^{**}$, (b) when $x < x^{**}$, and (c) when $x > x^{**}$.

The stable probability of the PCI platform practicing proactive low-carbon policy is denoted as VC1, while the stable probability of the PCI platform practicing reactive low-carbon policy is denoted as VC2. As indicated in Equations (22) and (23):

$$VC1 = \int_0^1 \int_0^1 x**dydz = \frac{-2Cm + 2Cn - Cp1 + Cp2}{2(Cp1 - Cp2)} \tag{22}$$

$$VC2 = 1\text{-}VC1 \tag{23}$$

Proposition 5. *The probability of proactive low-carbon policies on the PCI platform, decreases with an increase in Cm and Cp1, and increases with an increase in Cp2 and Cn.*

Please refer to Appendix 5 for the proof.

3.4. Stability analysis of equilibrium points in the tripartite evolutionary game system

When F(x), F(y), and F(z) are simultaneously equal to zero, the equilibrium points in the replication dynamic system can be obtained. According to Wang [46], the mixed strategy equilibrium in asymmetric game dynamics is not evolutionarily stable. Therefore, in this analysis, we focus solely on the evolutionary stability of pure policy strategies T1 through T8, as detailed in Table 3.

The Jacobian matrix of the three-player evolutionary game system is as follows:

$$J = \begin{bmatrix} J1 & J2 & J3 \\ J4 & J5 & J6 \\ J7 & J8 & J9 \end{bmatrix} = \begin{bmatrix} \partial F(x)/\partial x & \partial F(x)/\partial y & \partial F(x)/\partial z \\ \partial F(y)/\partial x & \partial F(y)/\partial y & \partial F(y)/\partial z \\ \partial F(z)/\partial x & \partial F(z)/\partial y & \partial F(z)/\partial z \end{bmatrix}$$

Where:

$$J1 : (-1+2x)(C1 - Cf - E2 + Uf1 - Uy1 - U21y + Uy1y - E1z + E2z - Ux1z + Uy1z - U11yz + U21yz + Ux1yz - Uy1yz)$$

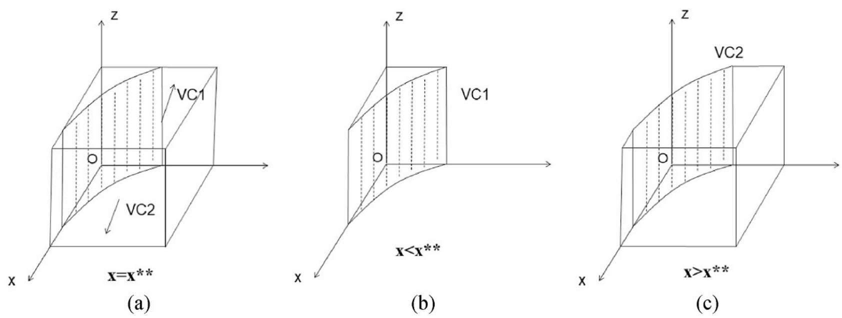

Fig. 4. The evolutionary phase diagram for the platform.

Table 3
Stability analysis of equilibrium points.

Equilibrium points	Matrix eigenvalues		Stability	Condition
	λ1, λ2, λ3	Sign		
T1 (0 0 0)	$\{-\text{Cm}+\text{Cn}, \text{E2}-\text{C1}+\text{Uy1}+\text{Cf}-\text{Uf1}, \text{E2}-\text{C1}+\text{Uy2}+\text{Cf}-\text{Uf2}\}$	-++	B	①②
T2 (1 0 0)	$\{-\text{Cm}+\text{Cn}-\text{Cp1}+\text{Cq1}, \text{E2}-\text{C1}+\text{U22}+\text{Cf}-\text{Uf2}, -\text{E2}+\text{C1}-\text{Uy1}-\text{Cf}+\text{Uf1}\}$	- + -	B	①②
T3 (0 1 0)	$\{-\text{Cm}+\text{Cn}-\text{Cp1}+\text{Cq1}, \text{E2}-\text{C1}+\text{U21}+\text{Cf}-\text{Uf1}, -\text{E2}+\text{C1}-\text{Uy2}-\text{Cf}+\text{Uf2}\}$	–	ESS	①③
T4 (0 0 1)	$\{\text{Cm}-\text{Cn}, \text{E1}-\text{C1}+\text{Ux1}+\text{Cf}-\text{Uf1}, \text{E1}-\text{C1}+\text{Ux2}+\text{Cf}-\text{Uf2}\}$	+++	B	
T5 (1 1 0)	$\{-\text{Cm}+\text{Cn}-2\text{Cp1}+2\text{Cp2}, \text{C1}-\text{Cf}-\text{E2}-\text{U21}+\text{Uf1}, \text{C1}-\text{Cf}-\text{E2}-\text{U22}+\text{Uf2}\}$	- + -	B	
T6 (1 0 1)	$\{\text{Cm}-\text{Cn}+\text{Cp1}-\text{Cp2}, \text{E1}+\text{U12}-\text{C1}+\text{Cf}-\text{Uf2}, -\text{E1}+\text{C1}-\text{Ux1}-\text{Cf}+\text{Uf1}\}$	++-	B	
T7 (0 1 1)	$\{\text{Cm}-\text{Cn}+\text{Cp1}-\text{Cp2}, \text{E1}+\text{U11}-\text{C1}+\text{Cf}-\text{Uf1}, -\text{E1}+\text{C1}-\text{Ux2}-\text{Cf}+\text{Uf2}\}$	++-	B	
T8 (1 1 1)	$\{\text{Cm}-\text{Cn}+2\text{Cp1}-2\text{Cp2}, -\text{E1}-\text{U11}+\text{C1}-\text{Cf}+\text{Uf1}, -\text{E1}+\text{C1}-\text{U12}-\text{Cf}+\text{Uf2}\}$	+–	B	

Note.

$$\text{J2}: (-1+x)x(-\text{U21}+\text{Uy1}-\text{U11z}+\text{U21z}+\text{Ux1z}-\text{Uy1z})$$

$$\text{J3}: (-1+x)x(-\text{E1}+\text{E2}-\text{Ux1}+\text{Uy1}-\text{U11y}+\text{U21y}+\text{Ux1y}-\text{Uy1y})$$

$$\text{J4}: (-1+y)y(-\text{U22}+\text{Uy2}-\text{U12z}+\text{U22z}+\text{Ux2z}-\text{Uy2z})$$

$$\text{J5}: (-1+2y)(\text{C1}-\text{Cf}-\text{E2}+\text{Uf2}-\text{Uy2}-\text{U22x}+\text{Uy2x}-\text{E1z}+\text{E2z}-\text{Ux2z}+\text{Uy2z}-\text{U12xz}+\text{U22xz}+\text{Ux2xz}-\text{Uy2xz})$$

$$\text{J6}: (-\text{E1}+\text{E2}-\text{Ux2}+\text{Uy2}-\text{U12x}+\text{U22x}+\text{Ux2x}-\text{Uy2x})(-1+y)y$$

$$\text{J7}: (\text{Cp1}-\text{Cp2})(-1+z)z$$

$$\text{J8}: (\text{Cp1}-\text{Cp2})(-1+z)z$$

$$\text{J9}: (\text{Cm}-\text{Cn}+(\text{Cp1}-\text{Cp2})(x+y))(-1+2z)$$

The stability of an equilibrium point can be ascertained based on the signatures of the eigenvalues of the Jacobian matrix [47]. An equilibrium point is classified as asymptotically stable if all the eigenvalues of the Jacobian matrix possess negative real parts. On the contrary, if any eigenvalue possesses a positive real part, the equilibrium point is deemed unstable. In instances where the Jacobian matrix carries eigenvalues with zero real parts, and the rest have negative real parts, the equilibrium point enters a critical state. For a thorough analysis of the stability of each equilibrium point, Table 3 can be consulted.

(1) The Table 3 uses the following notations: 'B' signifies an unstable state, 'ESS' represents an equilibrium state, '+' stands for a positive eigenvalue, '-' for a negative eigenvalue.
(2) The analysis proceeds under three conditions: ①Absent proactive low-carbon policies on the platform, the low-income individuals derive a higher utility from engaging in low-carbon behavior compared to passive low-carbon behavior, regardless of the strategy adopted by the high-income individuals. This is represented by -C1+E2+Uy2 > -Cf + Uf2 and -C1+E2+U22 > -Cf + Uf2. ② If the platform introduces passive low-carbon policies and low-income individuals choose not to practice low-carbon behavior, the overall utility derived from the high-income individuals' low-carbon behavior outweighs the utility from their non-engagement. Formally, -C1+E2+Uy1 > -Cf + Uf1. ③ Should passive low-carbon policies be introduced by the platform and low-income individuals decide to engage in low-carbon behavior, the overall utility derived from the high-income individuals' low-carbon behavior falls below the utility derived from their non-low-carbon behavior. This is expressed by -C1+E2+U21 < -Cf + Uf1.

As per Table 3, the system attains an evolutionarily stable state at point T3 (0, 1, 0). This state characterizes a situation where high-income individuals abstain from low-carbon behavior, low-income individuals engage in low-carbon behavior, and the PCI platform demonstrates a lukewarm response towards the implementation of proactive low-carbon policies.

Corollary 1. If the equation C1 - Cf - E2 - U21 + Uf1 < 0 holds, the ESS is pinpointed at point T5. Under these conditions, individuals of both high and low income adopt low-carbon behaviors, although the platform does not implement proactive low-carbon policies.

In China, new energy vehicles (NEVs) are recognized as an eco-friendly transportation option, increasingly favored by families of all income levels [48]. In 2023, NEV sales in China surged to 9.495 million units, a 37.9 % increase, achieving a market share of 34.7 %. The preference of low-income families for NEVs does not discourage high-income families from purchasing them. This is attributed to the low operational costs and superior driving comfort of NEVs. Moreover, the reward of 20 PCI carbon coins per day for NEV usage appeal to high-income families, further encouraging their shift towards NEVs.

Corollary 2. The ESS is recognized as point T8 when the condition Cm-Cn+2Cp1-2Cp2<0 is fulfilled. Under these circumstances—where the cost of introducing proactive low-carbon incentivization policies on the platform is lower than the expense of avoiding such proactive steps—all stakeholders, including high-income individuals, low-income individuals, and the platform itself, lean towards adopting proactive low-carbon behaviors or policies.

In practical scenarios, some companies seeking to enhance their corporate image, fulfill social responsibilities, and align with national low-carbon policies may choose to donate their products to PCI platforms at no cost. This strategy not only reduces the platform's operational expenses but also encourages a shift towards more proactive low-carbon policies.

4. Simulated analysis

4.1. Overview of the Zhejiang PCI scheme

The PCI scheme implemented in China's Zhejiang Province serves as a strategic initiative to promote carbon mitigation and catalyze the transition towards low-carbon development. Specifically, the province has adopted a standardized consumer-level carbon accounting system. This system quantifies and assigns value to individual actions towards energy conservation and carbon reduction. In addition, it introduces incentive mechanisms that encourage residents to choose low-carbon commodities and adopt sustainable lifestyles, thus steering their paths towards reduced carbon emissions. The ultimate goal is to cultivate a low-carbon lifestyle culture, contributing significantly to Zhejiang Province's targets of peaking carbon emissions and achieving carbon neutrality.

The Carbon Inclusion Mechanism in Zhejiang Province is actualized through the Zhejiang PCI Platform, established under the patronage of the provincial government. Officially launched on March 29, 2022, the platform enables public documentation of low-carbon practices through the Alipay application. A broad range of low-carbon activities, covering sectors such as green transportation and online transactions, are recorded daily and converted into 'carbon coins'. Residents can earn these coins (as illustrated in Fig. 5) through making environmentally mindful choices in various aspects of life, including clothing, food, housing, and transportation. The accrued carbon coins can be exchanged for an array of rewards and benefits, including eco-friendly products, access to airport VIP lounges, and admission tickets to protected natural reserves and tourist attractions. As of December 31, 2022, the platform has engaged over 1.3 million users, documented more than 26 million low-carbon behaviors, and accumulated over 20 million carbon coins. Thus, it has emerged as the most comprehensive and rewarding provincial-level platform for carbon inclusion, effectively mobilizing public participation in low-carbon living.

4.2. Simulated analysis

To substantiate the efficacy of the evolutionary stability analysis, a fundamental dataset (as shown in Table 4) was assembled. This dataset integrates specific data elements that are drawn from the operational data of the Zhejiang PCI platform.

The survey in this study was anonymous and did not involve human or animal subjects, and thus, no ethical approval was required.

Numerical simulations were conducted using Matlab2018b, and the simulation data satisfied the conditions ①, ②, and ③ outlined

Fig. 5. Applied scenarios and inclusive products of PCI platform in Zhejiang Province.

Table 4
Values of variables in the simulation.

Participants	Variables	Value	Illustration
The publics	C1 E1 Cf E2	40 20 60 10	As illustrated in Fig. 5, a canvas bag is valued at 500 carbon coins on the PCI platform, and its market price approximately equates to 20 RMB. Considering the example of low-carbon travel (public transportation, utilized twice daily, with the cost of a single public transportation trip in China ranging from 1 to 5 RMB), the public can accumulate roughly 20 carbon coins each day due to low-carbon travel. Consequently, the fixed low-carbon cost (C1) is designated as 40, and E1 is determined as 20 under a proactive low-carbon policy, while E2 is 10 under a passive low-carbon policy. If high-carbon behavior (self-driving) is chosen, the travel cost (Cf) is assigned a value of 60.
High-income individuals	U11 Ux1 Uf1 U21 Uy1	100 130 110 60 80	A questionnaire survey of 161 public members revealed that: (1) 90 % are inclined towards participation in low-carbon behaviors in the context of carbon inclusive incentives, acknowledging that personal low-carbon behaviors carry some ecological value. (2) Low-income individuals perceive higher carbon inclusive utility from low-carbon behaviors than high-income individuals. (3) The fewer the participants in low-carbon behaviors (e.g., public transportation), the greater the satisfaction derived from the participants' utility. (4) When all members of the public engage in high-carbon behaviors, the utility of the low-income individuals is inferior to that of low-carbon behaviors, whereas the utility of the high-income individuals is slightly superior to that in the context of low-carbon behaviors. The corresponding parameters are established in alignment with the survey results.
Low-income individuals	U12 Ux2 Uf2 U22 Uy2	120 150 90 80 100	
PCI platform	*Cm* Cn	30 20	The PCI platform's system construction and daily maintenance necessitate certain expenses. Following an interview about the costs on the Zhejiang Carbon PCI platform and considering its usage over a year, *Cm* is set to 30 and Cn to 20.
	Cp1 Cp2	15 10	Cp1 (Cp2) represents the variable cost of the platform, primarily encapsulating the cost of procuring carbon inclusive welfare products. The unit cost should be marginally less than E1 (E2), hence it is assigned values of 15 (10).

earlier. The evolutionary outcomes of 50 simulation runs are presented in Fig. 6, providing insights into the dynamics and stability of the system.

The simulation outcomes affirm the stability analysis conducted in Section 3, underscoring that the evolutionarily stable point is indeed (0, 1, 0). This connotes that within the context of the tripartite evolutionary game, high-income individuals abstain from engaging in low-carbon behaviors, whereas low-income individuals do partake in such behaviors. Meanwhile, the platform refrains from implementing proactive low-carbon policies.

Drawing from the data in Table 4, a more thorough analysis can be conducted to examine the influences of E1, E2, C1, Cf, Cp1, Cp2, *Cm*, and Cn on the evolutionary game's dynamics and results. The evolution process's initial starting point is designated as (0.3, 0.3, 0.3), facilitating a comprehensive understanding of how these variables mold the game's trajectory and eventual outcomes.

(1) Firstly, the effects of changes in E1 and E2 on the evolutionary game's outcomes are analyzed. More specifically, we allocate values of 10, 20, and 30 to E1, and values of 5, 10, and 20 to E2. The simulation results, which replicate the dynamic evolution equations, are illustrated in Figs. 7 and 8. These figures provide visual demonstrations of how modifications in E1 and E2 influence the evolutionary game's path and ultimate results.

As gleaned from the analysis in Fig. 7, variations in E1 significantly influence the dynamics of the tripartite game. With the system gravitating towards the evolutionarily stable state, augmenting E1 results in a diminishing likelihood (z) of the platform implementing proactive low-carbon policies. Concurrently, the probability (x) of high-income individuals adopting low-carbon behavior and the

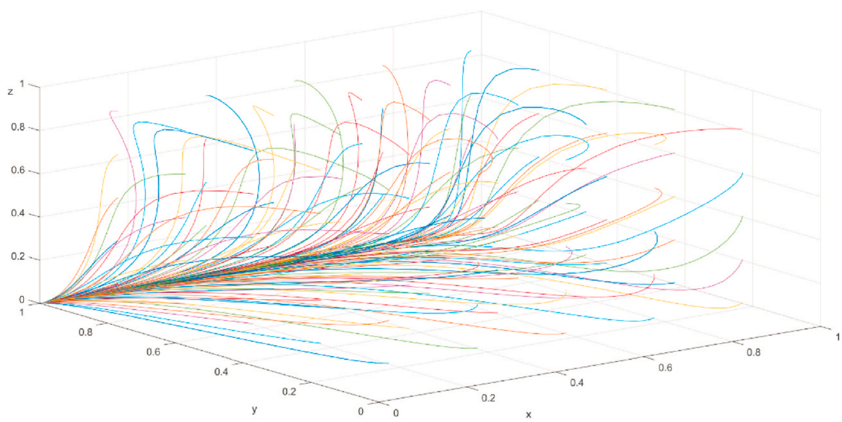

Fig. 6. The evolutionary process of system simulation.

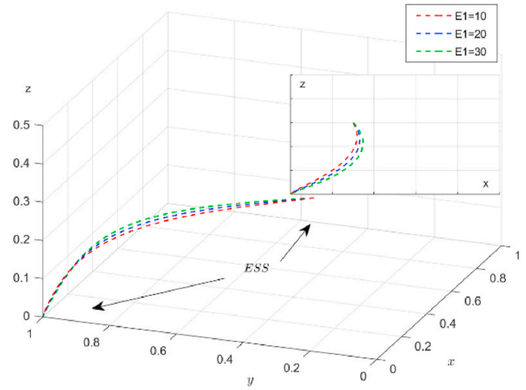

Fig. 7. The effect of changes in E1.

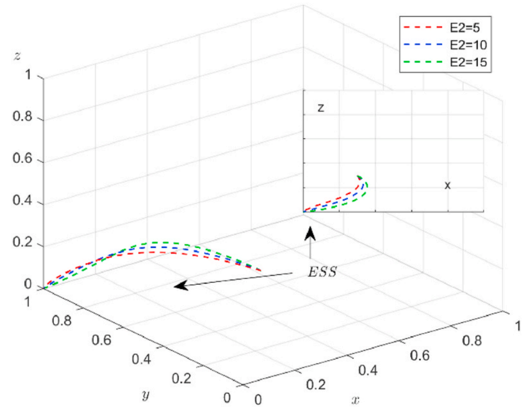

Fig. 8. The effect of changes in E2.

corresponding probability (y) among low-income individuals both witness an increase. Further, Fig. 8 depicts how the system's evolutionary path towards the stable state is shaped by the variable E2. A rise in E2 precipitates a decline in the probability of the platform deploying proactive low-carbon incentives, while simultaneously escalating the likelihoods of low-carbon behavior among both high-income and low-income individuals. These insights bolster the assertions made in Proposition 1 and Proposition 3, underlining the influence of E1 and E2 on the tripartite game's dynamics.

From these observations, it becomes clear that the formulation of pricing standards for low-carbon behavior on a PCI platform necessitates careful consideration of all stakeholders' acceptance levels. By judiciously adjusting the price for low-carbon behavior conversion within the constraints of financial feasibility, it's feasible to amplify the utility for low-income individuals and dissuade

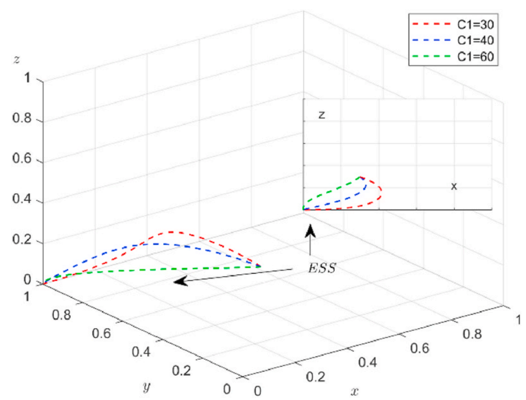

Fig. 9. The effect of changes in C1.

high-income individuals from high-carbon behavior. Such a strategic approach can stimulate a more sustainable and inclusive shift towards low-carbon practices.

(2) Secondly, the impact of variations in C1 and Cf on the evolutionary game process is analyzed. We assign values of C1 as 30, 40, 60, and Cf as 50, 60, 70.

The observations drawn from Figs. 9 and 10 underscore that variations in C1 and Cf considerably affect the outcome of the tripartite game. Elevating the cost of low-carbon behavior (C1) for the public results in a decrease in the probability of low-carbon behavior (x) among the high-income individuals and the probability of low-carbon behavior (y) among the low-income individuals as the system evolves. In contrast, amplifying the cost of high-carbon behavior (Cf) for the public causes an increase in the likelihood of low-carbon behavior (x) among the high-income individuals and the probability of low-carbon behavior (y) among the low-income individuals. These simulation results empirically reinforce the conclusions expressed in Proposition 2 and Proposition 4.

The fluctuations in C1 and Cf underscore the profound impact of public behavior costs on the strategic decisions of participants. These cost factors can be strategically utilized to mold the system's evolution. For example, in fostering green transportation through a PCI platform, one potential tactic could be to inflate the costs tied to high-carbon transportation modes, such as personal driving, while concurrently slashing the costs of greener transportation alternatives like public transit. This dual-pronged approach could effectively nudge the public towards adopting more sustainable and environmentally conscious transportation choices.

(3) Thirdly, the impact of Cp1 and Cp2 on the evolutionary game process is analyzed. We assign values to Cp1 as 10, 15, 25, and Cp2 as 5, 10, 15. The simulation results of the replicator dynamics equations are presented in Figs. 11 and 12.

The analysis from Fig. 11 reveals that as Cp1 increases, the likelihood of the platform proactively instituting low-carbon incentivization (z) diminishes. This suggests that escalated values of Cp1 dissuade the platform from actively fostering low-carbon behavior. Conversely, Fig. 12 illustrates that as Cp2 increases, the probability of the platform actively implementing low-carbon incentivization (z) intensifies. This insinuates that heightened values of Cp2 stimulate the platform to undertake proactive strategies to promote low-carbon behavior.

(4) Lastly, the impact of *Cm* and Cn on the evolutionary game process is analyzed. we assign values of *Cm* as 20, 30, 50, and Cn as 10, 20, 30.

The analysis gleaned from Figs. 13 and 14 elucidates the impactful role of *Cm* and Cn in the tripartite game. It becomes evident that as *Cm* (the system construction and daily maintenance cost for the PCI platform) inflates, the platform's probability of proactively implementing low-carbon incentivization policies (z) diminishes. This suggests that escalated values of *Cm* exert a discouraging effect on the platform, thwarting it from vigorously promoting low-carbon behavior. Conversely, as Cn increases, the probability of the platform actively endorsing low-carbon incentivization measures (z) intensifies.

5. Discussion

5.1. Theoretical implications

In this study, we have addressed a crucial question: the evolution of behavioral decision-making among participants in the PCI scheme. Consequently, we derive three key theoretical insights.

Firstly, PCI scheme is effective yet heterogeneous. PCI scheme is an effective system for reducing carbon emissions, as Section 3.4 shows. It encourages low-income individuals to adopt low-carbon behaviors and is sometimes effective with high-income individuals

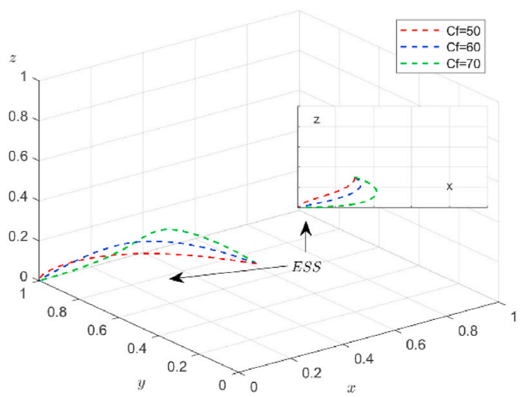

Fig. 10. The effect of changes in Cf.

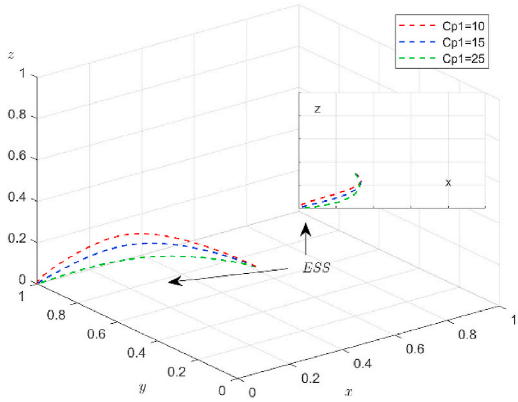

Fig. 11. The effect of changes in Cp1.

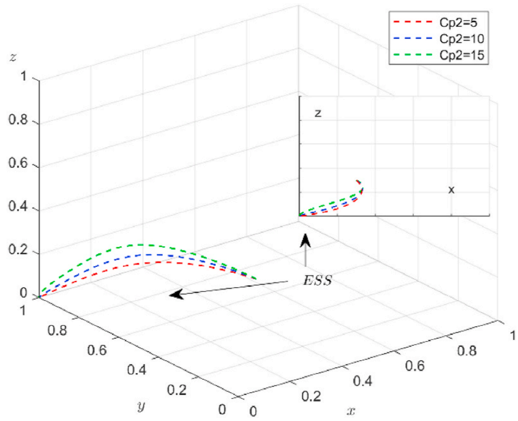

Fig. 12. The effect of changes in Cp2.

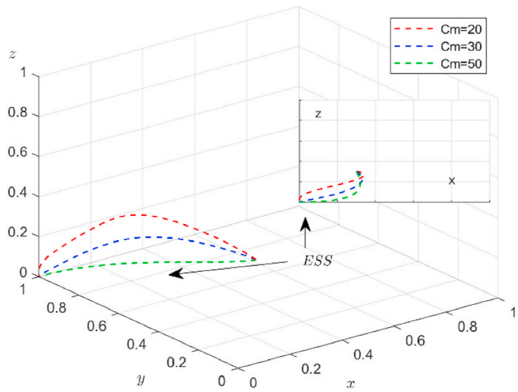

Fig. 13. The effect of changes in *Cm*.

as well. Widely accepted, the PCI scheme has earned a positive reputation in China. Guangdong Province launched the first such scheme in 2015, known as the Carbon Generalized System of Preferences (CGSP). By 2022, 16 provinces had their own PCI systems. In contrast, PCA/PCT faces acceptance challenges. Burgess [6] revealed that PCA would require one-third of low-income households to reduce fuel use or incur higher costs. Cam et al. [49] identified significant generational differences in PCA acceptance in Belgium, with older individuals showing less receptivity than younger ones. Consequently, the voluntary nature of the PCI scheme facilitates a shift towards low-carbon lifestyles more effectively [28].

However, the impact of PCI on promoting low-carbon lifestyles varies. It affects different income groups differently, with low-

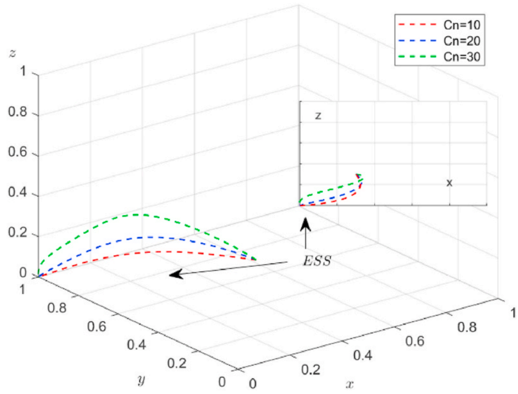

Fig. 14. The effect of changes in Cn.

income individuals more likely to embrace such lifestyles compared to their high-income counterparts. Additionally, its influence is not consistent within the same demographic group. For instance, high-income individuals find greater benefit in a low-carbon lifestyle when everyone adopts such behaviors, compared to a scenario where high-carbon lifestyles prevail. In this case, high-income individuals may also opt for a low-carbon lifestyle.

Secondly, PCI scheme can mitigate carbon inequity. Section 3.4 reveals that, generally, the PCI scheme encourages low-income individuals towards low-carbon lifestyles and high-income individuals towards high-carbon lifestyles. This outcome suggests that the scheme does not fully address carbon inequity, a key element for the public's acceptance of carbon policies, as emphasized by Fawcett & Parag [8]. Most countries lack comprehensive mandatory policies for reducing residential carbon emissions [21], allowing high-income individuals to maintain high-carbon lifestyles without facing environmental costs. In contrast, low-income individuals, restricted by their financial resources, are compelled to adopt low-carbon lifestyles, bearing an unequal share of environmental stress. Nonetheless, the PCI scheme does encourage high-income individuals to adopt low-carbon lifestyles in certain scenarios, helping to narrow the emission gap between income brackets. Furthermore, it offers subsidies to low-income participants, partially addressing carbon inequity. However, since the PCI scheme is voluntary and incentive-based, it is less forceful in ensuring carbon equity compared to the mandatory PCA scheme, especially as high-income individuals under PCI often continue with high-carbon lifestyles.

Thirdly, PCI Scheme should be a Transitional Strategy for Low-Carbon Guidance. The evolutionarily stable strategy shows that PCI platforms tend not to implement aggressive low-carbon guidance policies. As education and media coverage on environmental protection increase, public awareness improves, leading to higher adoption of low-carbon lifestyles. This increase in participation may place financial strain on the PCI platform, which relies heavily on government funding and lacks a stable income source. Tang et al. [21] have highlighted the difficulty PCI pilot projects face in securing long-term, stable funding. In comparison, the PCA scheme operates with rated carbon emission standards, allowing residents to trade excess carbon allowances, thus minimizing the need for government subsidies and ensuring sustainability. While the PCA scheme demonstrates greater viability due to its self-sustaining nature, the PCI scheme remains a valuable interim solution for countries not yet able to adopt the PCA scheme.

5.2. Policy implications

Based on the outcomes of our investigation, we propose the following Policy implications:

Firstly, the user experience on the PCI platform must be enhanced. Evolutionary game analysis reveals that the platform's value lies in facilitating users' adoption of low-carbon lifestyles. However, limitations in application scenarios and inadequate incentives diminish its appeal [26]. Optimizing these scenarios and increasing incentives are crucial for encouraging broader participation.

Secondly, the introduction of low-carbon portfolio management policies is essential. Sole reliance on the PCI platform's incentives fails to universally promote low-carbon lifestyles, especially among the wealthy. Utilizing a mix of policy tools can provide a clear benefit to low-carbon behaviors [50]. Combining government, market, and corporate efforts, such as the PCI scheme, CCER system, and Ant Forest project, has proven effective in China [51]. These policies can balance the costs and benefits of carbon-intensive and low-carbon lifestyles, encouraging wider adoption for low-carbon lifestyle.

Thirdly, diversifying incentives for low-carbon behaviors is crucial. The current PCI system fails to motivate high-income individuals towards low-carbon lifestyles due to their economic comfort. Beyond economic incentives, the prestige associated with low-carbon living may appeal more to this group [52]. The PCI platform should integrate both financial and non-financial rewards, aiming to transform low-carbon living into a societal norm driven by personal values and habits rather than just financial incentives.

6. Conclusion

This study develops a tripartite evolutionary game model based on the PCI scheme. It aims to examine the dynamics and determinants of low-carbon behavior decisions among high-income individuals, low-income individuals, and the PCI platform, offering insights from a micro-perspective. The contributions of this research are manifold.

Firstly, the paper develops a research framework for the voluntary PCI scheme, supplementing studies on mandatory personal carbon trading policy. It accounts for disparities between income groups, categorizing PCI platform users into high and low-income brackets. A tripartite evolutionary game model—comprising high-income, low-income groups, and the PCI platform—is constructed to explore the PCI's micro-evolution mechanism, offering a novel viewpoint on individual carbon emission reduction.

Secondly, the paper uncovers participant behavior decisions within the PCI scheme. Low-income individuals are more inclined towards a low-carbon lifestyle, whereas high-income individuals show reluctance, albeit with potential for low-carbon preferences under specific circumstances. Additionally, the PCI platform demonstrates a restrained enthusiasm in advancing low-carbon policies. The research also explores carbon equity issues and the strategic role of the PCI platform based on these behavioral attitudes.

Thirdly, the paper examines the factors influencing PCI participants' low-carbon behavior decisions. It constructs utility functions for high-income, low-income groups, and the PCI platform, calculates the likelihood of selecting low-carbon strategies, and analyzes the impact of various factors on these strategies. Key findings include: (1) Greater carbon incentives correlate with a higher public inclination towards low-carbon lifestyles. (2) Rising costs of low-carbon living deter public preference for it, while higher costs for high-carbon living encourage low-carbon choices. (3) An increase in carbon incentives reduces the PCI platform's motivation to promote low-carbon incentives, as does an increase in fixed costs.

In summary, this research not only deciphers the operational dynamics of the PCI scheme but also enhances understanding of its multifaceted role, contributing to a more nuanced comprehension of the PCI scheme and offering policy recommendations for its enhancement.

Limitations and suggestions for future research

While this study contributes valuable insights into the PCI scheme and low-carbon decision-making, it acknowledges certain limitations due to its scope:

Firstly, this paper evaluates the PCI scheme's effectiveness by constructing an evolutionary game model. According to the research requirements, it divides participants into two categories: high-income and low-income, assuming uniform utility from low-carbon behaviors within these groups. This approach facilitates the study of decision-making among different socioeconomic groups under the PCI system, providing a reasonable hypothesis for the investigation. However, in reality, individuals' preferences for low-carbon lifestyles may vary significantly, influencing their behavior. Future studies could enhance the precision of this analysis by employing detailed data collection methods such as surveys and web scraping. This would allow for a more nuanced segmentation of participants in the PCI mechanism and a thorough empirical analysis of their low-carbon behavior decisions.

Secondly, this paper primarily examines the role of economic incentives in influencing the low-carbon behavior decisions of PCI participants. Yet, real-world decisions are also shaped by non-economic factors, such as social prestige and personal preferences, which were not extensively explored in this study. Future research could delve into these additional influences, offering a more comprehensive understanding of the factors driving public carbon decisions. Investigating these dimensions could enrich the discourse on the PCI scheme, providing deeper insights into how to effectively motivate a broader spectrum of the population towards low-carbon behaviors.

Data availability statement

No additional data are available.

CRediT authorship contribution statement

Zhen Wei: Writing – original draft, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Zhaolin Cheng:** Writing – review & editing, Validation, Supervision, Methodology. **Ke Wang:** Visualization, Investigation, Formal analysis. **Shengjie Zhou:** Writing – review & editing, Resources, Data curation.

Declaration of competing interest

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Appendix1

Proposition 1. The probability (VA1) of high-income individuals consistently practicing low-carbon Behavior is a decreasing function with respect to variable C1 and an increasing function with respect to variable Cf.

Proof. Firstly, $\partial VA1/\partial C1 = \frac{\mathrm{Log}\left[\frac{U11-Ux1}{U21-Uy1}\right]}{U11-U21-Ux1+Uy1}$. Given that the numerator is greater than zero and the denominator is less than zero, it means that $\partial VA1/\partial C1$ is negative. This indicates a negative correlation between the probability of high-income individuals consistently adopting low-carbon behavior (VA1) and the cost of low-carbon behavior (C1). This phenomenon can be observed in real-world scenarios; for instance, an increase in the cost of public transportation may lead to a decrease in the number of people opting to use it.

Secondly, $\partial VA1/\partial Cf = \frac{(-U11+U21+Ux1-Uy1)Log\left[\frac{U11-Ux1}{U21-Uy1}\right]}{(U11-U21-Ux1+Uy1)^2}$. Given that $(-U11+U21+Ux1-Uy1) > 0$ and $Log[(U11-Ux1)/(U21-Uy1)] > 0$, it means that $\partial VA1/\partial Cf > 0$. This indicates a positive correlation between the probability of high-income individuals consistently practicing low-carbon behavior (VA1) and the cost of non-low-carbon behavior (Cf). For instance, in real-world situations, the higher the cost of using personal vehicles for transportation, the more likely high-income individuals are to choose low-carbon behavior.

Appendix2

Proposition 2. The probability (VA1) of high-income individuals consistently practicing low-carbon Behavior is an increasing function with respect to variables E1 and E2.

Proof. Because $\partial VA1/\partial E1 = \frac{-U11+U21+Ux1-Uy1+(U21-Uy1)Log\left[\frac{U11-Ux1}{U21-Uy1}\right]}{(U11-U21-Ux1+Uy1)^2}$, and given that $Ux1-U11 > Uy1-U21$, it follows that $\left(-U11+U21+Ux1-Uy1+(U21-Uy1)Log\left[\frac{U11-Ux1}{U21-Uy1}\right]\right)$

>0. Therefore $\partial VA1/\partial E1>0$. Similarly, $\partial VA1/\partial E2 = \frac{U11-U21-Ux1+Uy1+(-U11+Ux1)Log\left[\frac{U11-Ux1}{U21-Uy1}\right]}{(U11-U21-Ux1+Uy1)^2} > 0$.Hence, VA1 is an increasing function of E1 and E2. In real life, this observation aligns with the tendency of the public to lean more towards low-carbon behavior as the level of benefits provided by the PCI platform increases.

Appendix3

Proposition 3. The probability (VB1) of the low-income individuals stably adopting low-carbon behavior is a decreasing function of C1 and an increasing function of Cf.

Proof. Because $\partial VB1/\partial C1 = \frac{Log\left[\frac{U12-Ux2}{U22-Uy2}\right]}{U12-U22-Ux2+Uy2}$'given that $U12-U22-Ux2+Uy2 < 0$, $Log\left[\frac{U12-Ux2}{U22-Uy2}\right] > 0$, hence, $\partial VB1/\partial C1<0$. Similarly, $\partial VB1/\partial Cf = \frac{(-U12+U22+Ux2-Uy2)Log\left[\frac{U12-Ux2}{U22-Uy2}\right]}{(U12-U22-Ux2+Uy2)^2} > 0$.

This implies that the probability (VB1) of low-income individuals persistently engaging in low-carbon behavior decreases as the cost of adopting such behavior (C1) increases. Conversely, this probability (VB1) increases as the cost associated with non-low-carbon behavior (Cf) rises.

Appendix4

Proposition 4. The probability (VB1) of low-income individuals consistently adopting low-carbon behavior is an increasing function with respect to E1 and E2.

Proof. Because $\partial VB1/\partial E1 = \frac{-U12+U22+Ux2-Uy2+(U22-Uy2)Log\left[\frac{U12-Ux2}{U22-Uy2}\right]}{(U12-U22-Ux2+Uy2)^2}$, given that $Ux2-U12 > Uy2-U22$, hence, $-U12+U22+Ux2-Uy2+(U22-Uy2)Log\left[\frac{U12-Ux2}{U22-Uy2}\right] >0$. Therefore, $\partial VB1/\partial E1>0$. Similarly, $\partial VB1/\partial E2 = \frac{U12-U22-Ux2+Uy2+(-U12+Ux2)Log\left[\frac{U12-Ux2}{U22-Uy2}\right]}{(U12-U22-Ux2+Uy2)^2} >0$. Thus, VB1 is an increasing function of E1 and E2.

Appendix5

Proposition 5. The probability of proactive low-carbon policies on the PCI platform, decreases with an increase in Cm and Cp1, and increases with an increase in Cp2 and Cn.

Proof. Based the formula 22 and 23, it can be inferred that $\partial VC1/\partial Cm = \frac{-1}{(Cp1-Cp2)} < 0$,$\partial VC1/\partial Cn = \frac{1}{(Cp1-Cp2)} > 0$,$\partial VC1/\partial Cp2 = \frac{Cp1-Cp2}{2} + \frac{1}{2}(Cm-Cn+Cp1-Cp2) > 0$,

$\partial VC1/\partial Cp1 = \frac{1}{2}(-Cp1+Cp2) + \frac{1}{2}(-2Cm+2Cn-Cp1+Cp2) < 0$. Hence, Proposition 5 is proved.

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