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Incentives for personal carbon account: An evolutionary game analysis on public-private-partnership reconstruction

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A B S T R A C T

This paper explores the effective incentive mechanisms for personal carbon accounts (PCAs) to reduce carbon emissions from household. First, a novel Public-Private Partnership for personal carbon accounts (PPP—PCAs) is constructed to discover the incentive effect of the integration of government mechanisms and market mechanisms on emissions reduction from household energy consumption. Second, the evolutionary game model among the government, financial institution, and consumer is presented to analyze the evolutionary stability strategies (ESS) of participants and verify the effectiveness of PPP-PCAs. Finally, taking Ant Forest as an example, we perform sensitivity analyses of key parameters and describe the optimal path to promote the development of PCAs. The numerical results show that government mechanisms, such as subsidies and carbon taxes have little effect on consumers' low-carbon decisions, without any other participants. When the private sectors, e.g., financial institutions, enterprises and carbon platforms are introduced into model, the market mechanisms can effectively promote the healthy and rapid development of PCAs. It finds that the government's low-carbon subsidies for financial institutions are the most effective, followed by the low-carbon benefits provided by the private sectors to consumers. The above conclusions can provide a theoretical basis and reference for the incentive mechanisms to promote the development of PCAs.

1. Introduction

With the rapid economy development, the carbon emissions generated by the household energy consumption have achieved much more attention (Chen et al., 2019). The data from the British Energy Spare Trust displays that, about a quarter of global carbon emissions come from households. In Europe, nearly 50% of GHG (Green House Gas) is directly emitted by households.[1] As one of fast emerging economies in the world, China is experiencing the quickly increasing carbon emissions from households, accounting for 30% of the total emissions. According to the statistics (Xu, 2019), the carbon emissions from Chinese households rose to 3795 million tons in 2016, with an increase of 433% over 1996. Hence, it is urgent to explore how to increase the carbon emission reductions in the household sector, which could be a beneficial supplement for China to achieve emissions reduction target of 2030.

The personal carbon budget has been a favorable policy by many governments to encourage their citizens to reduce carbon emission from their daily activities (Lövbrand and Stripple, 2011). In China, the similar personal carbon account projects (PCAs), such as CCER Trading Platform, Carbon Account 4.0 and Ant Forest, are proposed to improve the citizens' awareness of environmental protection. PCAs are a series of voluntary emission reduction internet platforms that are used to measure the carbon emission reductions of people's daily activities. And they will become people's trading accounts for carbon assets in the future. Take Ant Forest as an example, from April 2017 to April 2019, the consumption-side

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[1] The data are drawn from Kick the Habit: A UN Guide to Climate Neutrality, a book jointly published by UNEP and Earthprint in 2008. Please refer to the website: http://www.indiaenvironmentportal.org.in/content/252809/kick-the-habit-a-un-guide-to-climate-neutrality/.

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carbon emission reductions accumulated by the platform increased from 670 thousand tons to 8 million tons, with a growth rate of 1194%.[2] This indicates that PCAs have a significance to reduce carbon emissions. However, the limited public acceptability is a problem which cannot be ignored in PCAs. Statistics show that from April 2017 to April 2019, Ant Forest's users grew at the annual rate of 59.1% and 42.9%. The growth rate declined. There are many reasons for the above problem, one of which is insufficient incentive. Consumers, as the investors and producers of consumption-side carbon emission reductions, need to pay the low-carbon cost. And they want to pursue a balance between costs and benefits. However, the low-carbon benefit provided by Ant Forest is just the naming right of a tree, which is too abstract and small to attract more people to adopt low-carbon consumption behaviors and become its users. Moreover, fund constraint is also a reason for the slowdown in the number of users. The insufficient fund limits the functional development and incentive measures of Ant Forest. And Ant Forest may face more severe fund constraint with the phasing out subsidies. How to ensure that the Ant Forest can not only encourage more consumers to participate in the low-carbon consumption ranks, but also alleviate the faced fund constraint? This is the focus of the future reform of PCAs, and it is also the problem to be solved in this paper.

Essentially, the consumption-side emission reduction is not only a private commodity, but also a public good (Paloheimo and Salmi, 2013). An effective solution to the issues of fund constraint and insufficient incentives in public projects is Public-Private Partnership (PPP) (Osei-Kyei and Chan, 2015). By introducing the private sectors (e.g., financial institutions, enterprises and carbon platforms, etc.) to the existing relationship between government and consumers in PCAs, we construct a public-private partnership for personal carbon accounts (PPP—PCAs). It is a low-carbon incentive model with a transaction of the consumption-side carbon emission reductions. Consumers, as the producers, gain spiritual and material low-carbon benefits by adopting low-carbon consumption behaviors. Private sectors, as the investors, obtain consumption-side emission reductions to reach carbon neutrality by providing low-carbon benefits. Government, as the leader, guides and regulates the low-carbon behaviors of the consumers and the private sectors by implementing the policies of subsidies and carbon tax. The transaction between consumers and private sectors realizes the commercialization of the consumption-side carbon emission reductions, which will effectively motivate consumers' enthusiasm for low-carbon consumption. And the private sectors provide the low-carbon benefits to consumers as the material incentives, which will help ease the financial pressure on government. Therefore, in theory, the PPP-PCAs can alleviate the issue of fund constraint and insufficient incentive existing in PCAs. It is conducive to breaking the carbon lock-in effect existing in consumer groups.

The main contributions of this paper are presented as follows. First, a novel public-private partnership on personal carbon accounts (PPP—PCAs) is constructed, exploring the financial incentive effect of PPP on the consumption-side carbon emission reductions. Second, the evolutionary equilibrium strategies of these three heterogeneous entities in PPP-PCAs are proposed, discovering the impact of the integration of government and market mechanisms on the personal carbon credits market. Third, the optimal ways are provided to promote the development of PCAs from the perspectives of the government, the private sectors, and consumers, referring to the case of Ant Forest in China.

[2] The data come from Alipay (2017)/2018 Sustainability Report released by Ant Financial. Please refer to the website: https://gw.alipayobjects.com/os/basement_prod/725efb2d-8e1b-4c7f-b311-4fd81339cd16.pdf, 2019-05-20/2019-12-15.

There is given a brief introduction to the rest of the paper. Section 2 reviews some related research. Section 3 builds two game models. A game model explores the strategic choice of government and consumers in PCAs, and an evolutionary game model discusses the evolutionary stability strategy (ESS) of consumers, financial institutions and government in PPP-PCAs. Section 4 simulates the evolutionary game model and gives analyses of the numerical results. Research conclusions and recommendations are displayed in Section 5.

2. Literature review

The literature related to this study can be divided into three sections: carbon tax and carbon subsidy, household energy consumption and personal carbon credits, and evolutionary game theory.

2.1. Carbon tax and carbon subsidy

As the directly environmental regulatory mean to reduce carbon emissions, carbon tax is controversial internationally because of its positive and negative impacts on the country's energy and economy. At present, a large number of scholars use the modeling and empirical methods to study the impact of carbon taxes on the emission reduction strategies of energy-intensive enterprises such as maritime logistics, air passenger transportation, thermal power industry, and so on (Tiwari et al., 2020; An and Zhai, 2020; Shi et al., 2019). The research results show that carbon taxes are very effective in reducing carbon emissions. However, they will also have the negative impacts on the national economy, social welfare and industrial development (Shi et al., 2019), especially in countries with high energy-intensive industries. It can be seen that carbon tax has an unfavorable trade-off between economic growth and climate change mitigation. In this context, how to formulate the best rate of carbon tax to minimize its negative economic spillover effects has become a hot issue in the field of carbon tax research (Chan, 2020). In addition, some scholars propose to return the carbon tax to the household sector (Ojha et al., 2020). This can not only encourage energy enterprises to reduce emissions, but also reduce social welfare losses. However, the specific implementation plan and its feasibility and cost issues have not yet been resolved.

Compared with carbon tax, carbon subsidy has no negative impact on the country's economy and social welfare. Meanwhile, it has a significant incentive effect to transform enterprises' low-carbon technologies, improve social welfare and promote clean energy. For example, Yang et al. (2019a,b) set up three subsidy schemes: initial investment subsidies, electricity price subsidies, and carbon dioxide utilization subsidies, and discuss their effect on the investment benefits of China's Carbon Capture Utilization and Storage (CCUS) projects. An et al. (2018) design the government compensation mechanism to the PPP project of water environment treatment, after considering the economic benefits of urban water environment governance. Abrell et al. (2019) evaluate the influence of renewable energy (RE) subsidies on the short-term direct program costs of reducing $CO2$ emissions in Germany and Spain. However, carbon subsidies also have their own shortcomings, that is, they have weak incentives for enterprises with higher initial carbon emissions (Zhu et al., 2019). Compared with carbon taxes, carbon subsidies have lower efficiency of carbon emission reduction, which also makes the phenomenon where it is very rare that carbon subsidies are used alone as an environmental policy in the world.

In summary, carbon taxes and carbon subsidies have their own advantages and disadvantages in terms of carbon emission reduction efficiency, national economy and social welfare. Therefore, formulating a combined plan of carbon subsidies and carbon taxes has become a policy choice for more countries. The government can implement different environmental policies according to different subjects and the products' energy consumption. For example, subsidize consumers who buy low-carbon products, but impose a carbon tax on manufacturers who produce high-carbon products (Xu et al., 2020). Or levy taxes on energy sources with high emission to energy price ratio and subsidize energy sources with low emission to energy price ratio (Galinato and Yoder, 2010). Which strategy should be chosen? What is the basis for strategy selection? These are also the focus of current environmental policy research.

2.2. Household energy consumption and personal carbon credits

As the accelerating process of urbanization, the proportion of carbon emissions from household sector in total emissions is rising. How to effectively control household energy consumption has aroused widespread concern in academia. Carbon subsidies and carbon taxes are two traditional control measures that indirectly affect household energy consumption. As analyzed in the previous content, carbon subsidies have the incentive effects on household carbon emission reductions. For example, carbon subsidies can increase households' willingness to purchase pure electric vehicles (Dong et al., 2020). Compared with carbon subsidies, carbon taxes not only reduce household carbon emissions, but also causes the loss of average household welfare (Saelim, 2019). And the welfare loss of the poorest and middle-income households is much higher than that of the richest households (Okonkwo, 2020). However, whether it is a carbon tax or a carbon subsidy, they all indirectly affect the consumers' low-carbon behaviors and social welfare through influencing the pricing and investment strategies of energy-intensive companies. In other words, the current carbon subsidies and carbon taxes are directly used to control the production-side carbon emissions, not consumers.

Personal carbon credit, as a direct measure to the consumption-side carbon emission reduction, is gradually becoming another novel attempt for countries to reduce household carbon emissions. Personal carbon allowance, first proposed by the UK Environment Secretary David Miliband, is designed to allocate carbon quotas to individuals in order to control individual carbon emissions. However, due to the complexity of budgeting, metering, and allocation of personal carbon allowances, this schedule has not yet been implemented in the true sense. It is only applicable to individuals at the company level (Jagers et al., 2010). Personal carbon trading (PCT), as a secondary trading market for personal carbon allowances, can provide a national and international framework for the realization of carbon reductions in the medium to long term (Fawcett and Parag, 2010). The research on PCT focus on two aspects: one is its impact analysis on individual carbon emission reduction behaviors, and the other is its policy effect comparison with carbon tax and carbon subsidy. The first is the analysis of the impact of PCT on individual carbon emission reduction behaviors. Fan et al. (2016) design a personal carbon trading (PCT) model to discuss the carbon price level that affects consumers' purchase of hybrid electric vehicles (HEVs). The research results show that when the carbon allowance price is higher than the critical value, consumers tend to buy hybrid vehicles. Moreover, the critical carbon price of HEVs for over-emissions is lower than that of under-emissions. Under a specific PCT scheme, Li et al. (2018a,b) simulate the impact of carbon allowance prices on consumer energy use choices, and find that energy consumption under PCT is a nonlinear function of the allowance price. Secondly, scholars conduct a lot of research on the policy effects of different low-carbon measures on household carbon emission reduction. The results show that carbon tax, carbon subsidy and PCT all can effectively encourage individuals to adopt low-carbon behaviors, but their incentive effects are different. Taking private transportation as an example, PCT is more effective than carbon tax in incentivizing households to purchase clean energy vehicles (Li et al., 2019), but it is not as effective as government subsidy (Li et al., 2018a,b). These conclusions are also generally accepted, because the market always has an advantage in achieving effective resource allocation.

In summary, PCT is forward-looking. Existing research prove theoretically the effectiveness of PCT in guiding consumer low-carbon behaviors, but they have not been tested in practice. The number of practical studies on PCT cases is limited, and their focus is on consumers' motivation for participation. For example, based on the survey data ($N = 1190$) of China's first voluntary PCT program (Carbon General Preference System, CGSP) piloted in Guangdong Province, Tan et al. (2019) construct a structural equation model to find that the driving factors of public participation willingness in the CGSP mainly include the institutional technical environment, perceived usefulness and participation risks. It can be seen that the public acceptance of PCT is not satisfactory. Therefore, how to design an effective PCT program and ensure its public's acceptance is a question worth pondering.

2.3. Evolutionary game theory

Evolutionary game theory (EGT) is good at analyzing the interaction mechanism between different groups. Specifically, it is about how participants continuously adjust their strategies and achieve their own maximum benefits according to the decisions of other participants. This makes it have advantages in analyzing some complex socio-economic issues. Scholars apply it in many research fields, such as network sharing, public services, and green development. In network sharing field, Hammoud et al. (2020) combine the genetic model with EGT to explore the possible problems in forming federated clouds. In public services field, by constructing an evolutionary game model, Fang et al. (2020) explore the effective incentive measures for electric vehicle charging infrastructure construction from the perspectives of the government and consumers. Shan and Yang (2019) analyze the strategic choices of government, poor households, and photovoltaic firms in photovoltaic poverty alleviation.

Scholars also apply EGT to the analysis of strategic interaction among multi-stakeholders in green projects, and achieve rich results. Considering that governments at all levels have different interests in environmental governance, Sheng et al. (2020) construct an evolutionary game model among local governments, national governments and enterprises to study environmental regulatory policies suitable for China's conditions. Taking a two-level supply chain as an example, Sun et al. (2019) explore the optimal green investment strategies for suppliers and manufacturers under government incentives. Regarding the incentive mechanisms of the Public-Private-Partnership reconstruction of buildings, Yang et al. (2019a,b) establish an evolutionary game model between government and investors, revealing the incentive effect of the government mechanism on the green transformation and strategic changes of investment groups. Referring the retail electricity market, Zhu et al. (2020) dynamically simulate the strategic interactions among stakeholders in the Renewable Energy Portfolio Standard. Some scholars explore the impact of carbon taxes and carbon subsidies on the diffusion efficiency of green manufacturing technologies (Zhang et al., 2019).

Reviewing the existing literature, we draw the following conclusions. First, more studies have applied EGT to explore the low-carbon strategic interaction between government and enterprises. There are few analyses on the incentive mechanisms of consumers' low-carbon behaviors. Second, carbon subsidies and carbon taxes are almost directly used to control the production-side carbon emissions, thus indirectly affect the low-carbon decisions of other social sectors. Research on carbon subsidies for consumers, financial institutions and other participants is also of practical significance. Finally, personal carbon credit, as a real consumption-side carbon reduction measure, is still in the stage of theoretical analysis of feasibility. It is necessary to combine practical cases to construct an incentive mechanism for multi-participations to increase consumers' willingness to participate. At present, China is developing a variety of voluntary PCT programs, and Personal Carbon Accounts (PCAs) represented by Ant Forest is a successful case. However, there are many resistance factors affecting its development at this stage, one of which is insufficient funds. Essentially, PCAs are the projects about the public welfare. Their development requires both the leadership of government and the driving force of private fund. Therefore, the ultimate goal of this article is to establish a tripartite evolutionary game model involving government, consumers, and financial institutions under the framework of a PPP project to explore a financing incentive mechanism for multi-participation in PCAs. This study will fully reflect the internal impact mechanism of PCAs and its evolutionary trends. And it also provides an important reference for the government to develop the personal carbon account market.

3. Method analysis

3.1. Game model based on the PCAs

3.1.1. Basic assumptions

Before establishing the game model, we make the following assumptions based on the status of household energy consumption and PCAs in China.

Assumptions 1. All participants who are bounded rationality want to get the maximum utility (Zhao et al., 2020), and their strategies are mutually exclusive.

Assumption 2. Consumers have two strategies: low-carbon consumption and high-carbon consumption. It is supposed that the probability that they choose low-carbon consumption is $x \in [0, 1]$, then the probability that they choose high-carbon consumption is $1 - x$. When the consumers adopt low-carbon consumption, they could obtain government subsidies $S1$ and the physical and mental health benefits $E1$ brought by low-carbon behaviors and environmental improvements. Meanwhile, they need to pay the low-carbon costs $C1$. When the consumers adopt high-carbon consumption, they need to pay the carbon taxes T. In reality, the elderly generally has the weaker awareness of environmental protection, and the young have high valuations for the time cost and search cost of learning about new low-carbon products or services. This leads to the existence of the "carbon lock effect", e.g., $E1 - C1 < 0$.

Assumption 3. Government has two strategies: encouraging low-carbon consumption and no action. It is supposed that the probability that he encourages low-carbon consumption is $y \in [0, 1]$, then the probability that he has no action is $1 - y$. When government chooses to encourage low-carbon consumption, he needs to pay the encouragement costs $C2$. When government chooses no action, he need not to pay the encouragement cost. Whatever the government adopts, as long as the consumers adopt the low-carbon consumption, government could obtain the social benefits $E2$ brought by environmental improvement, resource conservation, and technological development. Once the consumers adopt the high-carbon consumption, government would need to pay the pollution treatment costs $C3$. Under the China's people-oriented governance concept, there is an interest relationship of $E2 - C2 - C3 > 0$.

Table 1 provides the basic variable symbols and their meanings mentioned in the Assumptions 2-3, and the consumers-government relationship in PCAs is specifically shown in Fig. 1.

3.1.2. Game model and model analysis

Furthermore, we obtain the benefits of government and consumers under different strategies in PCAs. The specific payoff matrix is shown in Table 2.

From the game matrix, we can get the following results. When $E1 - C1 + S1 > E1 - T$, there is no equilibrium strategy. When $E1 - C1 + S1 < E1 - T$, there is a Nash Equilibrium, i.e., consumers choose high-carbon consumption and government chooses to encourage low-carbon consumption. In other words, government pays for the public's high-carbon consumption behavior. There is no doubt that the Nash equilibrium is not a Pareto optimal state. It would lead to inefficient allocation of resources and a decline in social total welfare.

Therefore, under the assumption of $E1 - C1 + S1 > E1 - T$, it is necessary to introduce the private sectors to ensure that consumers still have positive returns without government involvement. Private sectors, as third-party incentive agents, share a part of the government's environmental investment responsibility through the carbon trading with low-carbon consumers. In this way, there is a possibility that consumers will choose low-carbon consumption without government participation. This is also the Pareto optimal state of the personal carbon account we want.

Based on this, we intend to build a Public-Private Partnership for personal carbon accounts (PPP—PCAs) to explore the multi-agents incentive model for consumers' low-carbon behaviors. A tripartite evolutionary game model among consumers, government, and financial institutions is constructed as follows to verify its effectiveness.

3.2. Evolutionary game model based on PPP-PCAs

3.2.1. Problem description and basic assumptions

Fig. 2 displays the consumers-government-private sectors relationship in PPP-PCAs in this article. We divide the main participants in personal carbon accounts (PCAs) into five categories: government, consumers, financial institutions, enterprises, and carbon platforms. Government is the leader, financial institutions are the builders of PCAs, and consumers are the owners of PCAs. Consumers can trade personal carbon credits with enterprises and carbon platforms through their PCAs. The carbon platforms here mainly include various consulting and trading agencies for personal carbon credits. It can be seen that it is crucial whether financial institutions establish PCAs. Therefore, we select financial institutions as representatives of the private sectors, and further make the following assumptions.

Assumption 4. Financial institutions have two strategies: providing PCAs and not providing PCAs. It is supposed that the probability that they provide PCAs is $z \in [0, 1]$, and the probability that they do not providing PCAs is $1 - z$. When financial institutions choose to provide PCAs, they could obtain government subsidies $S2$ and the future potential benefits $E3$ brought by the increased customer loyalty. Meanwhile, they also need to pay the business costs $C4$. When financial institutions choose not to provide PCAs, their payoff is zero.

Assumption 5. For government, when choosing to encourage the low-carbon consumption, he needs to pay additional incentive costs $\Delta C2$ for financial institutions who establish PCAs.

Assumption 6. For consumers, they have two credit accounts: a capital credit account and a carbon credit account. Purchasing low-

Table 1
Variables symbol descriptions in models.

Entities	Variables	Meaning
consumers	E_1	Physical and mental benefits from environmental improvements
	$S1$	Government subsidies
	$C1$	Low-carbon costs
	T	Carbon taxes
government	$C2$	Incentive costs for low-carbon consumers
	$C3$	Pollution treatment costs
	$E2$	Social benefits
	$\varDelta C2$	Additional incentive costs for financial institutions
Financial institutions	$S2$	Government subsidies
	$E3$	Future potential gains of providing PCAs
	$C4$	Business costs of providing PCAs
	B	Low-carbon benefits provided by private sectors
	p	Participation degree of low-carbon enterprises
	q	Participation degree of carbon platforms
	A	Carbon financial service ability

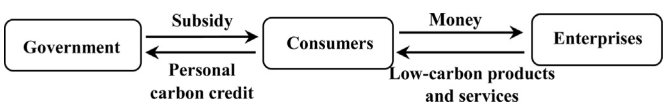

Fig. 1. The consumers-government relationship in PCAs.

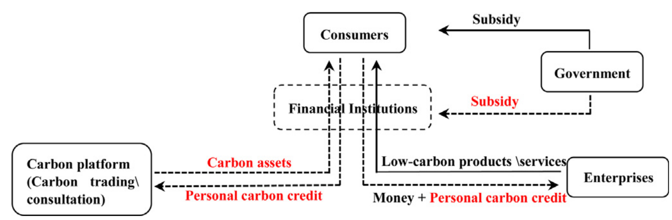

Fig. 2. The consumers-government-private sectors relationship in PPP-PCAs.

carbon products or services can increase consumers' carbon credits. When carbon credits increase to a certain standard, they can be used to exchange corresponding low-carbon benefits B. Here, the low-carbon benefits include the consumer financial benefits provided by the financial institutions, the low-carbon products provided by the enterprises or carbon assets provided by carbon platforms. Thus, the low-carbon benefits B depend not only on whether financial institutions establish PCAs, but also on the participation degree of enterprises $p \in (0,1)$ and the participation degree of carbon platforms $q \in (0,1)$. If we consider the participations of enterprises and carbon platforms as "inputs" and the low-carbon benefits as "outputs", then we can use the Cobb Douglas production function $B = Ap^e q^f$ to indicate the low-carbon benefits that consumers receive. Among them, A reflects the carbon financial service level of financial institutions, including carbon accounting technology and carbon financial innovation capabilities and so on.

The new parameter symbols and their meanings mentioned in the Assumptions 4-6 are shown in Table 1.

3.2.2. *Evolutionary game model*

We obtain the benefits of consumers, financial institutions and government under different strategies in PPP-PCAs. The specific payoff matrix is shown in Table 3. And the analysis of evolutionary stability strategy of three heterogeneous entities will be developed below.

There are the payoffs of consumers with different strategies. $U11$ is the fitness payoff of consumers choosing low-carbon consumption, $U12$ is the fitness payoff of consumers choosing high-carbon consumption, and $\overline{U}1$ is the average earning of consumers.

$$U11 = zB + yS1 + E1 - C1 \tag{3.1}$$

$$U12 = y(E1 - T) \tag{3.2}$$

$$\overline{U}1 = xU11 + (1-x)U12 = y(E1 - T) + x(T - C1)xyS1 + xzB \tag{3.3}$$

There are the payoffs of government with different strategies. $U21$ is the fitness payoff of government encouraging low-carbon consumption, $U22$ is the fitness payoff of government choosing no action, and $\overline{U}2$ is the average earning of government.

$$U21 = xC3 - z\varDelta C2 + E2 - C2 - C3 \tag{3.4}$$

$$U22 = xE2 \tag{3.5}$$

$$\overline{U}2 = yU21 + (1-y)U22 = xE2 - y(C2 + C3) + xyC3 - yz\varDelta C2 \tag{3.6}$$

There are the payoffs of financial institutions with different strategies. $U31$ is the fitness payoff of financial institutions providing PCAs, $U32$ is the fitness payoff of financial institutions not providing PCAs, and $\overline{U}3$ is the average earning of financial institutions.

Table 2
The payoff matrix among each game agent in the game model.

		Government	
		Encouraging low-carbon consumption	No action
Consumers	Low-carbon consumption	$(E1 - C1 + S1, E2 - C2)$	$(E1 - C1, \underline{E2})$
	High-carbon consumption	$(E1 - T, \underline{E2 - C2 - C3})$	$(\underline{0}, 0)$

Table 3
The payoff matrix among each game agent in the evolutionary game model.

				Financial institutions	
				Providing PCAs	Not providing PCAs
Consumers	Low-carbon consumption	Government	Encouraging low-carbon consumption	$E1-C1+S1+B$ $E2-C2-\varDelta C2$ $E3-C4+S2$	$E1-C1+S1$ $E2-C2$ 0
			No action	$E1-C1+B$ $E2$ $E3-C4$	$E1-C1$ $E2$ 0
	High-carbon consumption	Government	Encouraging low-carbon consumption	$E1-T$ $E2-C2-\varDelta C2-C3$ $S2-C4$	$E1-T$ $E2-C2-C3$ 0
			No action	0 0 $-C4$	0 0 0

$$U31 = yS2 + xE3 - C4 \quad (3.7)$$

$$U32 = 0 \quad (3.8)$$

$$\overline{U}3 = zU31 + (1-z)U32 = yzS2 + xzE3 - zC4 \quad (3.9)$$

3.2.3. Replicator dynamic analysis of each agent

Replication dynamic equation is a mechanism used to describe the dynamic strategy adjustment of the bounded rational game groups. Its basic principle is that the strategy that has a better-than-average result will be gradually adopted by more individuals in a bounded rational group, and eventually converge to a stable strategy without changing easily (Friedman, 1991). Therefore, we provide the replication dynamic equations for the strategic choices of consumers, governments, and financial institutions, as shown below.

$$L(x) = \frac{dx}{dt} = x(U11 - \overline{U}1) = x(1-x)[zB + y(S1 + T - E1) + E1 - C1] \quad (3.10)$$

$$M(y) = \frac{dy}{dt} = y(U21 - \overline{U}2) = y(1-y)[E2 - C2 - C3 - z\varDelta C2 - x(E2 - C3)] \quad (3.11)$$

$$N(z) = \frac{dz}{dt} = z(U31 - \overline{U}3) = z(1-z)[yS2 + xE3 - C4] \quad (3.12)$$

Referring to the stability theorem of replication dynamics equation, we solve the evolutionary stability strategies of consumers, governments, and financial institutions in PPP-PCAs. The related propositions and their proofs are shown below.

Proposition 1. (1) *If* $y = A1 = \frac{zB+E1-C1}{E1-S1-T}$, *then* $L(x) \equiv 0$. *That is, the probability of consumers choosing low-carbon consumption is any value between 0 and 1, and it will be at a steady state over time.*

(2) *If* $y \neq A1 = \frac{zB+E1-C1}{E1-S1-T}$ *and* $L(x) = 0$, *then the probability of consumers choosing low-carbon consumption* $x = 0$ *or* $x = 1$.

Proof.
The second derivative of formula (3.10) is:

$$L'(x) = (1-2x)[zB + y(S1 + T - E1) + E1 - C1] \quad (3.13)$$

By calculating formula (3.10), we can get that $x = 0, x = 1$ *and* $y = A1 = \frac{zB+E1-C1}{E1-S1-T}$. *Then, under the restraints of* $S1 + T > C1 > E1$, *the evolutionary stable strategies of the consumers' behavior of low-carbon consumption are obtained as follows. While* $zB + E1 - C1 > 0$, $A1 < 0$ (*i.e.*, $y > A1$). $L'_{x=1} < 0$ *and* $L'_{x=0} > 0$. *Therefore, the probability of consumers choosing low-carbon consumption* $x = 1$, *as shown in Fig. 3(a). While* $zB + E1 - C1 < 0$, $A1 > 0$. *The following two cases are discussed further.*

(1) *If* $1 > y > A1$, *then* $L'_{x=1} < 0$ *and* $L'_{x=0} > 0$. *The probability of consumers choosing low-carbon consumption* $x = 1$, *as shown in Fig. 3(a).*
(2) *If* $0 < y < A1$, *then* $L'_{x=1} > 0$ *and* $L'_{x=0} < 0$. *The probability of consumers choosing low-carbon consumption* $x = 0$, *as shown in Fig. 3(b).*

Proposition 2. (1) *If* $z = A2 = \frac{C2+C3-E2+x(E2-C3)}{-\varDelta C2}$, *then* $M(y) \equiv 0$. *That is, the probability of government encouraging low-carbon consumption is any value between 0 and 1, and it will be at a steady state over time.*

(2) *If* $z \neq A2 = \frac{C2+C3-E2+x(E2-C3)}{-\varDelta C2}$ *and* $M(y) = 0$, *then the probability of government encouraging low-carbon consumption* $y = 0$ *or* $y = 1$.

Proof.
The second derivative of formula (3.11) is:

$$M'(y) = (1-2y)[E2 - C2 - C3 - z\varDelta C2 - x(E2 - C3)] \quad (3.14)$$

By calculating formula (3.11), we can get that $y = 0, y = 1$ *and* $z = A2 = \frac{C2+C3-E2+x(E2-C3)}{-\varDelta C2}$. *Then, under the restraints of* $E2 > C2 + C3$, *the evolutionary stable strategies of the government's behavior of*

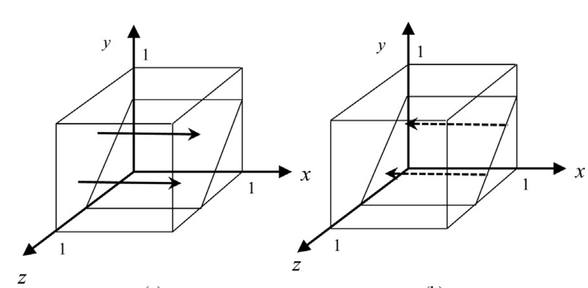

Fig. 3. Replicator dynamic phase diagram of consumers.

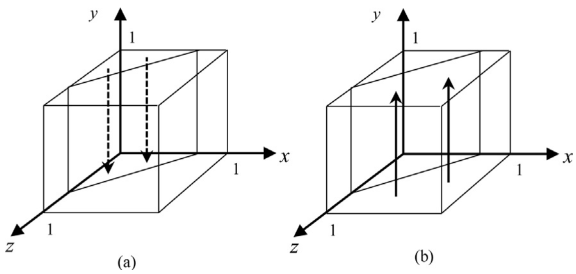

Fig. 4. Replicator dynamic phase diagram of government.

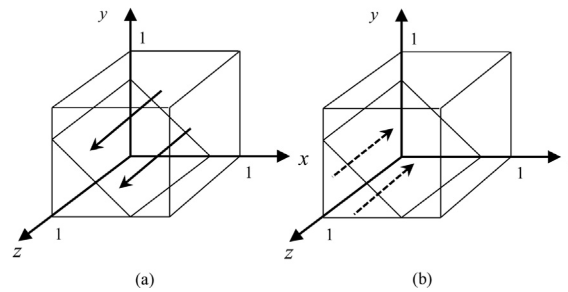

Fig. 5. Replicator dynamic phase diagram of financial institutions.

encouraging low-carbon consumption are obtained as follows. While $E2 - C2 - C3 < x(E2 - C3), A2 < 0$ *(i.e.,* $z > A2$*).* $M'_{y=1} > 0$ *and* $M'_{y=0} < 0$*. The probability of government encouraging low-carbon consumption* $y = 0$*, as shown in Fig. 4(a). While* $E2 - C2 - C3 > x(E2 - C3)$*,* $A2 > 0$*. The following two cases are discussed further.*

(1) *If* $1 > z > A2$*, then* $M'_{y=1} > 0$ *and* $M'_{y=0} < 0$*. The probability of government encouraging low-carbon consumption* $y = 0$*, as shown in Fig. 4(a).*
(2) *If* $0 < z < A2$*, then* $M'_{y=1} < 0$ *and* $M'_{y=0} > 0$*. The probability of government encouraging low-carbon consumption* $y = 1$*, as shown in Fig. 4(b).*

Proposition 3. (1) *If* $x = A3 = \frac{C4 - yS2}{E3}$*, then* $N(z) \equiv 0$*. The probability of financial institutions providing PCAs is any value between 0 and 1, and it will be at a steady state over time.*

(2) *If* $x \neq A3 = \frac{C4 - yS2}{E3}$ *and* $N(z) = 0$*, then the probability of financial institutions providing PCAs* $z = 0$ *or* $z = 1$*.*

Proof.

The second derivative of formula (3.12) is:

$$N'(z) = (1 - 2z)[yS2 + xE3 - C4] \tag{3.15}$$

By calculating formula (3.12), we can get that $z = 0$*,* $z = 1$ *and* $x = A3 = \frac{C4 - yS2}{E3}$*. Then, the evolutionary stable strategies of the financial institutions' behavior of providing PCAs are obtained as follows. While* $C4 < yS2$*,* $A3 < 0$ *(i.e.,* $x > A3$*).* $N'_{z=1} < 0$ *and* $N'_{z=0} > 0$*. Hence, the probability of financial institutions providing PCAs* $z = 1$*, as shown in Fig. 5(a). While* $C4 > yS2$*,* $A3 > 0$*. The following two cases are discussed further.*

(1) *If* $1 > x > A3$*, then* $N'_{z=1} < 0$ *and* $N'_{z=0} > 0$*. The probability of financial institutions providing PCAs* $z = 1$*, as shown in Fig. 5(a).*
(2) *If* $0 < x < A3$*, then* $N'_{z=1} > 0$ *and* $N'_{z=0} < 0$*. The probability of financial institutions providing PCAs* $z = 0$*, as shown in Fig. 5(b).*

In the evolutionary game model, y and z are correlated. That is, there is an interaction between the government's strategic selection and the financial institutions' strategic selection. Likewise, x is related to y and z. Conclusively, the strategic choices of consumers, governments and financial institutions influence each other. Evolutionary stability strategy is a tripartite game result.

3.2.4. Stability analyses of replicator dynamic system

Through the above analyses, we understand how a single subject could dynamically adjust his own equilibrium strategy in different situations. Next, by combining formulas (3.10), (3.11), and (3.12) into a replication dynamic system (I), we analyze the dynamic strategy adjustments of consumers, governments, and financial institutions simultaneously.

Proposition 4. *Under the restraints of* $T + S1 > C1 > E1$ *and* $E2 > C2 + C3$*,* $(1, 0, 1)$ *is the only ESS of the tripartite evolutionary game model.*

Proof.

When formulas (3.10), (3.11), (3.12) are equal to zero at the same time, the replication dynamic system (I) has nine equilibrium points, i.e., (1,1,1), (1,1,0), (1,0,1), (0,1,1), (1,0,0), (0,1,0), (0,0,1), (0,0,0), *and* (x^*, y^*, z^*)*. And if and only if* $x^* \in [0, 1]$*,* $y^* \in [0, 1]$ *and* $z^* \in [0, 1]$*,* (x^*, y^*, z^*) *is an equilibrium point.*

$$x^* = \frac{-\Delta C2[C4(E1 - S1 - T) + S2(C1 - E1)] + S2B(E2 - C2 - C3)}{S2B(E2 - C3) - E3(E1 - S1 - T)\Delta C2} \tag{3.16}$$

$$y^* = \frac{(E2 - C2 - C3)BE3 + \Delta C2(E1 - C1)E3 - C4B(E2 - C3)}{\Delta C2(E1 - S1 - T)E3 - S2B(E2 - C3)} \tag{3.17}$$

$$z^* = \frac{(E2 - C3)[C4(E1 - S1 - T) - S2(E1 - C1)] - E3(E2 - C2 - C3)(E1 - S1 - T)}{(E2 - C3)S2B - \Delta C2E3(E1 - S1 - T)} \tag{3.18}$$

However, not all equilibrium points are ESS. Jacobian matrix, composed of first-order partial derivatives, can reflect an optimal linear approximation of a differentiable equation and a given point. Therefore, according to the eigenvalues of the Jacobian matrix, we can judge whether an equilibrium point is an ESS. And here is the Jacobian matrix J_1 *of the replication dynamic system (I).*

$$J1=\begin{bmatrix}\frac{\partial L(x)}{\partial x} & \frac{\partial L(x)}{\partial y} & \frac{\partial L(x)}{\partial z}\\ \frac{\partial M(y)}{\partial x} & \frac{\partial M(y)}{\partial y} & \frac{\partial M(y)}{\partial z}\\ \frac{\partial N(z)}{\partial x} & \frac{\partial N(z)}{\partial y} & \frac{\partial N(z)}{\partial z}\end{bmatrix}=\begin{bmatrix}\Pi 11 & \Pi 12 & \Pi 13\\ \Pi 21 & \Pi 22 & \Pi 23\\ \Pi 31 & \Pi 32 & \Pi 33\end{bmatrix}$$

where

$$\Pi 11=(1-2x)[zB+y(S1+T-E1)+E1-C1] \quad (3.19)$$

$$\Pi 12=x(1-x)(S1+T-E1) \quad (3.20)$$

$$\Pi 13=x(1-x)B \quad (3.21)$$

$$\Pi 21=y(1-y)(C3-E2) \quad (3.22)$$

$$\Pi 22=(1-2y)[E2-C2-C3-z\Delta C2-x(E2-C3)] \quad (3.23)$$

$$\Pi 23=-y(1-y)\Delta C2 \quad (3.24)$$

$$\Pi 31=z(1-z)E3 \quad (3.25)$$

$$\Pi 32=z(1-z)S2 \quad (3.26)$$

$$\Pi 33=(1-2z)[yS2+xE3-C4] \quad (3.27)$$

According to the signs of the eigenvalues of the Jacobian matrix J_1 after being substituted into an equilibrium point, we can judge whether the point is an ESS (Sandholm, 2010). If and only if the three eigenvalues are all negative, this point is an ESS. If there exists a positive eigenvalue, this point is an unstable point. If there exists an eigenvalue of 0, this point is a saddle point. The local stability analysis of the replication dynamic system (I) based on the Jacobian matrix J_1 is shown in Table 4.

From the results of stability analyses, we can know that there exists the only one ESS (1,0,1), if and only if $B+E1>C1$ and $E3>C4$. At this time, financial institutions would provide PCAs and consumers would actively choose low-carbon consumption, even if government is absent. This is the Pareto optimal state. That is to say, the personal carbon account market will automatically reach the Pareto optimal state over time, when the following conditions are met. For financial institutions who provide PCAs, future potential gains of PCAs is greater than their business costs. For consumers who adopt low-carbon consumption, the sum of low-carbon benefits provided by private sectors and physical and mental benefits is greater than the low-carbon costs.

Therefore, it can be seen that the entry of private sectors can indeed increase consumers' enthusiasm for low-carbon consumption. And Public-Private Partnership for personal carbon accounts (PPP–PCAs) effectively solve the issues of fund constraint and insufficient incentive that currently exist in the development of PCAs.

Table 5
Initial values of the parameters.

$E1$	$C1$	$S1$	T	$E2$	$C2$	$C3$	$\Delta C2$	$E3$	$S2$	$C4$	A	$p\backslash q$	$e\backslash f$
0.5	10	5	0.66	4	2	1	0.6	2	1	1.6	5	0.5	0.5

4. Numerical results

Using CCER Trading Platform and Ant Forest as examples, we verify how key parameters affect the evolutionary stability strategies of consumers, government and financial institutions. These could theoretically be used for developing the PCAs in China and even other countries.

4.1. Case description and parameter settings

In Ant Forest, users could get green energy by taking some low-carbon behaviors. The behaviors include green travel (e.g., walking, public transportation, subways and bicycles, etc.), and paper-reduction behaviors (e.g., paperless reading, environmental protection cups and green takeout, etc.). The conversion between low-carbon behaviors and green energy adopts the scientific algorithm of carbon emission reduction provided by CCER Trading Platform.

The parameters about consumers are set as follows. Since the establishment of Ant Forest, carbon emission reductions have totaled 7.92 million tons with an annual average of 2.94 million tons. The benefits of low-carbon behaviors are equivalent to the carbon taxes paid by high-carbon consumers. Therefore, based on the certified emission reductions price of 25 CNY/ton, the carbon taxes paid by high-carbon consumers T is 66 million CNY/year. Eco-friendly materials will increase the outlay cost, and green travel will increase the time cost and search cost. Hence, it is assumed that the low-carbon costs paid by low-carbon consumers $C1$ are 800 million CNY/year. The government subsidies for low-carbon consumers $S1$ are 750 million CNY/year. And we suppose that the value of consumers' physical and mental health brought by the environmental improvement $E1$ is 50 million CNY/year.

The parameters about government are set as follows. For implementing low-carbon incentive policies, government needs to pay for policy formulation and promulgation. The incentive cost paid by the government for low-carbon consumers $C2$ totals about 200 million CNY/year. The additional incentive cost paid by the government for private sectors $\Delta C2$ is 60 million CNY/year. And the pollution treatment costs paid by government $C3$ is 100 million CNY/year. The benefits brought by Ant Forest $E2$ mainly include

Table 4
Stability analyses among consumers, government and financial institutions.

Equilibrium points	Eigenvalues	Symbol of eigenvalues	Local stability	Stability condition
$(0,1,1)$	$B+S1+T-C1,\ -[-\Delta C2+E2-C2-C3],\ -[S2-C4]$	(+,N,N)	Unstable point	–
$(1,0,1)$	$-[B+E1-C1],\ -[C2+\Delta C2],\ -[E3-C4]$	(N,-,N)	ESS	$B+E1>C1_{\text{and}}E3>C4$
$(1,1,0)$	$-[S1+T-C1],\ -[-C2],S2+E3-C4$	(-,+,N)	Unstable point	–
$(1,0,0)$	$-[E1-C1],\ -C2,E3-C4$	(+,-,N)	Unstable point	–
$(0,1,0)$	$S1+T-C1,\ -[E2-C2-C3],S2-C4$	(+,-,N)	Unstable point	–
$(0,0,1)$	$B+E1-C1,\ -(C2+\Delta C2)+E2-C3,\ -[-C4]$	(N,N,+)	Unstable point	–
$(0,0,0)$	$E1-C1,E2-C2-C3,\ -C4$	(-,+,-)	Unstable point	–
$(1,1,1)$	$-[B+S1+T-C1],\ -[-\Delta C2-C2],\ -[S2+E3-C4]$	(+,-,N)	Unstable point	–
(x^*,y^*,z^*)	$0,0,0$	(0,0,0)	Saddle point	–

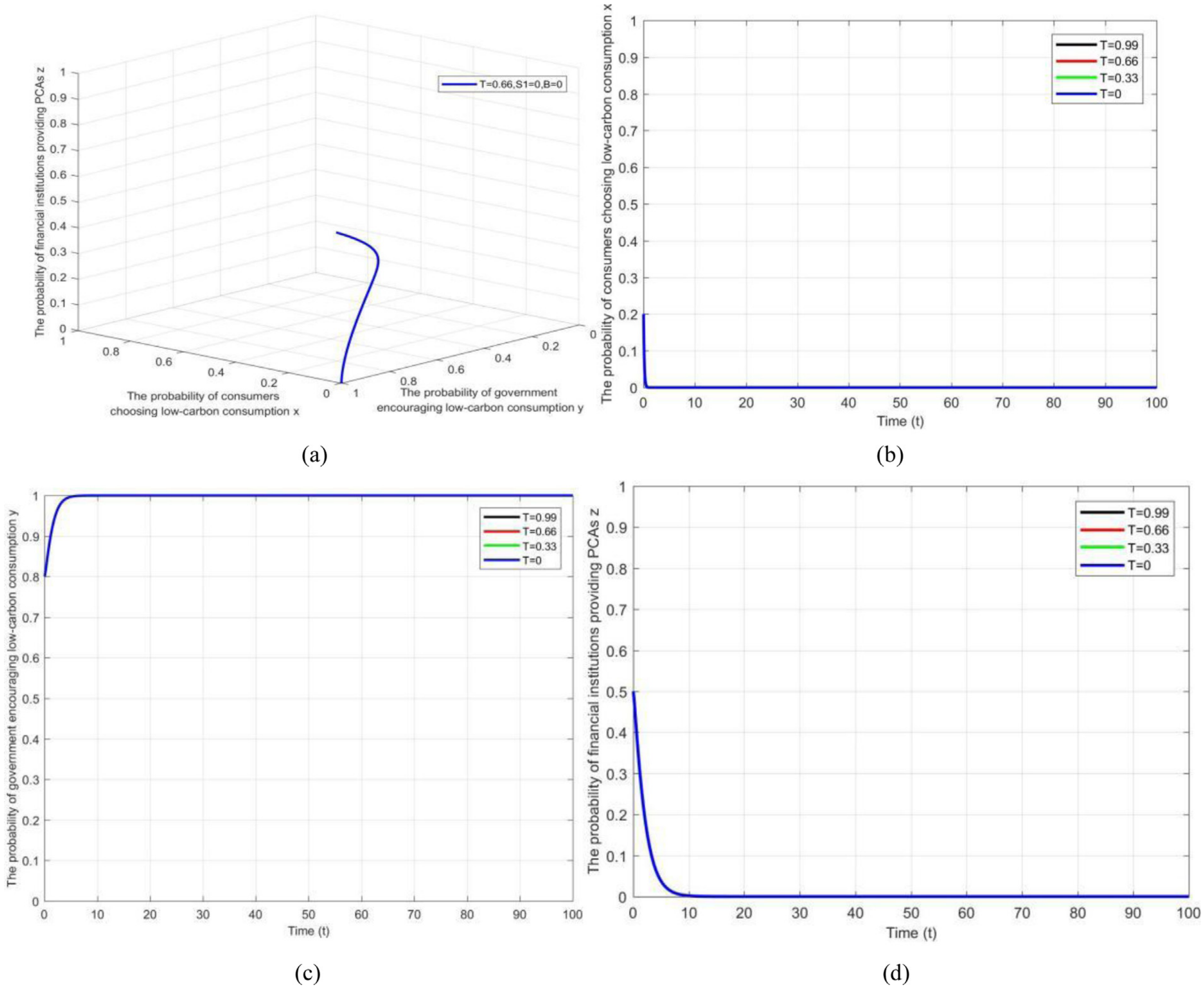

Fig. 6. The influence of carbon taxes T on the system.

ecological benefits and social benefits, totals about 400 million CNY/year.

The parameters about financial institutions are set as follows. Referring to Alipay 2017/2018 Sustainability Report and other related reports, we evaluate that the future potential gains obtained by Ant Forest $E3$ is 200 million CNY/year, and the government subsidy $S2$ is 100 million CNY/year. According to the financial industry's general profit margin of 20%, the business cost of Ant Forest $C4$ is set at 160 million CNY/year. The low-carbon benefits provided by private sectors $B = Ap^e q^f$. At present, the personal carbon market in China is still in the incubation stage. Therefore, it is assumed that $A = 5$, $p = q = 0.5$, $e = f = 0.5$.

Considering the weak low-carbon awareness of consumers, the positive attitude of government to encourage low-carbon consumption, and the relatively backward personal carbon credit system, we set the initial probabilities of the three entities' strategic choices as follows. The probability of consumers adopting low-carbon consumption $x = 0.2$. The probability of government encouraging low-carbon consumption $y = 0.7$. And the probability of financial institutions providing PCAs $z = 0.5$. The specific parameter settings are shown in Table 5.

4.2. Simulation

4.2.1. The impact of carbon taxes T on evolutionary results

Under the premise of $S1 = 0$ and $B = 0$, we set $T = 0.99, 0.66, 0.33, 0$ respectively to reflect the impact of carbon taxes T on evolutionary paths and results in Fig. 6.

As we can see, no matter what value T is, the evolutionary result does not change over time. That is, the probability of consumers choosing low-carbon consumption $x = 0$, the probability of government encouraging low-carbon consumption $y = 1$, and the probability of financial institutions providing PCAs $z = 0$. The above results are consistent with the equilibrium result of the game between consumers and government in Chapter 3.1. So, when there is only regulation policy, or the regulatory effort is small, the personal carbon account market hardly reaches the Pareto optimal state (1, 0, 1).

4.2.2. The impact of government subsidies for low-carbon consumers $S1$ on evolutionary results

With the increasing emphasis on the ecological environment, government has begun to implement the subsidy policies for low-carbon consumption on the basis of carbon taxes. Therefore, under the premise of $T = 0.66$, $B = 0$, we set $S1 = 10, 7.5, 5, 2.5$ respectively to reflect the impact of government subsidies for low-carbon consumers $S1$ on evolutionary paths and results in Fig. 7.

Fig. 7(a) shows that the evolutionary path presents a loop. This means that the behavior strategies of the three participants are quite unstable. Fig. 7(b), (c) and (d) specifically reflect the impacts of $S1$ on the strategic choice of consumers, government and financial institutions. The larger $S1$, the more stable the evolution

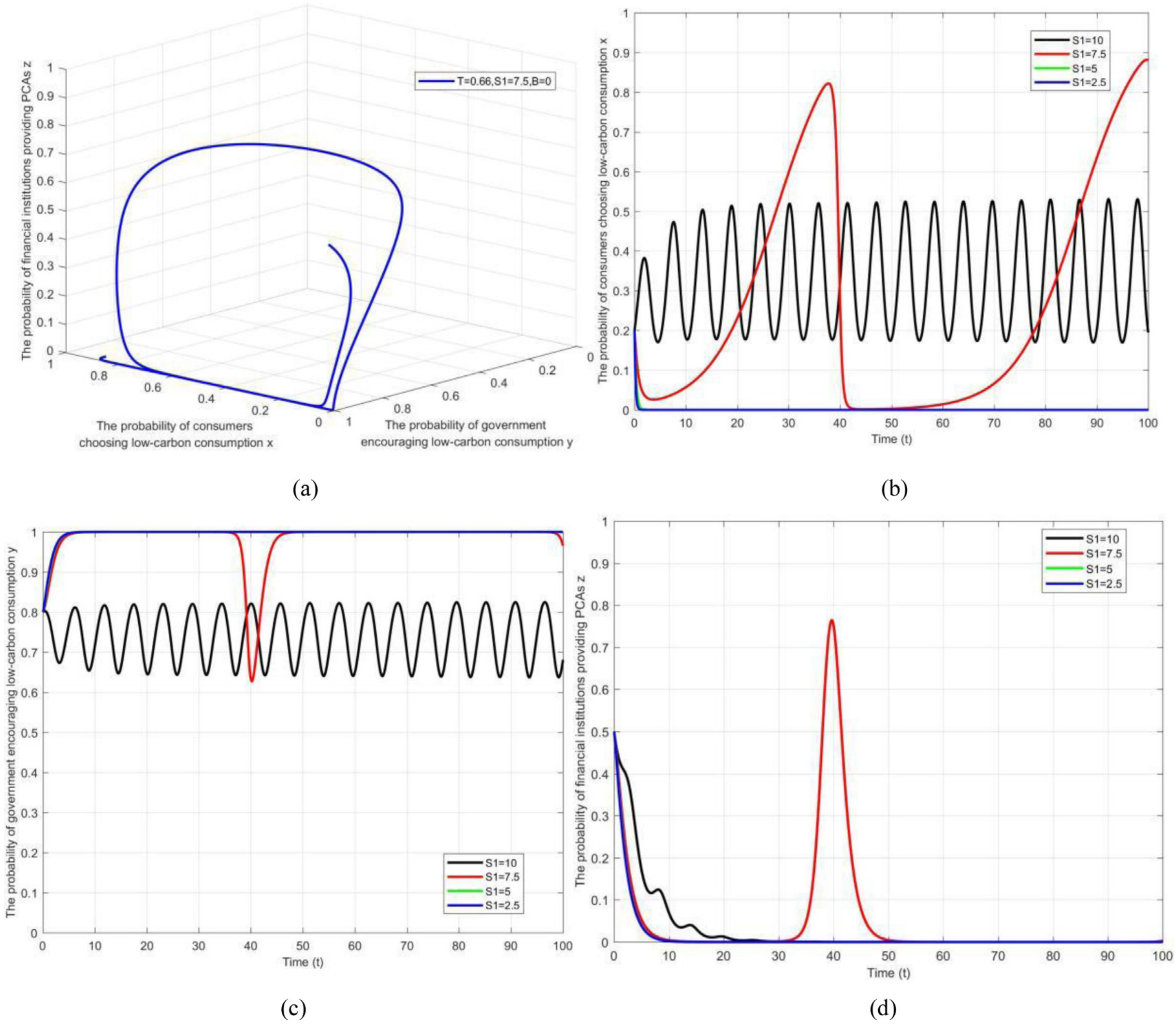

Fig. 7. The influence of government subsidies $S1$ for low-carbon consumers on the system.

process. When $S1 = 10$, the probability of consumers choosing low-carbon consumption x will fluctuate within the range [0.17, 0.53] as shown in Fig. 7(b), the probability of government encouraging low-carbon consumption y will fluctuate within the range [0.64, 0.82] as shown in Fig. 7(c), the probability of financial institutions providing PCAs z will converge to 0 as shown in Fig. 7(d).

The above results indicate that it is not sustainable for government to pay for consumers' high-carbon consumption. Next, we would simulate the impact of low-carbon benefits provided by the private sectors on system evolutionary results with $B \neq 0$.

4.2.3. The impact of low-carbon benefits from financial institutions A on evolutionary results

Under the premise of $T = 0.66$ and $S1 = 7.5$, we set $A = 20, 15, 10, 5$ respectively to analyze the impact of low-carbon benefits from financial institutions A on evolutionary paths and results in Fig. 8.

Fig. 8 (a) shows that the value of A has an effect on both the evolutionary path and the evolutionary result. In Fig. 8(b), (c) and (d), it is shown specifically that as A increases, the probability of consumers choosing low-carbon consumption x increases, the probability of government encouraging low-carbon consumption y decreases, and the probability of financial institutions providing PCA z increases. When A increases to 20, the ESS evolves into Pareto optimal state (1, 0, 1). What's more, the larger the value of A, the more stable the evolutionary paths over time. This indicates that low-carbon benefits from financial institutions have an active effect on the market reaching to the Pareto optimal state (1, 0, 1).

4.2.4. The impact of low-carbon benefits from enterprises/carbon platforms p/q on evolutionary results

Under the premise of $T = 0.66, S1 = 7.5$ and $A = 15$, we set $p = 1, 0.7, 0.4, 0.1$ respectively to analyze the impact of low-carbon benefits from enterprises p on evolutionary paths and results in Fig. 9.

Fig. 9(a) reflects that the value of p has an effect on the evolutionary path and result. As shown in Fig. 9(b), (c) and (d), with p increasing, the probability of consumers choosing low-carbon consumption x increases, the probability of government encouraging low-carbon consumption y decreases, and the probability of financial institutions providing PCAs z increases. When p increases to 1, the ESS evolves into Pareto optimal state (1, 0, 1). Additionally, the greater the value of p is, the more stable the evolution path is. Thus, low-carbon benefits from enterprises have an active impact on the market reaching to the Pareto optimal state (1, 0, 1).

The Cobb Douglas function $B = Ap^e q^f$ reflects that the low-

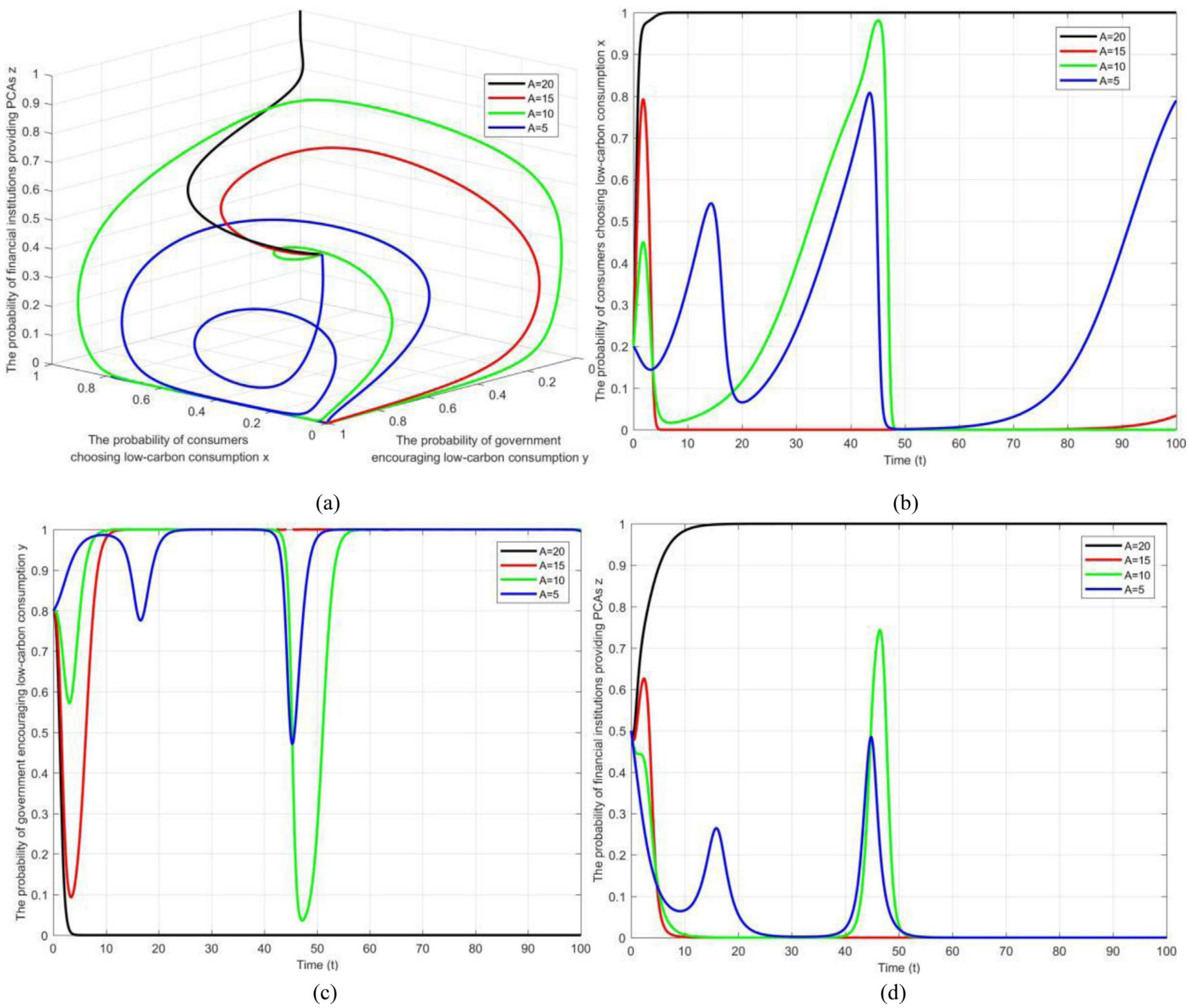

Fig. 8. The influence of low-carbon benefits from financial institutions *A* on the system.

carbon benefits from carbon platforms q have the same impact on the evolution results as the low-carbon benefits from enterprises p. Therefore, we decide here to omit the analysis of the impact of the low-carbon benefits from carbon platforms on the evolution results.

4.2.5. The impact of government subsidies $S2$ for financial institutions on evolutionary results

Under the premise of $T = 0.66$ and $S1 = 7.5$, we set $S2 = 2.5, 2, 1.5, 1$ respectively to analyze the impact of government subsidies for financial institutions $S2$ on evolutionary paths and results in Fig. 10.

Fig. 10(a) expresses the value of $S2$ has an effect on both the evolutionary path and the evolutionary result. As we can see, there exists a threshold $S2^*$ $(1.5 < S2^* < 2)$. When $S2 < S2^*$, as time goes by, the ESS finally evolves to (0, 1, 0). And the smaller the $S2$ is, the faster the evolutionary rate is. When $S2 = 2$, as time goes by, the ESS finally evolves to (1,0,1). When $S2 = 2.5$, the ESS finally evolves to (0.87, 0, 1) over time. Further, in Fig. 10(b), when $S2 = 2$, the probability of consumers choosing low-carbon consumption $x = 1$. But its evolutionary path is unstable. When $S2 = 2.5$, the probability of consumers choosing low-carbon consumption $x = 0.87$. And its evolutionary path is stable. In Fig. 10(c), when $S2 > S2^*$, the larger $S2$, the more stable the probability of government encouraging low-carbon consumption. Similarly, in Fig. 10(d), when $S2 > S2^*$, the larger $S2$, the more stable the probability of financial institutions providing PCAs.

Therefore, considering the comprehensive influence on the evolutionary result and path, we believe that government subsidies for financial institutions are beneficial for market to reach the Pareto optimal state (1, 0, 1).

5. Conclusions and recommendations

Considering the issues of fund constraint and insufficient incentive that currently exist in the development of personal carbon accounts (PCAs), we introduce private sectors to construct a novel Public-Private Partnership for personal carbon accounts (PPP–PCAs). It highlights the incentive effect of the integration of government mechanisms and market mechanisms on emissions reduction from household energy consumption. Through the numerical results of the tripartite evolutionary game, we find that government mechanisms, such as subsidies and carbon taxes have little effect on consumers' low-carbon decisions, without any other participants. When the private sectors, e.g., financial institutions, enterprises and carbon platforms are introduced into model, the market mechanisms can effectively promote the healthy and rapid development of PCAs. It finds that the government's low-carbon

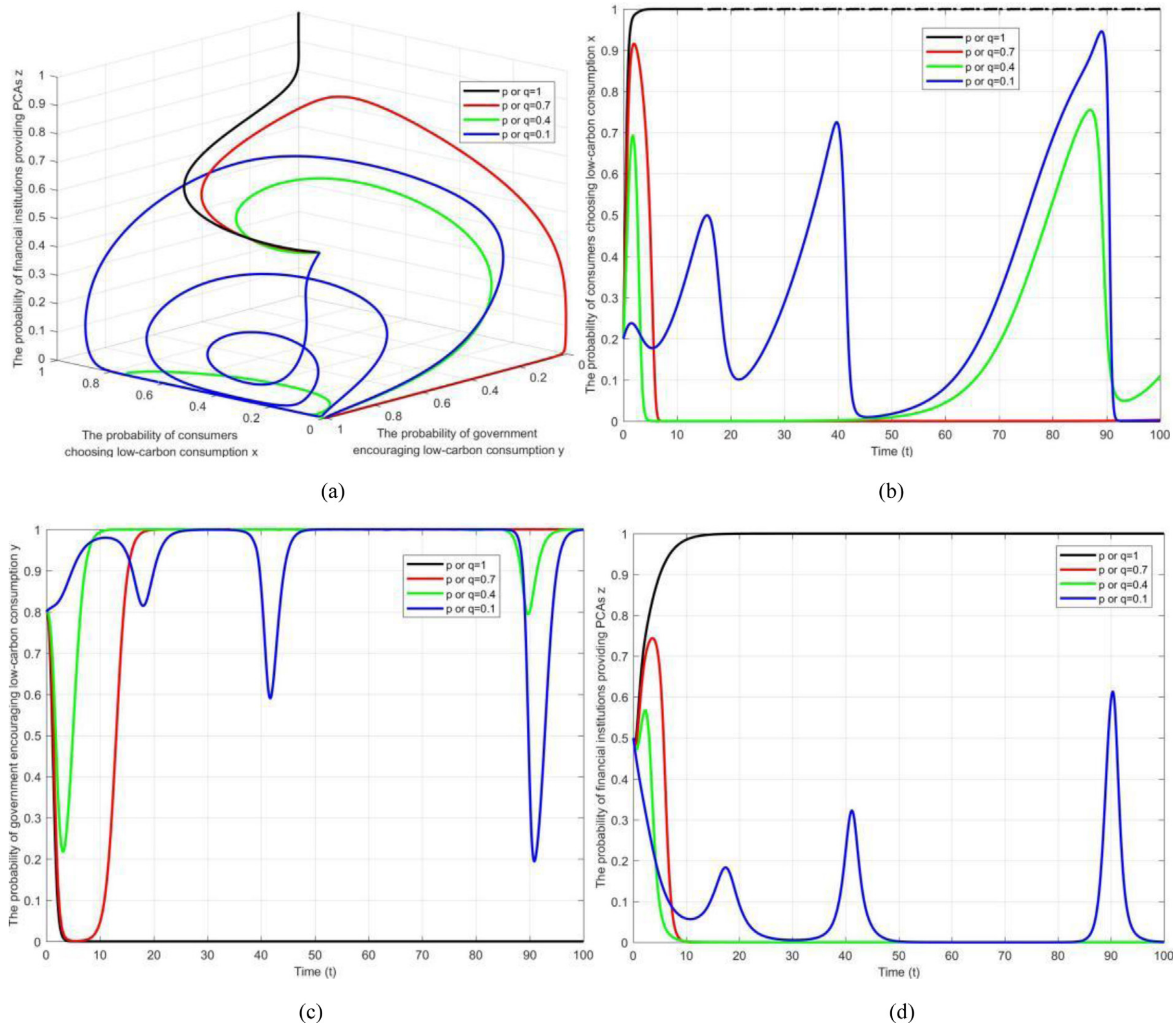

Fig. 9. The influence of low-carbon benefits from enterprises/carbon platforms p/q on the system.

subsidies for financial institutions are the most effective, followed by the low-carbon benefits provided by the private sectors to consumers. Based on these conclusions, the following recommendations are made.

First, it is necessary to combine the market incentive mechanisms with the government regulation mechanisms for carbon emissions reduction from household energy consumption. Currently, in developed or developing countries, the carbon emission governance for household energy consumption are mainly dominated by government, such as carbon taxes and carbon quotas (Bristow et al., 2010). Hence, it needs to lower the threshold for enterprises to enter the personal carbon trading market. These enterprises are encouraged to take innovations to motivate households to reduce carbon emissions voluntarily. The government functions are to take supervision and supportive measures. It is helpful to follow the households' market behavior to guide the consumers' emission reductions.

Second, the market incentive mechanisms for PCAs can be designed on the commodity trading credit between private sectors and households. The reason is that the direct traders with households, such as the sellers and enterprises, especially financial institutions, can obtain carbon emission data from household energy consumption with a cheaper, more accurate and more convenient way. They can clearly understand the consumers' trading habit. Personal carbon trading (PCT) proposed by the British government in 2006 is the earliest market incentive mechanism for personal carbon credits in the world, but it has not been able to operate normally until now (Jagers et al., 2010). Ant Forest, established in 2016, has become the world's largest personal carbon accounts with a normal operating model.

Third, the government incentive mechanisms for PCAs should encourage more heterogeneous private sectors to enter the carbon trade market. Currently, some countries provide subsidies for new energy vehicles (Ji et al., 2019). But they focus on the producers, such as energy and electricity. Low-carbon subsidies for the financial industries also need to be increased to promote the construction and improvement of personal carbon credit systems. Then, much more heterogeneous private sectors jointly providing households with low-carbon consumption services, and commoditizing carbon emission reductions can increase the low-carbon benefits for low-carbon households. Hence, establishing the carbon financial supervision system gradually would be an important guarantee for the healthy development of the PCAs in the future.

However, this paper divides the private sectors into three categories: financial institutions, enterprises, and carbon platforms. And it uses the Cobb Douglas function to express the low-carbon

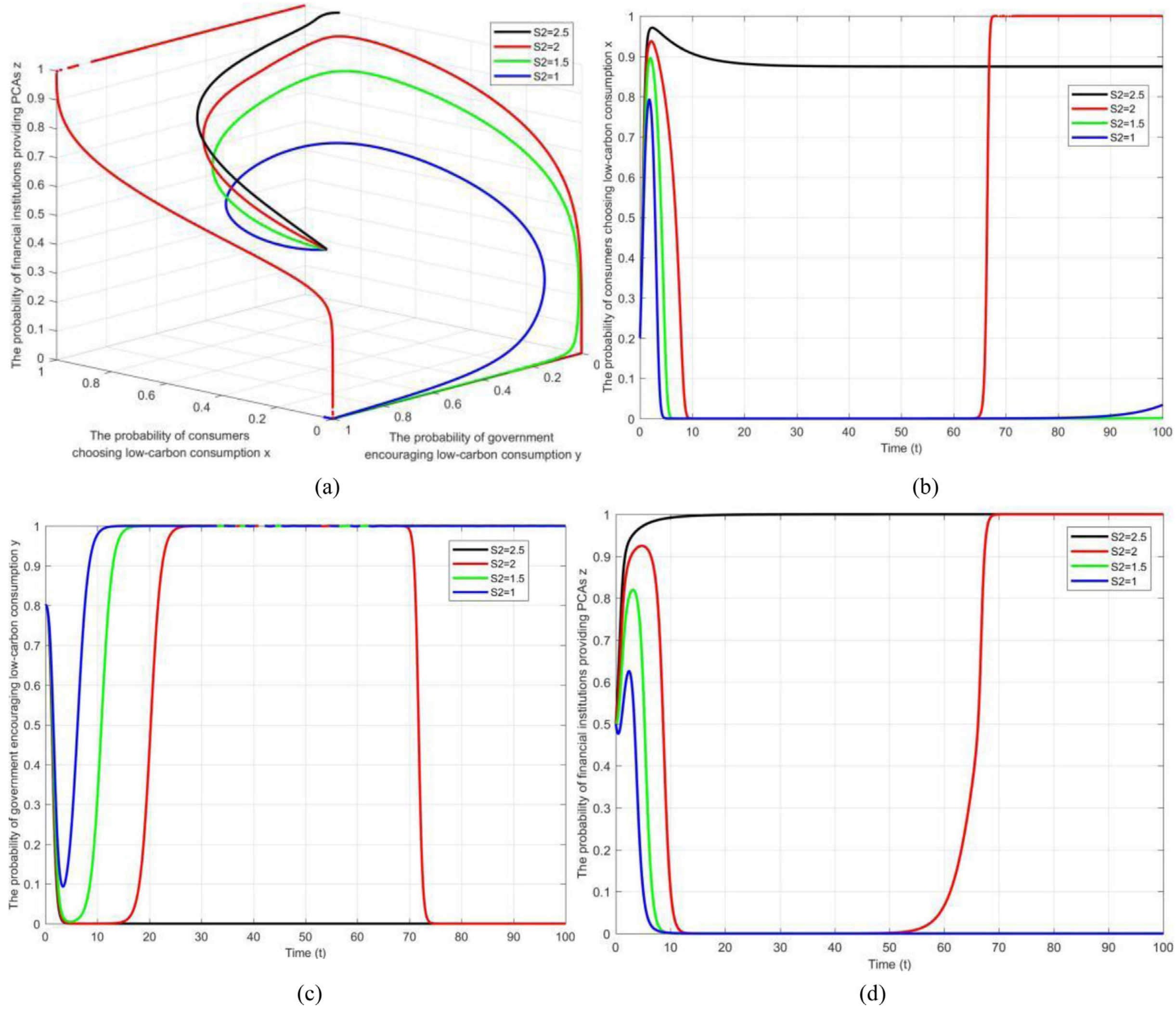

Fig. 10. The influence of government subsidies *S*2 for financial institutions on the system.

benefits provided by the three. These have certain limitations. Refining the types of the private sectors and accurately expressing the relationships among them are the areas where future work will improve.

CRediT authorship contribution statement

Xin Zhao: Conceptualization, Writing - original draft. **Yu Bai:** Writing - original draft, Software, Visualization. **Lili Ding:** Methodology, Investigation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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