Heliyon 9 (2023) e23131

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

A tripartite evolutionary game behavior analysis of the implementation strategy of the internal carbon pricing of enterprises under governments supervision

Kai Wu [a], E. Bai [a,*], Hejie Zhu [a], Zhijiang Lu [a], Hongxin Zhu [b]

[a] *Management School, Harbin University of Commerce, China*
[b] *School of Finance, Southwest University of Finance and Economics, China*

ARTICLE INFO

Keywords:
Internal carbon pricing
Carbon emission reduction
Low-carbon economy
Three-party evolutionary game
Government supervision

ABSTRACT

Internal Carbon Pricing (ICP) represents an innovative approach to carbon emission reduction. The implementation of the ICP involves enterprises and internal organizations, with its outcomes closely tied to government actions. In this study, a tripartite evolutionary game model comprising these subjects was constructed, and subsequent simulation analyses were conducted. The results revealed the following key findings: (1) When the combined total of carbon fees and governments' emission reduction subsidies surpasses the aggregate of carbon fees returned to internal organizations and ICP implementation costs, and when enterprises' revenues exceed governments' subsidies, all three parties will evolve towards ESS (1,1,1). This signifies that enterprises opt for the ICP, internal organizations actively reduce emissions, and governments engage in proactive regulation. (2) Reducing the cost of implementing ICP, increasing the carbon fee rebate ratio, raising governments' subsidies, and elevating the internal carbon price all contribute to promoting the attainment of the evolutionary game results ESS (1,1,1). However, it's important to note that higher governments' subsidies and carbon fee rebate ratios do not necessarily lead to a greater incentive for the three parties to reach the ESS(1,1,1). These findings provide a solid theoretical foundation for enterprises considering the implementation of the ICP in the future.

1. Introduction

Since the Industrial Revolution, environmental issues such as the greenhouse effect, atmospheric pollution, and acid rain, resulting from excessive carbon dioxide emissions, have significantly impacted the quality of people's lives and have become crucial factors constraining the sustainable development of society. According to the bulletin released by the World Meteorological Organization (WMO), the global average concentration of carbon dioxide has reached a record high of 417.06 parts per million, reaching the highest level in nearly one million years [1]. Furthermore, the WMO also reports that in 2022, the global average temperature is approximately 1.15° Celsius higher than pre-industrial levels, marking the eighth consecutive year with annual temperatures exceeding pre-industrial levels by at least 1 °C [2]. The increasing carbon emissions have now become a key impediment to achieving high-quality development for nations worldwide. Reducing carbon emissions can optimize economic structure, promote the development of a green economy,

---

* Corresponding author.
E-mail addresses: wukai@hrbcu.edu.cn (K. Wu), baie@s.hrbcu.edu.cn, baie18883786892@163.com (E. Bai), zhj@s.hrbcu.edu.cn (H. Zhu), luzj@s.hrbcu.edu.cn (Z. Lu), sassyzhx@smail.swufe.edu.cn (H. Zhu).

https://doi.org/10.1016/j.heliyon.2023.e23131
Received 6 June 2023; Received in revised form 4 November 2023; Accepted 27 November 2023

reduce energy consumption and dependence, lower energy costs, and alleviate climate problems to a certain extent. Therefore, the development of a low-carbon economy and the reduction of carbon emissions are not only significant strategic measures for countries to address global climate change but also an inevitable choice for the future economic development of nations [3].

Enterprises are the main body of the market economy and the main emitters of atmospheric pollutants. Reducing the carbon emissions of enterprises can significantly decrease the overall carbon footprint of society. Currently, an increasing number of enterprises, to address the multiple risks posed by climate change and enhance their corporate image, are taking active steps to shoulder social responsibility by implementing various measures to proactively reduce their carbon emissions. Among these measures, internal carbon pricing (ICP), as an internal mechanism adopted by enterprises for managing carbon emissions, is designed to promote the reduction of greenhouse gas emissions and raise environmental awareness within enterprise sectors. Nowadays, the ICP is gaining popularity among a growing number of enterprises due to its flexibility, strong incentives, and diversity of forms [4].

The ICP is a voluntary carbon reduction strategy developed by enterprises that imitates the operation of the external carbon market, while it is implemented within enterprises. Its core concept involves enterprises assigning a cost per unit of carbon emissions to internal organizations to incentivize them to take measures to reduce emissions. This approach not only regulates the behavior of employees in the short term to achieve emission reduction goals but also stimulates innovation in low-carbon technologies through the redesign of incentive structures over the long term. When establishing the ICP, enterprises can base their pricing on various factors such as the social cost of carbon (SCC), carbon regulatory prices, or prices used by leading enterprises [5]. Currently, the most commonly used models for pricing internal carbon emissions within enterprises include carbon fees, shadow pricing, and implicit pricing. Carbon fees refer to charges imposed by enterprises on all or some business units for their carbon emissions. By levying carbon fees, enterprises incorporate the cost of greenhouse gas emissions into their operational decisions, thereby incentivizing business units to reduce carbon emissions and invest in technological innovations. The price of the carbon fee is typically set at relatively low levels to encourage greater participation among business units, and the carbon fee collected is often used to achieve the enterprise's carbon reduction objectives [6]. The second internal carbon pricing model is shadow pricing. Shadow pricing involves setting a virtual or internal cost for carbon emissions within the enterprise to assess the economic impact of carbon emissions and inform related decisions. Shadow pricing is typically set at a higher level than carbon fees and is used to support risk management and strategic planning within the enterprise [5]. The last internal carbon pricing method is implicit pricing. Implicit pricing determines the cost of carbon emissions based on the expenses incurred by the enterprise in greenhouse gas reduction and regulatory compliance efforts. Thus, the price per ton of carbon under implicit pricing is calculated as the marginal cost of reducing and regulating greenhouse gas emissions. Implicit pricing is particularly useful for assessing the historical carbon emission costs of the enterprise [7]. To conduct a more in-depth study on how enterprises' unites (internal organizations) react to ICP, and to understand how enterprises and internal organizations engage in strategic game to maximize their respective interests when implementing the ICP, this paper will focus on the first type of ICP method. In this method, enterprises charge internal organizations carbon fees to incentivize them to save energy, reduce emissions, and innovate technology. Internal organizations contribute carbon fees based on their carbon emissions, and the collected fees are allocated toward energy conservation and emission reduction initiatives within the enterprise.

The effective implementation of the ICP relies on the collaborative efforts of governments, enterprises, and internal organizations within enterprises. In this process, governments assume the role of guidance and regulation, typically enacting policies and regulations to standardize the carbon emissions behavior of enterprises and compel them to adopt emissions reduction measures. On the other hand, enterprises are composed of multiple internal organizations that work together, forming a unified entity. The interactions and cooperation between enterprises and their internal organizations directly impact the effectiveness and feasibility of the ICP. Therefore, how to deal with the interaction between governments, enterprises, and internal organizations is a challenge for the implementation of an ICP.

First, governments bear the significant responsibility of national economic development and environmental protection. Active governments' regulation of enterprise carbon emissions can enhance governments' credibility [8]. To achieve the country's carbon reduction goals and promote economic structural transformation, governments often utilize economic or administrative measures to reduce enterprises' carbon emissions, ultimately encouraging enterprises to actively implement ICP. For example, when governments actively regulate enterprises' carbon emissions, governments may require enterprises to publicize their carbon emissions data and carbon pricing policies, to increase the transparency of carbon emission reduction, and to monitor and evaluate the process of carbon emission reduction [9]. Governments incentivize enterprises to reduce carbon emissions by imposing taxes on carbon emissions, setting carbon emission targets, or establishing carbon trading markets, which further encourages enterprises to implement ICP [10]. Additionally, Governments also encourage enterprises to implement ICP through laws and regulations [11]. Second, enterprises are the primary promoters and implementers of ICP. They formulate carbon pricing policies and mechanisms, establish carbon fee charging standards for internal organizations, and supervise the implementation of carbon pricing policies. Enterprises are responsible for ensuring that internal organizations comply with carbon pricing policies and remit carbon fees as prescribed [12]. Third, internal organizations are the subjects of ICP systems within enterprises. Internal organizations have the choice to either cooperate with the implementation of ICP or not. When internal organizations choose to cooperate, they are responsible for calculating and reporting their carbon emissions and remitting carbon fees based on the set standards by enterprises. Simultaneously, internal organizations need to take emission reduction measures to lower carbon emissions and control carbon fee expenditures [4]. In cases where internal organizations choose not to cooperate, internal organizations will not incur carbon fees, which will reduce their operational costs. While enterprises' ICP may likely face implementation challenges, and enterprises may struggle to meet government-mandated carbon targets.

Taking into account the different stances of the three principal parties mentioned above, this paper offers the following observations: if governments fail to consider enterprises' actual carbon emission situations, opt for passive regulation on carbon emissions, or rely exclusively on market self-regulation, there is a significant probability that enterprises will decrease their likelihood of adopting ICP. In such scenarios, internal organizations may refrain from taking action regarding energy conservation and emission reduction, rendering the achievement of the nation's carbon emissions and environmental protection objectives unattainable. Hence, the strategic game among governments, enterprises, and internal organizations plays a pivotal role in the successful and effective implementation of ICP. Consequently, addressing the strategic dynamics among these three entities is an immediate concern that requires resolution during the execution of ICP.

The subsequent sections of this paper are structured as follows: Section 2 provides an overview of relevant research. Section 3 outlines the methodology, detailing the fundamental assumptions and model construction. Section 4 delves into model analysis. Section 5 allocates values to crucial model parameters and executes simulation analysis. The final section, Section 6, concludes and presents management recommendations, as well as limitations and research directions of this paper.

2. Literature review

2.1. Review of research status

Reducing carbon emissions by enterprises and protecting the environment has always been a focal point for both researchers and governments. ICP is considered the most flexible and cost-effective means currently available to effectively mitigate the impact of greenhouse gas emissions, which has a significant incentive effect on reducing enterprises' energy consumption [11]. Currently, there is limited research on ICP. In existing literature concerning ICP within enterprises, scholars predominantly approach ICP from two perspectives: macro and micro. At a macro level, scholars primarily focus on exploring the macro reasons that affect the implementation of ICP. While, at a micro level, scholars primarily explore the economic effects of the implementation of ICP within enterprises.

Existing literature that investigates the macro-level factors influencing the implementation of ICP within enterprises includes: Nuno et al. [13] analyzed the factors influencing the adoption of the ICP by multinational enterprises, examining carbon reports disclosed by governments during 2015–2017. Their findings highlighted that the implementation of the ICP by enterprises was significantly influenced by national carbon policies and development plans. Franziska et al. [14], through the analysis of 18 semi-structured questionnaires, explored the reasons for enterprises not adopting the ICP. Their research revealed that the financial status and information technology infrastructure of enterprises were the primary determinants of ICP implementation. In the work of Oliver et al. [8,15,16], various promising approaches to ICP implementation were proposed. This was achieved by comparing and analyzing the motivations, methods, impacts, and key implementation barriers of enterprises from different countries to provide a comprehensive understanding of ICP, condensed into a flow chart. Trinks et al. [17]. Observed that enterprise adoption of the ICP mechanism was mainly influenced by government-imposed carbon quota restrictions and carbon pricing mechanisms, with industry and local climate characteristics following as secondary factors. Walid et al. [18]. Analyzed carbon disclosure reports of global enterprises spanning from 2016 to 2018 to investigate the reasons behind the adoption of ICP. Their findings indicated that enterprises were more inclined to implement ICP when facing higher carbon risks and operating within more stringent regulatory frameworks set by governments.

Existing literature examining the microeconomic implications of Internal Carbon Pricing (ICP) within enterprises includes studies such as that of Lopin et al. [19]., who conducted an empirical analysis of 1994 Japanese enterprises. They utilized the narrative logistic regression method to investigate whether Japanese enterprises could effectively employ carbon management tools, such as scientific carbon targets and ICP, to enhance their corporate carbon management reputation. The empirical findings indicated that enterprises that established scientific carbon targets or implemented ICP achieved higher reputations. Among Chinese scholars, Jiang et al. [20]. Emphasized the encouragement of enterprises to establish ICP. They argued that this approach not only helps enterprises address "carbon risks" but also contributes to the enhancement of the Chinese carbon pricing mechanism, thereby expediting the achievement of targeted carbon neutrality. Additionally, Zhu et al. [21]. Analyzed a sample dataset comprising 500 American-listed companies in the Carbon Disclosure Project from 2011 to 2020. They applied instrumental variables, propensity score matching, and unbalanced panel regressions to investigate the impact of ICP implementation on enterprise performance. Their results demonstrated that the ICP promoted technological innovation through increased investment in research and development (R&D), resulting in improved overall enterprise performance. Previous literature has shown that government policies, the financial condition of enterprises, and the carbon risks faced by enterprises are crucial factors in determining whether enterprises decide to implement the ICP. Furthermore, ICP can enhance enterprises' carbon management reputation, better address carbon risks, and accelerate technological innovation and transformation, ultimately leading to improved enterprise performance.

2.2. Research gaps based on prior studies

The main research gaps of the above literature are as follows: First, currently, research on ICP within enterprises primarily focuses on investigating the macro-level factors influencing the implementation of ICP and the microeconomic outcomes associated with it. There is little research addressing the systematic strategy analysis of the tripartite evolutionary game involving enterprises, internal organizations, and government entities. Second, there is limited literature that analyzes how the strategic choices of internal organizations, such as passive emissions reduction or active emissions reduction, affect the evolution and stability strategies of the tripartite entities. Third, most of the above literature on ICP mainly focuses on theoretical studies or empirical studies, with few papers analyzing mathematical models from a comprehensive and dynamic perspective. Finally, traditional game theory assumes that all participants are fully rational and possess complete market information, which is challenging to achieve during the game, especially in real-life scenarios, where it involves the dynamic selection problem of participants. In other words, all participants will adjust their strategies opportunistically based on market information and the actions of their gaming counterparts. Therefore, this paper adopts the evolutionary game approach, which combines game theory analysis with dynamic evolution to investigate the process of enterprises, internal organizations, and governments reaching equilibrium from a dynamic perspective, and uses evolutionary stable equilibrium (ESS) to predict the behavior of the three parties.

2.3. Research problems and main innovations

Building on previous research gaps, this paper primarily aims to address the following problems: (1) From the perspective of government participation, how can the stable strategies of the tripartite evolutionary game between enterprises and internal organizations in the implementation of ICP be scientifically achieved? (2) How to systematically analyze the impact of various factors, such as internal carbon price, the implementation cost of internal carbon pricing, carbon emissions reduction subsidies, and the carbon pricing rebate ratio, on the strategic choices of tripartite entities regarding the implementation of the ICP. (3) How to profoundly comprehend the evolution and stability strategies of enterprises, internal organizations, and governments in various scenarios when all entities are bounded rationality? To answer the above questions, this paper firstly combines macro and micro perspectives, based on three parties, constructs a tripartite evolutionary game model of enterprises, governments, and internal organizations under governments' different supervision policies, and analyses implementation conditions of the ICP system. Through the phase diagrams, the interrelationship of the probability of strategy choice of the three subjects can be obtained. Second, this paper analyzes the strategies of each game party from a dynamic perspective, using Lyapunov's first law to analyze the stability and obtaining the evolutionary stable strategy (ESS) of the three parties, and further analyzes the factors that affect each game party to reach the ESS. Finally, this paper applies Matlab 2021b to carry out simulation analyses and makes suggestions.

Compared to previous studies, the most prominent innovations of this paper are as follows: First, it analyzes the impact of several factors such as implementation costs of ICP, the proportion of internal carbon fee return, government emissions reduction subsidies, and the impact of the internal carbon price, etc., on the evolution and stable strategies of all players, thus broadening the research perspective within the ICP. Second, traditional game theory is typically static and assumes that all participants are perfectly rational actors. And it does not consider the adaptability and evolutionary processes of the participants. However, in the real world, individual strategies and behaviors may gradually evolve and adapt according to experience and environment. Evolutionary game theory is dynamic and assumes that each participant can adjust their strategies in response to other participants and market information. Furthermore, evolutionary game theory assumes that participants are bounded rational, unable to access complete market information. In real-world scenarios, evolutionary game theory complements the limitations of traditional game theory. This paper employs evolutionary game theory, which not only aligns better with real-world conditions but also provides a more comprehensive understanding of the dynamic game behavior among enterprises, internal organizations, and the government during the implementation of ICP. Finally, this paper incorporates governments into the tripartite evolutionary game model. Considering the relationship between enterprises and internal organizations, it investigates the game mechanisms among enterprises, internal organizations, and governments.

The main contributions of this paper are as follows: Theoretical, first, the population evolution theory and bounded rationality hypothesis are introduced to analyze the dynamic evolution of several internal and external factors in the strategy choices of enterprises, internal organizations, and governments under the implementation of the ICP. It assumes that the strategic choices of these entities result from their mutual learning and competition, aligning with the characteristics of ecological population and environmental evolution. Second, Considering the practical background of the development of ICP and the specific practices of enterprises, a systematic analysis is conducted to delve into the impact of internal and external factors, such as initial probabilities, internal carbon fees, carbon fee rebate ratios, carbon pricing, government carbon emissions reduction subsidies, and enterprises' operating income, on the dynamic evolutionary characteristics of enterprises, internal organizations, and governments entities during the implementation of ICP. Third, through the utilization of three complementary research methods – evolutionary game theory, phase diagrams, and simulation analysis, this paper conducts a thorough examination of the evolutionary and stable strategies of the tripartite game participants, namely enterprises, internal organizations, and government entities in different situations. This can provide certain theoretical support for the successful implementation of ICP by enterprises in the future. Practically, the positive effect of the ICP in reducing the carbon emissions of enterprises is demonstrated, which provides management enlightenment and suggestions for the application of the ICP in the future.

3. Methodology

3.1. Evolutionary game

Game theory is a discipline that examines how decision-makers formulate strategies and engage in competitive interactions. It employs mathematical and logical methods to scrutinize the dynamics of these strategies and interactions [22]. Game theory focuses on how individuals or entities make decisions in different contexts to achieve their individual or collective goals, taking into account the strategies and actions of other participants. This theory attempts to predict the behavior and ultimate outcomes by analyzing the strategic choices of different participants. Hence, mathematical models are an indispensable tool in game theory, allowing researchers to study game situations in a precise, clear, and comparable manner, delve into the nature of strategies and equilibria, and provide support and predictive methods for decision-makers [23]. Based on the completeness of information available to the participating game entities, game theory can be divided into complete information games and incomplete information games. In complete information games, each participant has a clear understanding of all elements of the game, including the strategies and historical actions of other participants. In incomplete information games, participants do not always possess complete information, and sometimes they may not know the strategies or information of other participants. Incomplete information games involve more complex strategic analysis because participants need to consider the uncertainty of the other party's information and possible strategy choices. At present, game theory has become one of the analytical tools of economics [24], and it is widely used in political science [25], finance [26], computers [27], biology [28], mathematics [29], and other disciplines.

Evolutionary game theory is a specialized branch of game theory that delves into the development of games within groups. The fundamental concept underlying evolutionary game theory is that the proliferation and transformation of strategies are influenced by the reproductive and survival prospects of individuals employing various strategies across successive generations [22]. In evolutionary games, strategies among individuals are typically not rationally chosen but transmitted to offspring through genetics or imitation. Key aspects emphasized in evolutionary game theory include fitness (the degree of success of each strategy, often used to describe an individual's survival and reproductive prospects), replicator dynamics (a mathematical model employed in evolutionary game theory to depict the spread and evolution of different strategies within a population), and evolutionarily stable strategies (a strategy in an evolutionary game that, if resistant to invasion by other strategies over an extended period, is deemed stable) [30]. Evolutionary game theory differs from traditional game theory in several aspects: First, the traditional game theory holds that people are perfectly rational and the market is completely competitive. Different from the traditional game theory, the evolutionary game theory is based on the hypothesis of finite rational man to analyze the resource allocation and strategy selection behavior of game players [31,32]. Second, the evolutionary game takes the population as the research subject, whose evolutionary mechanism is that the individuals with limited rationality will not choose the optimal strategy initially, but will eventually reach the evolutionary stable state through continuous learning, adjustment, and optimization [33]. Third, traditional game theory typically considers strategy selection within a single game, often involving static analysis. In contrast, evolutionary game theory places a stronger emphasis on the evolution and dissemination of strategies across multiple generations, highlighting the long-term evolution of strategies.

The suitability of evolutionary game theory as the game theory for this paper is justified for the following reasons: First, in the process of implementing the ICP, enterprises, internal organizations, and governments are not entirely rational, in other words, they cannot obtain all information from other participants or the market, and can only make decisions based on limited information. Second, the strategies of enterprises, internal organizations, and governments are not static, they will dynamically adjust their strategies according to the strategies of other participants and finally reach the evolutionary stability point. The replicated dynamic equations in the theory of evolutionary games can simulate the evolution process of different strategies. Lastly, the selection and optimization of strategies by enterprises, internal organizations, and governments constitute a dynamic process. In this process, the primary focus should be on how the strategies of the tripartite participants evolve and change over time and the long-term stability of their stable strategies, which is very consistent with evolutionary game theory. Hence, evolutionary game theory is well-suited for examining the evolutionary strategies of different participants when it comes to implementing the ICP. Analyzing the evolutionary game involves the calculation of the payoff matrix and the average payoff matrix for each participant, the development of replication dynamic equations for each participant, and the examination of stability points (ESS). ESS represents the optimal state to which each participant evolves based on the available information and is the most probable strategy that each participant selects [30].

3.2. Model description

Enterprises activities result in greenhouse gas emissions, which in turn contribute to phenomena like the greenhouse effect and extreme weather, causing societal losses. However, these costs are not entirely borne by the enterprises but are externalized. Internal carbon pricing (ICP) incorporates these external costs by quantifying them at a specified price, thus achieving internalization of costs. This not only helps enterprises comprehensively assess the true cost of carbon emissions, but also helps them better optimize resource allocation, mitigate climate policy risks, accelerate progress towards carbon reduction goals, and enhance the corporate social image. Consequently, an increasing number of enterprises globally are adopting the ICP. In this paper, a tripartite evolutionary game model involving enterprises, internal organizations, and governments is constructed to address how factors related to enterprises, internal organizations, and governments influence the implementation of ICP.

In this paper, governments refer to local governments, which are the subsidiary bodies of the central government. They are responsible for the lawful administration of economic, educational, cultural, civil affairs, and other administrative matters within their respective administrative region, carrying out tasks delegated by higher-level government authorities. Therefore, governments are responsible for the legitimate supervision of enterprise activities. Enterprises refer to entities that can produce, provide products, and make profits normally, and generate a certain amount of greenhouse gases during their production and operation processes. Therefore, enterprises are subject to government oversight and regulation. Internal organizations refer to functional units or branch entities affiliated with enterprises. Typically, these internal organizations lack independent legal entity status. However, if duly authorized by enterprises, they can operate within the scope of that authorization under the enterprise name and assume the corresponding legal responsibilities. In addition, according to the enterprises' internal management system, they also form internal rights and obligations with the enterprise, possessing a relatively independent legal status. Therefore, a certain level of strategic interaction or game behavior exists between enterprises and internal organizations. In the model of this paper, the specific game behavior of the above three parties is as follows:

Enterprises decide whether to adopt ICP based on stakeholder considerations. Governments oversee enterprises' compliance with carbon emission reduction standards. Under active regulation, governments provide emission reduction subsidies to enterprises actively engaged in emission reduction. In the case of negative regulation, no such subsidies are extended. Internal organizations, in response to enterprises' initiatives, make choices regarding carbon emission reduction. In the course of emission reduction, internal organizations may opt for either active or passive reduction strategies. Fig. 1 illustrates the game relationships and strategies among these three subjects.

3.3. *Model assumptions*

The strategic decisions of enterprises and internal organizations are critical factors influencing the successful implementation of ICP. Given the presence of a certain level of strategic game behavior between enterprises and internal organizations, both entities make decisions to maximize their interests. Therefore, when enterprises choose to implement ICP or not, internal organizations can choose to actively cooperate with the enterprise (actively engage in carbon reduction) or not (passively engage in carbon reduction). In particular, in the case where enterprises choose to implement the ICP and the internal organization chooses to cooperate with the enterprise (actively engage in carbon reduction), enterprises will incur a certain amount of ICP implementation costs, as well as receive a carbon fee from the internal organization. To incentivize the internal organization to actively reduce emissions, enterprises will return a portion of the carbon fees it has received to these internal organizations. On the other hand, for internal organizations, taking an active role in emissions reduction first incurs certain emission reduction costs. Second, internal organizations are required to calculate their carbon emissions and remit carbon fees to enterprises. Finally, due to their active emissions reduction efforts, internal organizations will receive a portion of the carbon fees returned by enterprises. Additionally, governments play a significant role in this process. Governments serve as the supervisors of enterprises' carbon emissions. When governments adopt an active regulatory strategy for enterprise emissions, they provide subsidies to enterprises actively implementing ICP as an incentive. Conversely, when governments take a passive approach to regulating enterprises, those implementing ICP do not receive subsidies. In this scenario, whether or not to implement ICP largely depends on the enterprises' strategic positioning and willingness. Hence, in different scenarios, the strategies for enterprises to implement ICP and for internal organizations to engage actively in emissions reduction may vary. In the context of evolutionary game theory, all participants are bounded rational agents, and their decisions adjust dynamically in response to the external environment and the decisions of other participants, aiming to evolve towards optimal stable points. Therefore, to better reflect the model described above, this paper proposes the following assumptions.

Assumption 1. Enterprises and internal organizations can be considered as a cohesive system [34]. In normal operational conditions, both entities coexist within this system as bounded rational agents, meaning that their strategic decisions are driven by the pursuit of maximizing their interests. In our game, there are three participants: enterprises, internal organizations, and governments. In the context of this study, enterprises are considered representative models for typical enterprises, effectively mitigating behavioral disparities within this group. To protect the environment and reduce the carbon emissions of enterprises, local governments need to regulate the carbon emissions of enterprises [35]. Meanwhile, the implementation of ICP is a long-term process, enterprises will choose whether to implement ICP according to their strategic positioning and government regulatory policies, and internal organizations will adjust their strategic behavior according to the strategic decisions of enterprises. It's essential to underscore that all three participants mentioned above are characterized as bounded rational agents, and the entire game process involves multiple iterations to seek the optimal decisions. Therefore, we propose enterprises are the first participants, internal organizations are the second participants, and governments are the third participants. Due to the fast-changing external environment and asymmetric market information, this game is an asymmetric game, and the strategies of the three parties are adjusted at any time with the changes of other game subjects and the external environment, and gradually stabilize over time [36].

Assumption 2. g represents governments, m represents enterprises, and z represents internal organizations. Within the game, governments can choose the strategy of "active supervision " or "passive supervision " strategy. When governments opt for the "active supervision " strategy, it signifies that governments will provide a certain subsidy, denoted as M, to enterprises that voluntarily

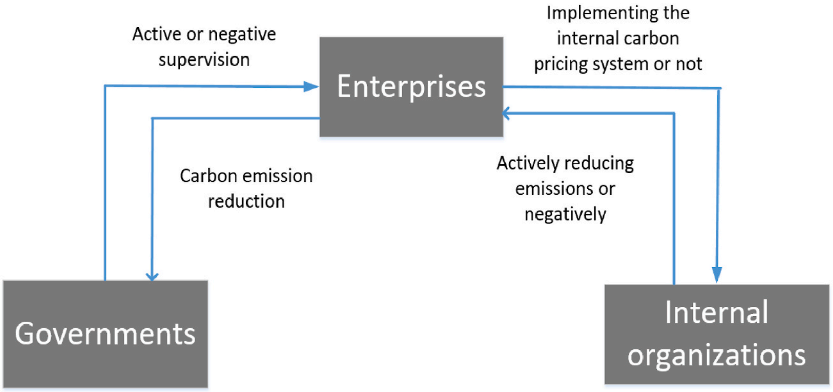

Fig. 1. The evolutionary game model of the three tripartite.

implement ICP [37]. In contrast, when governments select the" passive supervision" strategy, whether enterprises implement ICP depends on their strategic arrangements and leadership willingness. Therefore, governments' strategic choices are represented by the set {active supervision, passive supervision}. Both enterprises and internal organizations formulate appropriate strategies based on their respective needs. When enterprises choose to "implement the internal carbon pricing" strategy, they incur certain implementation costs, denoted as C_m, and receive carbon fees from internal organizations, denoted as $P * E$ $(0 < \mathrm{P} < 1)$ [4]. When enterprises choose not to "implement the internal carbon pricing" strategy, they will not be able to receive governments' emission reduction subsidies and will not incur costs related to ICP. Therefore, enterprises' strategic choices are represented by the set {implementing internal carbon pricing, not implementing internal carbon pricing}. Internal organizations, as the specific implementers of emission reduction actions within enterprises, often determine their strategies according to their needs and enterprises decisions. When internal organizations choose to "actively reduce emissions," they incur certain emission reduction costs, denoted as C_z [38]. When they opt for the "passive emission reduction" strategy, they do not incur related costs. Therefore, the strategic choices for internal organizations are represented by the set {actively reducing emissions, passively reducing emissions}.

Assumption 3. The operating revenue of the enterprises is denoted as R_m, while the revenue of internal organizations is typically a certain proportion of the enterprises' revenue. This proportion is represented as $f(0 < \mathrm{f} < 1)$, meaning that the operational revenue of internal organizations is equal to $f * R_m$. The operational revenue of both the enterprises and internal organizations is independent of their carbon reduction strategies. In other words, whether the enterprises implement ICP or internal organizations actively reduce emissions or not, their revenue remains unaffected. When governments actively regulate carbon reduction by enterprises, governments' credibility is enhanced, resulting in certain benefits denoted as R_g [39].

Assumption 4. Internal carbon pricing is a carbon management system implemented by enterprises within their internal organizations, and the relevant management system of enterprises will affect the effectiveness of the implementation of ICP [40]. When enterprises choose to implement ICP and the internal organizations choose to actively reduce emissions, enterprises will return a portion of the carbon fee collected to the internal organizations as a reward to incentivize them to continue to reduce emissions. This return ratio is denoted as a $(0 < a < 1)$. In the case where enterprises implement ICP, while the internal organizations do not cooperate with enterprises and opt for passive emission reduction, enterprises will not provide any fee return.

Assumption 5. The operating revenue of enterprises is denoted as R_m, and the operating revenue of internal organizations is given by fR_m. In the case where enterprises choose to implement ICP, internal organizations choose to actively reduce emissions, and governments choose active regulation, the net earnings for the enterprises are as follows: $R_m + M - C_m + (1 - a)PE$ (enterprises' operating revenue minus the cost of implementing ICP, plus the government's emission reduction subsidy, and the carbon fees submitted by internal organizations). The net earnings for internal organizations are: $(a-1)PE + fR_m - C_z$ (internal organizations' operating revenue plus the carbon fees returned by enterprises minus the internal organizations' emission reduction costs). The net earnings for governments are: $R_g - M$ (governments' enhanced credibility minus the emission reduction subsidy granted to enterprises). In cases where enterprises choose not to implement ICP, the net earnings for enterprises are equivalent to their operating revenue R_m. When internal organizations opt for passive emission reduction, they are not entitled to receive carbon fees returned by enterprises. When governments negatively regulate enterprises, governments will not provide emission reduction subsidies to enterprises and their credibility will not rise.

Based on the above assumptions, the model parameters and their descriptions are shown in Table 1, and the specific evolutionary game mode will be constructed in the next section.

3.4. Model construction

In this model, enterprises, internal organizations, and governments all make their strategic decisions based on the principle of maximizing their profit. We assume that the probability of enterprises choosing to "implement the internal carbon pricing" strategy is x, and the probability of choosing the "not implementing internal carbon pricing" strategy is $(1 - x)$, with $0 < x < 1$. The probability of internal organizations choosing the "active supervision " strategy is y, and the probability of choosing the" passive supervision"

Table 1
Summary of model parameters.

Parameter	Description
R_m	The operating revenue of enterprises
C_m	Costs incurred by enterprises in implementing ICP
PE	Carbon fees received from internal organizations are denoted as $P * E$ $(0 < \mathrm{P} < 1)$, where P represents the price of carbon emissions, and E represents the amount of carbon emissions
a	The return ratio of carbon fee refunds determined by enterprises $(0 < a < 1)$
C_z	Carbon emission reduction costs of internal organizations
fR_m	The operating revenue of internal organizations, $(0 < \mathrm{f} < 1)$
R_g	Government benefits due to increased credibility
M	Emission reduction subsidies provided by governments to enterprises that have taken the initiative to implement ICP
x	The probability of enterprises choosing the "implementing internal carbon pricing" strategy
y	The probability of internal organizations choosing to " actively reducing emissions " strategy
z	The probability of governments choosing to " active supervision " strategy

strategy is $(1 - y)$, with $0 < y < 1$. The probability of governments choosing the “active supervision " strategy is z, and the probability of choosing the” passive supervision” strategy is $(1 - z)$, with $0 < z < 1$. According to previous assumptions, the payment matrix of the mixed strategy game among enterprises, internal organizations, and governments is shown in Table 2.

This paper assumes that E_{ij} and $\widetilde{E}_i$ represent the expected return and average expected return of the game players respectively, $i =$ 1,2,3 represent enterprises, internal organizations, and governments, and $j = 1,2$ stand for two different decisions of participants.

Based on the above-mixed strategy game matrix, the expected return of enterprises choosing the“implement the internal carbon pricing” strategy and choosing " not implementing internal carbon pricing” strategy can be determined and are denoted as E_{11} *and* E_{12}, respectively. The average expected return of enterprises is presented as $\widetilde{E_1}$.

$$\begin{aligned} E_{11} &= yz(R_m + M - C_m + (1 - a)PE) + y(1 - z)(R_m - C_m + (1 - a)PE) \\ &+z(1 - y)(R_m + M - C_m + PE) + (1 - y)(1 - z)(R_m - C_m + PE) \end{aligned} \tag{1}$$

$$E_{12} = yzR_m + y(1 - z)R_m + (1 - y)zR_m + (1 - y)(1 - z)R_m \tag{2}$$

$$\widetilde{E_1} = xE_{11} + (1 - x)E_{12} \tag{3}$$

Similarly, the expected return of internal organizations choosing the " actively reducing emissions " strategy and choosing the” passively reducing emissions " strategy can be determined and are denoted as E_{21} *and* E_{22}, respectively. The average expected return of internal organizations is presented as $\widetilde{E}_2$.

$$\begin{aligned} E_{21} &= xz((a-1)PE + fR_m - C_z) + x(1 - z)(fR_m + (a-1)PE - C_z) \\ &+(1 - x)z(fR_m - C_z) + (1 - x)(1 - z)(fR_m - C_z) \end{aligned} \tag{4}$$

$$\begin{aligned} E_{22} &= xz(fR_m - C_z - PE) + x(1 - z)(fR_m - PE - C_z) \\ &+(1 - x)zfR_m + (1 - x)(1 - z)fR_m \end{aligned} \tag{5}$$

$$\widetilde{E}_2 = yE_{21} + (1 - y)E_{22} \tag{6}$$

And, the expected return of governments choosing the"active supervision " strategy and choosing the” passive supervision” strategy can be determined and are denoted as E_{31} *and* E_{32}, respectively. The average expected return of governments is presented as $\widetilde{E}_3$.

$$\begin{aligned} E_{31} &= xy\left(R_g - M\right) + x(1 - y)\left(R_g - M\right) \\ &+(1 - x)yR_g + (1 - x)(1 - y)R_g \end{aligned} \tag{7}$$

$$E_{32} = 0 \tag{8}$$

$$\widetilde{E}_3 = zE_{31} + (1 - z)E_{32} \tag{9}$$

4. Model analysis

4.1. Analysis of the strategy stability of enterprises

In evolutionary game theory, the replicator dynamics equation serves as the cornerstone for describing the dynamics of group behavior, i.e., with an increase in the number of game iterations, the population of individuals adopting successful strategies also increases [41]. Based on the fundamental principles of replicator dynamics, its expression is derived as the difference between an individual’s expected payoff and the average expected payoff, multiplied by the probability of selecting their strategy [42]. Thus, following the fundamental principles of replicator dynamics and equations (1)–(3), this paper can establish the replicator dynamics

Table 2
Payment matrix for enterprises, internal organizations, and governments.

Enterprises	Internal Organizations	Governments Active supervision z.	Governments Negative supervision $1 - z$
Implementing the internal carbon pricing system x.	Active emission reduction y.	$R_m + M - C_m + (1 - a)PE$ $(a - 1)PE + fR_m - C_z$ $R_g - M$	$R_m - C_m + (1 - a)PE$ $fR_m + (a - 1)PE - C_z$ 0
	Negative emission reduction $1 - y$	$R_m + M - C_m + PE$ $fR_m - C_z - PE$ $R_g - M$	$R_m - C_m + PE$ $fR_m - PE - C_z$ 0
Not implementing the internal carbon pricing system $1 - x$	Active emission reduction y.	R_m $fR_m - C_z$ R_g	R_m $fR_m - C_z$ 0
	Negative emission reduction $1 - y$	R_m fR_m R_g	R_m fR_m 0

equation for enterprises as equation (10):

$$\begin{aligned} F(x) &= \frac{dx}{dt} = x\left(E_{11} - \widetilde{E_1}\right) = x(1-x)(E_{11} - E_{12}) \\ &= (-1+x)x(Pe(-1+ay) - Mz + C_m) \end{aligned} \tag{10}$$

$$\frac{dF(x)}{dx} = (-1+2x)(Pe(-1+ay) - Mz + C_m) \tag{11}$$

According to the stability theorem of the evolutionary game, the necessary conditions that need to be satisfied for enterprises to reach the evolutionary stable point are: $F(x) = 0$ and $\frac{dF(x)}{dx} < 0$ [43]. For the sake of simplicity in the following analysis, we make $G_y = Pe(-1+ay) - Mz + C_m$, then $F(x) = (x-1)x * G_y$. From the expression of G_y, we can know that when $G_y = 0$, $y = \frac{Pe+Mz-C_m}{aPe}$.And due to $\frac{dG_y}{dy} = a\,Pe > 0$, therefore G_y is an increasing function of y.In other words when $y > \frac{Pe+Mz-C_m}{aPe}$, then $G_y > 0$, when $y < \frac{Pe+Mz-C_m}{aPe}$, then $G_y < 0$. Furthermore we calculate the first-order partial derivative of x for $F(x)$, as shown in equation (11). F rom the expression of $F(x)$, It is clear that if we let $F(x) = 0$, then x can only equal 0 or 1, or $G_y = 0\left(y = \frac{Pe+Mz-C_m}{aPe}\right)$. Thus the following analysis can be obtained: If $y = \frac{Pe+Mz-C_m}{aPe}$, then $G_y = 0$, at this time, $\frac{dF(x)}{dx} \equiv 0$, $F(x) \equiv 0$, then enterprises cannot determine their stabilization strategies. If $y > \frac{Pe+Mz-C_m}{aPe}$, then $G_y > 0$, to satisfy the conditions of $\frac{dF(x)}{dx} < 0$ and $F(x) = 0$, x can only equal 0. At this point, $x = 0$ is the evolutionary stable strategy (ESS) of enterprises. If $y < \frac{Pe+Mz-C_m}{aPe}$, then $G_y < 0$, to satisfy the conditions of $\frac{dF(x)}{dx} < 0$ and $F(x) = 0$, x can only be equal to 1. At this point, $x = 1$ is the evolutionary stable strategy (ESS) of enterprises. According to $G_y = 0\left(y = \frac{Pe+Mz-C_m}{aPe}\right)$, The cross-section of $G_y = 0\left(y = \frac{Pe+Mz-C_m}{aPe}\right)$ can be represented in a three-dimensional coordinate graph, as shown in Fig. 2. The points in cross-section $G_y = 0\left(y = \frac{Pe+Mz-C_m}{aPe}\right)$ remain stable along the x-axis, while the points to the left of cross-section $G_y = 0\left(y = \frac{Pe+Mz-C_m}{aPe}\right)$ evolve toward $x = 1$, and the points to the right of cross-section $G_y = 0\left(y = \frac{Pe+Mz-C_m}{aPe}\right)$ evolve toward $x = 0$.

Fig. 2 shows that the probability of enterprises implementing the ICP is the volume of A_1 (the left of cross-section), and the probability of not implementing the ICP is the volume of A_2 (the right of cross-section). Then it can be known by integration:

$$V_{A_1} = \iint_0^1 \frac{Pe+\mathrm{Mz}-C_m}{aPe}\,dzdx = \frac{2Pe+M-2C_m}{2aPe}\ ,\ V_{A_2} = 1 - V_{A_1}$$

The following corollaries can therefore be drawn.

Corollary 1. The probability that enterprises implement the ICP system ($\mathrm{V}_{\mathrm{A}_1}$) is negatively correlated with $\mathrm{C_m}$, and is positively related to M, and negatively correlated with a.

Proof: Let $\mathrm{V}_{\mathrm{A}_1}$ take partial derivatives of $\mathrm{C_m}$ and M, respectively. $\frac{\partial \mathrm{V}_{\mathrm{A}_1}}{\partial \mathrm{C_m}} = -\frac{1}{\mathrm{aPe}} < 0$, $\frac{\partial \mathrm{V}_{\mathrm{A}_1}}{\partial \mathrm{P}} = \frac{1}{2\mathrm{aPe}} > 0$. In addition, from the expression of $\mathrm{V}_{\mathrm{A}_1}$, it is known that since a is the part of the denominator of the fraction, as a increases, the entire fraction decreases. In other words, as a increases, the probability of enterprises implementing ICP decreases. Therefore, the larger the a, the smaller the $\mathrm{V}_{\mathrm{A}_1}$, the smaller the a , the larger the $\mathrm{V}_{\mathrm{A}_1}$.

Corollary 1 suggests that enterprises are more likely to implement the ICP when the amount of carbon subsidies given to them by governments is higher and the cost of implementing the ICP system is less. At the same time, the more subsidies enterprises give to their internal organizations, the more unfavorable it is for enterprises to implement the ICP. The low implementation cost of ICP enables enterprises to introduce ICP without incurring significant additional expenses. Enterprises are rational entities that generally pursue cost minimization and revenue maximization. A low-cost internal carbon pricing mechanism offers a cost-effective way to achieve emissions reductions. A lower carbon fee rebate ratio means that internal organizations will bear a larger portion of the carbon fees, while enterprises retain most of the carbon fees to support other emission reduction efforts. This significantly reduces the emission reduction costs for enterprises. Government-provided carbon reduction subsidies can effectively reduce the net cost of implementing ICP for enterprises. More governments' subsidies mean that enterprises can more easily afford the costs of implementing ICP and receive additional financial support during the emission reduction process.

Therefore, first, enterprises should strive to reduce the implementation costs of ICP, which includes adopting more efficient emission reduction technologies, optimizing energy use, or finding innovative low-cost emission reduction solutions. By continuously

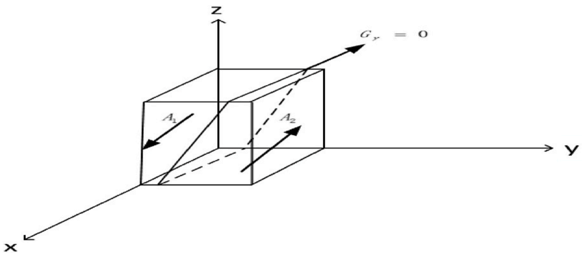

Fig. 2. Phase diagram of the evolution of enterprises' strategies.

seeking more cost-effective methods, the likelihood of enterprises implementing ICP is increased. Second, enterprises should set a prudent internal carbon fee rebate rate to incentivize internal organizations to reduce emissions. If the ratio is too low, the internal organization will bear more costs, and the economic pressure on the internal organization will increase, which may affect their motivation to reduce emissions. Finally, enterprises can actively engage in governments' carbon reduction initiatives to secure more carbon reduction subsidies. This involves collaborating with government agencies to understand available financial support and incentive programs, thereby reducing the net implementation cost of the ICP. By seeking governments' support, enterprises can better advance ICP.

Corollary 2. *The probability of enterprises implementing ICP increases with the increasing probability of passive emission reduction by internal organizations and with the increasing probability of active governments' regulation during the evolutionary process.*

Proof: *When* $y > \frac{Pe+Mz-C_m}{aPe}$, $z < \frac{-Pe+aPey+C_m}{M}$, $x=0$ *is the evolutionary stabilization strategy* (*ESS*) *of enterprises. When* $< \frac{Pe+Mz-C_m}{aPe}$, $z > \frac{-Pe+aPey+C_m}{M}$, $x=1$ *is the evolutionary stabilization strategy* (*ESS*) *of enterprises. It shows that as y decreases, z increases, x gradually evolves from* 0 *to* 1, *in other words, the enterprises' strategies have evolved from not implementing the ICP to implementing the ICP.*

Corollary 2 suggests that enterprises prefer to implement the ICP when internal organizations are passive in reducing emissions and governments are active in supervising them. On one hand, enterprises' social reputation is crucial for their business success. An increase in the probability of passive emission reduction by internal organizations may draw attention and dissatisfaction from the public. To protect their social reputation, enterprises may take proactive measures to address emission reduction issues within internal organizations. Implementing ICP can be seen as a proactive emission reduction step, helping to mitigate the risk of reputational damage for enterprises. In addition, many enterprises once publicly committed to reducing carbon emissions and participating in climate change response and environmental protection in their social responsibility reports. When the probability of passive emission reduction by internal organizations increases, enterprises may feel the need to fulfill these commitments to maintain their image of social responsibility. Implementing ICP can be viewed as a way for enterprises to fulfill their emission reduction commitments, sending a positive emission reduction signal to society in response to social pressure, thereby enhancing their social responsibility performance. On the other hand, when governments' probability of actively regulating enterprises' carbon emissions increases, enterprises will experience heightened regulatory pressure. To mitigate potential climate risks, enterprises are more likely to proactively fulfill their emission reduction obligations. They may take voluntary emission reduction measures, including the implementation of ICP. Therefore, an increase in the probability of proactive governments' regulation serves as an incentive for enterprises to implement ICP to comply with emission reduction regulations. Overall, the adoption of ICP by companies is typically a response to the lack of enthusiasm for emission reduction within internal organizations and the increased regulatory pressure from governments. The lower the motivation for emission reduction within internal organizations and the higher the governments' regulatory pressure, the more likely enterprises are to adopt ICP to reduce potential climate risks.

Based on the above analysis, enterprises can also optimize the design of their ICP to better incentivize internal organizations to reduce emissions. This includes adjusting the carbon fee rebate ratio to provide greater financial incentives, as well as developing an incentive-based internal carbon price to drive emissions reductions. Additionally, it is crucial for enterprises to maintain close cooperation and communication with governments to understand regulatory expectations and ensure that their emission reduction measures comply with legal requirements. Proactively responding to governments' regulations helps reduce enterprises' potential environmental risks.

4.2. *Analysis of the strategy stability of internal organizations*

According to the fundamental principles of replicator dynamics and equations (4)–(6), this paper can establish the replicator dynamics equation for internal organizations as follows:

$$\begin{aligned} F(y) = \frac{dy}{dt} = y\left(E_{21} - \widetilde{E_2}\right) = y(1-y)(E_{21} - E_{22}) \\ = (1-y)y(aPex + (-1+x)C_z) \end{aligned} \tag{12}$$

$$\frac{dF(y)}{dy} = (1-2y)(aPex + (-1+x)C_z) \tag{13}$$

Based on the stability theorem of evolutionary game, the necessary conditions that need to be satisfied for internal organizations to reach the evolutionary stable point are: $F(y)=0$ and $\frac{dF(y)}{dy} < 0$. For the sake of simplicity in the following analysis, we make $J_x = aPex + (-1+x)C_z$, then $F(y) = (1-y)y * J_x$. From the expression of J_x, we can know that when $J_x = 0$, $x = \frac{C_z}{aPe+C_z}$. And due to $\frac{dJ_x}{dx} = aPe + C_z > 0$, therefore J_x is an increasing function of x. In other words when $x > \frac{C_z}{aPe+C_z}$, then $J_x > 0$, when $x < \frac{C_z}{aPe+C_z}$, then $J_x < 0$. Furthermore we calculate the first-order partial derivative of y for $F(y)$, as shown in equation (13). From the expression of $F(y)$, It is clear that if we let $F(y) = 0$, then y can only equal 0 or 1, or $J_x = 0\left(x = \frac{C_z}{aPe+C_z}\right)$. Thus the following analysis can be obtained: If $x = \frac{C_z}{aPe+C_z}$, then $J_x = 0$, at this point, $F(y) \equiv 0$, $\frac{dF(y)}{dy} \equiv 0$, then internal organizations cannot determine their stabilization strategies. If $x > \frac{C_z}{aPe+C_z}$, then $J_x > 0$, to satisfy the conditions of $F(y)=0$ and $\frac{dF(y)}{dy} < 0$, y can only equal 1. At this point, $y=1$ is the evolutionary stable strategy (ESS) of internal organizations. If $x < \frac{C_z}{aPe+C_z}$, then $J_x < 0$, to satisfy the conditions of $F(y)=0$ and $\frac{dF(y)}{dy} < 0$, y can only be equal to 0. At this point, $y=0$ is the evolutionary stable strategy (ESS) of internal organizations. According to $J_x = 0\left(x = \frac{C_z}{aPe+C_z}\right)$, The cross-section of $J_x = 0\left(x = \frac{C_z}{aPe+C_z}\right)$ can be represented in a three-dimensional coordinate graph, as shown in Fig. 3. The points in cross-section $J_x = 0\left(x = \frac{C_z}{aPe+C_z}\right)$ remain stable along the y-axis, while the points in front of cross-section $J_x = 0\left(x = \frac{C_z}{aPe+C_z}\right)$ evolve toward $y = 1$, and the points to the behind of cross-section $J_x = 0\left(x = \frac{C_z}{aPe+C_z}\right)$ evolve toward $y = 0$.

Fig. 3 indicates the probability of internal organizations actively reducing is the volume of B_1 (in front of cross-section J_x). The probability of negative abatement is the volume of B_2 (behind of cross-section J_x). And from this cross-section J_x, it is clear that the cross-section J_x passes through the point M $\left(\frac{C_z}{aPe+C_z}, 0, 0\right)$, $N\left(\frac{C_z}{aPe+C_z}, 1, 0\right)$, $P\left(\frac{C_z}{aPe+C_z}, 0, 1\right)$ and $Q\left(\frac{C_z}{aPe+C_z}, 1, 1\right)$. And $V_{B_2} = \frac{C_z}{aPe+C_z}$, $V_{B_1} = 1 - V_{B_2} = \frac{aPe}{aPe+C_z}$.Therefore, the following corollaries can be drawn from the phase diagram.

Corollary 3. *The probability of active abatement of internal organizations increases as coefficient a and parameter P increase, and parameters C_z decreases.*

Proof: When other parameters remain constant and the coefficient a and parameter P increase, the points , N , P, and Q will move toward the negative half-axis of x axis. At this time, the probability of negative reduction of internal organizations decreases, while the probability of positive reduction increases. Similarly, from the expression of $V_{B_1} = \frac{aPe}{aPe+C_z}$, the relationship between the parameter C_z and the probability of active emission reduction of internal organizations can be obtained. C_z is the part of the denominator of the fraction $\frac{aPe}{aPe+C_z}$, as C_z increases, the entire fraction decreases, the probability of active abatement of internal organizations decreases. As C_z decreases, the probability of active abatement of internal organizations increases.

Corollary 3 suggests that the higher the return ratio of internal carbon fees and the higher the internal carbon price, the more favorable it is for internal organizations to actively reduce emissions. The higher the emission reduction cost of internal organizations, the less favorable it is for internal organizations to actively reduce emissions. Regarding the carbon fee return ratio, the degree of active emission reduction by internal organizations is often directly linked to economic incentives. When enterprises offer a high carbon fee return ratio, meaning that a significant portion of the collected carbon fees is returned to internal organizations, it can create economic incentives for these organizations. This means that they have the opportunity to receive some financial return on their emission reduction measures, which can motivate them to participate more actively in emission reduction efforts. Regarding internal carbon pricing, this refers to the price set by enterprises for carbon emissions. When internal carbon pricing is high, internal organizations may feel greater pressure since they need to cover higher costs. This can prompt them to take more proactive emission reduction actions to avoid substantial internal carbon pricing expenses. Concerning emission reduction costs, if the costs incurred by internal organizations are high, for example, due to the purchase of expensive technologies or equipment, they may be more inclined toward passive emission reduction. Taking all these factors into account, a high carbon fee return ratio and elevated internal carbon pricing typically provide stronger incentives for internal organizations to actively participate in emission reduction efforts. However, when emission reduction costs become excessively high, it may have a negative impact on the motivation of internal organizations, as they might find it economically unfeasible.

Therefore, policymakers and enterprises should consider these factors comprehensively to develop appropriate policies and measures that incentivize internal organizations to engage actively in emission reduction. To maximize incentives for internal organizations to actively reduce emissions, enterprises should provide technical assistance to internal organizations as much as possible to reduce their emission reduction costs. At the same time, enterprises should be aware of the importance of carbon price and rebate ratios for internal organizations to actively reduce emissions, and corporate with internal organizations to develop a reasonable carbon price and rebate ratio to incentivize them to actively reduce emissions. For internal organizations, they can actively seek a higher carbon fee return ratio to obtain more financial incentives. They can engage in communication with enterprises' leadership, emphasizing the importance of increasing the carbon fee return ratio for enhancing the willingness of internal organizations to actively reduce emissions. Furthermore, internal organizations can proactively explore new technologies and innovative methods to lower emission costs. This may involve adopting renewable energy sources, process improvements, or finding more efficient ways to utilize energy.

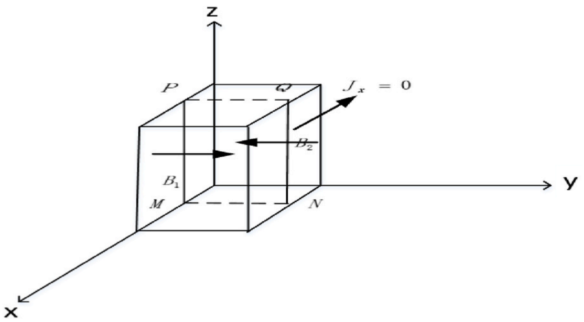

Fig. 3. Phase diagram of internal organizations' strategies evolution.

Corollary 4. In the process of evolution, the probability of internal organizations actively reducing emissions increases as the probability of enterprises implementing the ICP increases.

Proof: When $\mathrm{x} < \frac{\mathrm{C_z}}{\mathrm{aPe+C_z}}$ at this time, $\mathrm{y} = 0$ is the evolutionary stable strategy (ESS) of internal organizations. When $\mathrm{x} > \frac{\mathrm{C_z}}{\mathrm{aPe+C_z}}$, then $\mathrm{y} = 1$ is the evolutionary stable strategy (ESS) of internal organizations. Therefore, with x increasing, y gradually evolves from 0 to 1.

Corollary 4 shows the probability of internal organizations actively reducing emissions increases with the likelihood of enterprises implementing the ICP. This is primarily due to several factors. First, as the probability of enterprises implementing ICP increases, enterprises may align emission reduction targets and performance metrics with the objectives and tasks of internal organizations. This alignment serves as an incentive for internal organizations to actively engage in emissions reduction efforts to achieve the company's emission reduction goals. Second, internal organizations are typically the primary implementers of enterprises' policies, and any decisions made by enterprises directly impact the behavior of these internal organizations. When enterprises decide to implement ICP, internal organizations may be motivated to participate actively in emission reduction efforts, as they understand that enterprises have committed to taking emission reduction measures. Lastly, when enterprises decide to implement ICP, internal organizations may participate in the decision-making and execution processes of ICP. This implies that internal organizations have more opportunities to influence ICP and ensure its implementation within the organization. In summary, the probability of internal organizations actively reducing emissions increases with the likelihood of enterprises implementing ICP because ICP directly impacts internal organizations, motivating their participation in emission reduction efforts and ensuring policy implementation. Internal organizations typically become one of the primary implementers of enterprises' policies, and therefore, they actively respond to the enterprises' emission reduction decisions.

Therefore, when enterprises decide to implement ICP, there are several steps that internal organizations can take. First and foremost, internal organizations can actively engage in the development and revision of ICP to ensure that it takes into account the specific needs and circumstances of internal organizations. Second, internal organizations can collaborate with enterprises to establish clear and defined emission reduction targets, integrating these targets into their internal work processes and performance evaluations. This alignment ensures that internal organizations remain focused on achieving emission reduction objectives. Additionally, internal organizations can proactively seek support and commitment from enterprises' leadership, particularly during the formulation and implementation of ICP. Establishing effective communication channels with top management is crucial to ensure their understanding and endorsement of emission reduction goals and their willingness to provide the necessary resources and support. These recommendations are designed to encourage greater involvement of internal organizations in the implementation of the enterprises' ICP, ultimately facilitating the achievement of the enterprise' carbon reduction objectives.

4.3. Analysis of the strategy stability of governments

According to the fundamental principles of replicator dynamics and equations (7)–(9), the replicator dynamics equation of governments is established as equation (14):

$$\begin{aligned} F(z) &= \frac{dz}{dt} = z\left(E_{31} - \widetilde{E_3}\right) = z(1-z)(E_{31} - E_{32}) \\ &= z(z-1)\left((x-1)R_g + x(M - R_{\mathrm{m}})\right) \end{aligned} \tag{14}$$

$$\frac{dF(z)}{dz} = (2z-1)(\,(x-1)R_g + x(M - R_{\mathrm{m}})) \tag{15}$$

Based on the stability theorem of evolutionary game, the necessary conditions that need to be satisfied for governments to reach the evolutionary stable point are: $F(z) = 0$ and $\frac{dF(z)}{dz} < 0$. For the sake of simplicity in the following analysis, we make $H_x = (x-1)R_g + x(M - R_{\mathrm{m}})$, then $F(z) = z(z-1)H_x$. From the expression of H_x, we can know that when $H_x = 0$, $x = \frac{R_g}{R_g + M - R_{\mathrm{m}}}$. And due to $\frac{dH_x}{dx} = R_g + M - R_{\mathrm{m}}$, therefore When $R_g + M - R_{\mathrm{m}} > 0$, H_x is an increasing function of x. When $R_g + M - R_{\mathrm{m}} < 0$, H_x is a decreasing function of x. Furthermore, we calculate the first-order partial derivative of z for $F(z)$, as shown in equation (15). From the expression of $F(z)$, it is known that if $F(z) = 0$, then z equal to 0 or 1, or $H_x = 0\left(x = \frac{R_g}{R_g + M - R_{\mathrm{m}}}\right)$. Thus there are the following situations. If $R_g + M - R_{\mathrm{m}} > 0$, H_x is

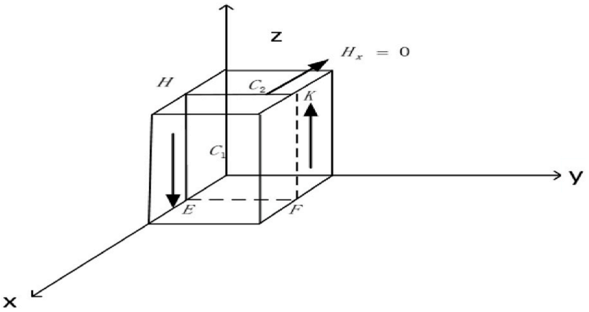

Fig. 4. Phase diagram of governments' strategies evolution.

an increasing function of x. Then $H_x > 0$, when $x > \frac{R_g}{R_g+M-R_m}$, $H_x < 0$, when $x < \frac{R_g}{R_g+M-R_m}$,.At this time, similar to strategic stability analysis of enterprises and internal organizations. When $x > \frac{R_g}{R_g+M-R_m}$, $z = 0$ is the evolutionary stable strategy (ESS) of governments. When $x < \frac{R_g}{R_g+M-R_m}$, $z = 1$ is the evolutionary stable strategy (ESS) of governments. If $R_g + M - R_m < 0$, H_x is a decreasing function of x.Then $H_x < 0$, when $x > \frac{R_g}{R_g+M-R_m}$, $H_x > 0$ when $x < \frac{R_g}{R_g+M-R_m}$,.Similarly, when $x > \frac{R_g}{R_g+M-R_m}$, $z = 1$ is the evolutionary stable strategy (ESS) of governments. When $x < \frac{R_g}{R_g+M-R_m}$, $z = 0$ is the evolutionary stable strategy (ESS) of governments.

In addition, $x = \frac{R_g}{R_g+M-R_m}$, when $H_x = 0$, therefore, x must be greater than 0, then $R_g + M - R_m > 0$. Thus there is no case of $R_g + M - R_m < 0$. According to $H_x = 0\left(x = \frac{R_g}{R_g+M-R_m}\right)$, The cross-section of $H_x = 0\left(x = \frac{R_g}{R_g+M-R_m}\right)$ can be represented in a three-dimensional coordinate graph, as shown in Fig. 4. The points in cross-section $H_x = 0\left(x = \frac{R_g}{R_g+M-R_m}\right)$ remain stable along the z-axis, while the points in front of cross-section $H_x = 0\left(x = \frac{R_g}{R_g+M-R_m}\right)$ evolve toward $z = 0$, and the points to the behind of cross-section $H_x = 0\left(x = \frac{R_g}{R_g+M-R_m}\right)$ evolve toward $z = 1$.

Fig. 4 shows that the probability of the governments' active supervision is the volume of C_2(the behind of cross − section), and the probability of the governments' negative supervision is the volume of C_1(in front of cross − section). And it can be seen from this cross-section that the cross-section passes through the point $E\left(\frac{R_g}{R_g+M-R_m}, 0, 0\right)$, $F\left(\frac{R_g}{R_g+M-R_m}, 1, 0\right)$,$K\left(\frac{R_g}{R_g+M-R_m}, 1, 1\right)$ *and* $H\left(\frac{R_g}{R_g+M-R_m}, 0, 1\right)$. Then, it can be known that: $V_{C_2} = \frac{R_g}{R_g+M-R_m}$, $V_{C_1} = 1 - V_{C_2}$. The following corollaries can therefore be drawn.

Corollary 5. The probability of governments' positive supervision increases as the parameter $\mathrm{R_m}$ increases, and the parameter M decreases.

Proof: Calculate the first-order partial derivative of parameters $\mathrm{R_m}$, and M for $\mathrm{V_{C_2}}$, $\frac{\partial \mathrm{V_{C_2}}}{\partial \mathrm{R_m}} = \frac{\mathrm{R_g}}{(\mathrm{M}+\mathrm{R_g}-\mathrm{R_m})^2} > 0$, $\frac{\partial \mathrm{V_{C_2}}}{\partial \mathrm{M}} = -\frac{\mathrm{R_g}}{(\mathrm{M}+\mathrm{R_g}-\mathrm{R_m})^2} < 0$.

Corollary 5 suggests that the more the operating income of enterprises, the more inclined governments are to actively regulate the enterprises' carbon emissions. The more subsidies governments provide to enterprises for carbon emission reduction, the less inclined governments are to actively regulate the enterprises' carbon emissions. Possible explanations for this include: First, higher-income enterprises typically have more financial resources. Therefore, governments may believe that these companies have the capacity to implement more extensive emission reduction measures. Second, governments may want to ensure that high-income enterprises are subject not only to voluntary emission reductions but also to active regulation, thereby driving larger-scale emission reductions. Furthermore, high-income enterprises are often more visible to the public and politically, which means governments might face greater pressure from the public and interest groups to subject these enterprises to rigorous carbon emission regulations. Additionally, high-income enterprises often bear more significant social responsibilities, thus governments may expect them to set an example by taking proactive emission reduction measures to uphold social equity and sustainability. Therefore, the higher the operating income of enterprises, the greater the probability that governments actively regulate their carbon emissions reduction. On the other hand, governments incentivize emission reductions by providing subsidies to enterprises. When governments offer substantial carbon reduction subsidies to enterprises, they may view this as a proactive support measure, reducing the need for excessive regulation. In other words, governments may consider subsidies themselves as a means to encourage emission reductions. Moreover, governments' resources are limited, which means they may need to choose where to focus their regulatory efforts. If governments have already provided subsidies to enterprises, they may reduce regulatory intensity to ensure resources can be better allocated to other environmental issues.

Based on this phenomenon, governments can consider the following recommendations to more effectively manage carbon emissions and carbon reduction policies, ensuring fairness and effectiveness of the policies: First, governments can establish differential regulatory policies based on enterprises' operating income and level of carbon reduction subsidies, tailoring specific regulatory strategies for different companies. High-income and low-income enterprises can face varying degrees of regulation to ensure equity and fairness. Second, governments can set clear emission reduction targets and standards, then reward or regulate based on a company's actual emission reduction achievements. This will encourage companies to take active emission reduction measures, regardless of their operating income or subsidy levels. Finally, governments should ensure that policies and subsidies do not result in unfair competition, maintaining market fairness. These recommendations can help governments strike a better balance in carbon emission policies, and ensure policy fairness and effectiveness.

Corollary 6. The impact of parameters $\mathrm{R_g}$ on the governments implementing active supervision strategies depends on the combined effect of parameters M and $\mathrm{R_m}$.

Proof: Calculate the first-order partial derivative of the parameter $\mathrm{R_g}$ for $\mathrm{V_{C_2}}$, $\frac{\partial \mathrm{V_{C_2}}}{\partial \mathrm{R_g}} = \frac{\mathrm{M}-\mathrm{R_m}}{(\mathrm{M}+\mathrm{R_g}-\mathrm{R_m})^2}$. When $\mathrm{M} - \mathrm{R_m} > 0$, then $\frac{\partial \mathrm{V_{C_2}}}{\partial \mathrm{R_g}} > 0$. When $\mathrm{M} - \mathrm{R_m} < 0$, then $\frac{\partial \mathrm{V_{C_2}}}{\partial \mathrm{R_g}} < 0$.

Corollary 6 suggests when the governments' subsidy to enterprises for carbon emission reduction exceeds the enterprises' operating income, the increase in government credibility will increase the probability of the government actively regulating the enterprises' carbon emission reduction. On the contrary, when the government's subsidy to enterprises for carbon emission reduction is lower than the enterprises' operating income, increasing the government's credibility will reduce the probability of the government actively regulating the enterprises' carbon emission reduction. The possible reasons for this situation are as follows: Governments' credibility plays a vital role in environmental policies. Governments' credibility refers to the extent of public trust in the government's commitments, including whether governments will rigorously enforce environmental regulations and policies. The higher the governments' credibility, the more the public believes that governments will actively regulate enterprises' environmental behaviors, including carbon reduction. When governments provide carbon reduction subsidies to enterprises that exceed their operating income, it means that governments show great determination in supporting enterprises in reducing emissions. In this case, enterprises will feel the active support of the government because the government is willing to provide large sums of money for emission reduction. As a result, the increased credibility of governments will further increases the probability of enterprises complying with environmental regulations and policies, as well as further increase the probability of governments actively regulating enterprises. Conversely, when the government-provided subsidies for carbon reduction fall below enterprises' operating income, enterprises may perceive inadequate governments' support. This could lead to skepticism regarding governments' environmental policies because of the lower financial support provided by governments. In this situation, an increase in governments' credibility may instead reduce the likelihood of governments actively supervising corporate carbon reduction, as enterprises may doubt the governments' commitment to policy enforcement.

Therefore, when regulating enterprises' carbon reductions, the government can consider the following recommendations: First, governments can enhance the transparency of the policy to ensure that the public and enterprises can clearly understand the policy objectives and implementation methods. Simultaneously, governments should establish traceable mechanisms to monitor enterprises carbon reduction outcomes, thereby strengthening the credibility of the policy. Second, ensure that governments' carbon reduction policies are equitably consistent across different enterprises. Avoid providing excessive subsidies to certain enterprises while offering inadequate support to others, as this helps enhance the policy's credibility. Furthermore, governments can establish incentive systems that provide additional motivation based on enterprises' actual carbon reduction achievements. This will encourage enterprises to actively participate in carbon reduction and ensure the effectiveness of policy implementation. Finally, in regulating carbon reductions, governments should consider enterprises' operating income comprehensively to determine the most appropriate subsidy levels. This means that governments should not adopt a one-size-fits-all or uniform approach and should not apply the same subsidy amount to all companies. Instead, governments should cleverly design personalized support measures based on the specific circumstances and needs of each company.

Corollary 7. During the evolutionary process, the probability of governments actively supervising enterprises increases with the reduction of the probability of enterprises implementing the ICP.

Proof: When $\mathrm{x} < \frac{\mathrm{R_g}}{\mathrm{R_g+M-R_m}}$, then $\mathrm{z} = 1$ is the governments' evolutionary stable strategy (ESS). When $\mathrm{x} > \frac{\mathrm{R_g}}{\mathrm{R_g+M-R_m}}$, then $\mathrm{z} = 0$ is the evolutionary stable strategy (ESS) of governments. Therefore, as x decreases, the z gradually evolves from 0 to 1.

Corollary 7 suggests that the probability of governments' active supervision is affected by the strategy choices of enterprises. The governments' regulatory objectives are to ensure that enterprises comply with environmental protection and emission reduction regulations. When enterprises voluntarily adopt emission reduction measures and implement ICP, governments may perceive them as having taken proactive steps to reduce emissions. Consequently, governments may reduce their level of oversight. Furthermore, governments' regulatory resources are finite, necessitating efficient resource management. If enterprises have already implemented the ICP, governments may allocate more resources to those enterprises that have not taken emission reduction measures to ensure broader emission reduction actions, as strict regulation of enterprises that have implemented ICP may increase the regulatory burden on governments. Therefore, when enterprises tend not to implement the ICP, governments will be more inclined to actively supervise them. On the contrary, governments tend to have negative supervision.

Therefore, governments can implement differentiated regulatory approaches and allocate regulatory resources according to the carbon emission reduction status of enterprises. For those enterprises that have not yet implemented ICP, governments can strengthen their regulatory efforts to ensure that they comply with emission reduction regulations. Simultaneously, for those enterprises that have already implemented ICP, governments can reduce regulatory burdens, encouraging them to continue voluntary emission reductions and rewarding their efforts. Second, governments can establish incentive mechanisms to encourage enterprises to adopt voluntary emission reduction measures. These incentives can include emission reduction subsidies, tax incentives, carbon market incentives, and so on. By providing economic incentives, governments can motivate more companies to engage in voluntary emission reduction, thus reducing the need for stringent regulation. Finally, governments can engage in active cooperation with enterprises, providing them with technical support and resources to help them implement ICP.

4.4. System stability analysis

Considering that the game behaviors of the three subjects in this paper are asymmetric evolutionary game behaviors under information asymmetry, it is sufficient to discuss the Nash equilibrium point under pure strategies. According to $F(x) = 0, F(y) = 0, F(z) = 0$, all the pure strategy equilibrium points of the game system can be obtained as follows: $E_1(0,0,0)$,$E_2(1,0,0)$,$E_3(0,1,0)$,$E_4(0,0,1)$, $E_5(1,1,0)$,$E_6(1,0,1)$,$E_7(0,1,1)$,$E_8(1,1,1)$. According to assumptions, the equilibrium point must be in the three-dimensional space, in other words, the condition $V = \{(x,y,z)|0\leq x \leq 1, 0\leq y \leq 1, 0\leq z \leq 1,\}$ must be satisfied. According to Friedman's analysis of dynamic stability using differential equations, the stability of the equilibrium point is assessed using a local stability analysis of the system's Jacobian matrix [44]. Then, taking the derivative of the respective replicator dynamic equations for the three parties with respect to x, y, and z results in the system's Jacobian matrix for the evolutionary game, as equation (16) shows. Substituting all the pure strategy equilibrium points into the Jacobian matrix allows us to determine the eigenvalues corresponding to each equilibrium point. Then, according to Liapunov's first law [45], if all eigenvalues obtained by substituting equilibrium points into the Jacobian matrix are negative, the equilibrium point is stable. If at least one eigenvalue is positive, the equilibrium point is unstable. When there are both positive and negative eigenvalues, the equilibrium point is a saddle point. Therefore, the stability analysis of each equilibrium point can be deduced as shown in Table 3.

$$J=\begin{bmatrix} \dfrac{\partial F(x)}{\partial x} & \dfrac{\partial F(x)}{\partial y} & \dfrac{\partial F(x)}{\partial xz} \\ \dfrac{\partial F(y)}{\partial x} & \dfrac{\partial F(y)}{\partial y} & \dfrac{\partial F(y)}{\partial z} \\ \dfrac{\partial F(z)}{\partial x} & \dfrac{\partial F(z)}{\partial y} & \dfrac{\partial F(z)}{\partial z} \end{bmatrix}$$

$$=\begin{bmatrix} (x-1)(Pe(ay-1)-Mz+Cm)+x(Pe(ay-1)-Mz+Cm) & aPe(-1+x)x & -M(-1+x)x \\ (1-y)y(aPe+C_z) & (2y-1)(aePx+(x-1)Cz) & 0 \\ (Rg+M-Rm)(-1+z)z & 0 & (-1+2z)((x-1)Rg+x(M-Rm)) \end{bmatrix} \tag{16}$$

In the game model of this paper, we focus on the effect of initial probability on system stability. The initial probability of the three parties refers to the initial probability that governments choose to “actively regulate enterprises’ carbon emission reduction” strategy, the initial probability that enterprises choose to “implement the ICP” strategy, and the initial probability that internal organizations chooses “active emission reduction” strategy. From Tables 3 and it can be seen that only $E_4(0,0,1)$, $E_5(1,1,0)$, $E_8(1,1,1)$ need to be performed in the analysis of the evolutionary stabilization strategy (ESS). Therefore, the following three scenarios are discussed:

Scenario 1: When $Pe - C_m + M < 0$ (that is, the sum of carbon fee Pe and subsidies M imposed by governments is less than the cost of implementing ICP C_m), the eigenvalues of the Jacobi matrix corresponding to equilibrium point $E_4(0,0,1)$ are all negative, satisfying the condition of the evolutionary stability point. The corresponding evolutionary strategies of the three players are {not implementing the ICP, negatively reducing emissions, positive supervision}, meaning enterprises will tend not to implement the ICP, and internal organizations will tend to reduce emissions negatively, at the same time governments will tend to actively supervise enterprises. In this scenario, both enterprises and internal organizations choose passive strategies, and ICP cannot be implemented. Therefore, this situation should be avoided.

Scenario 2: When $-Pe + aPe + C_m < 0$, and $R_m - M < 0$ (namely, the sum of carbon fee returned to the internal organizations aPe and ICP implementation costs C_m is less than carbon fee Pe, and the governments’ subsidies M are more than enterprises’ production and operation R_m), the eigenvalues of the Jacobi matrix corresponding to equilibrium point $E_5(1,1,0)$ are all negative, satisfying the condition of the evolutionary stability point. At this point, the corresponding evolutionary strategies of the three players are {implementing the ICP, positively reducing emissions, negative supervision}.

Scenario 3: When $-M - Pe + aPe + C_m < 0$, and $M - R_m < 0$ (namely, the sum of carbon fee Pe and governments subsidies M is more than the sum of carbon fee returned to the internal organizations aPe and ICP implementation costs C_m, and enterprises’ production and operation R_m is more than the governments’ subsidies M), the eigenvalues of the Jacobi matrix corresponding to equilibrium point $E_8(1,1,1)$ are all negative, satisfying the condition of the evolutionary stability point. The corresponding evolutionary strategies of the three players are{implementing the ICP, positively reducing emissions, positive supervision}, meaning enterprises tend to implement the ICP, internal organizations tend to actively reduce emissions, and governments also tend to actively supervise enterprises. At this point, the whole system can achieve the Pareto optimum.

In conclusion, based on the research assumptions and the analysis of the scenarios mentioned above, we can deduce that in scenario 1, $E_4(0,0,1)$ is the equilibrium point. In scenario 2, $E_5(1,1,0)$ is the equilibrium point, and in scenario 3, $E_8(1,1,1)$ is the equilibrium point. However, for the equilibrium point E_4 where both enterprises and internal organizations choose passive strategies, ICP cannot be realized, then this situation should be avoided. For the equilibrium point E_5, in this scenario, governments select negative regulation of enterprises’ carbon reduction, meaning that enterprises cannot obtain carbon emission reduction subsidy. This is also not conducive to

Table 3
Analysis of equilibrium points.

Equilibrium point	Eigenvalue			Stability
	λ_1	λ_2	λ_3	
$E_1(0,0,0)$	$Pe - C_m$	$-C_z$	R_g	Saddle Point
$E_2(1,0,0)$	$R_m - M$	$C_m - Pe$	aPe	Unstable point
$E_3(0,1,0)$	$Pe - C_m - aPe$	R_g	C_z	Unstable point
$E_4(0,0,1)$	$Pe - C_m + M$	$-C_z$	$-R_g$	When $Pe - C_m + M < 0$, it is the ESS, otherwise, it is the unstable point or saddle point
$E_5(1,1,0)$	$-Pe + aPe + C_m$	$R_m - M$	$-aPe$	When $-Pe + aPe + C_m < 0$, and $R_m - M < 0$, It is the ESS. Otherwise, it is the unstable point or saddle point
$E_6(1,0,1)$	$-Pe + C_m - \mathrm{M}$	$M - R_m$	aPe	Unstable point
$E_7(0,1,1)$	$M + Pe - aPe - C_m$	C_z	$-R_g$	Unstable point
$E_8(1,1,1)$	$-M - Pe + aPe + C_m$	$-aPe$	$M - R_m$	When $-M - Pe + aPe + C_m < 0$, and $M - R_m < 0$, It is the ESS. Otherwise, it is the unstable point or saddle point

the implementation of ICP and should be avoided as much as possible. As for the equilibrium point E_8, where enterprises, internal organizations, and governments all choose positive strategies, the entire system reaches the optimal state. The analysis of scenarios 1–3 shows that the evolution of enterprises, internal organizations, and governments leads to three possible outcomes: {not implementing the ICP, negatively reducing emissions, positive supervision}, {implementing the ICP, positively reducing emissions, negative supervision}, {implementing the ICP, positively reducing emissions, positive supervision}. However, the analysis above merely presents the outcomes of the evolutionary game model and does not explain the reasons for the final evolutionary results or provide the evolutionary process from the initial state to the equilibrium points. A more in-depth and intuitive analysis will be discussed in the next section.

5. Numerical simulation analysis

The analysis of the evolutionary game equilibrium regarding the implementation of ICP reveals that there are various factors influencing the three main parties in reaching an evolutionary equilibrium. In addition, the process of achieving equilibrium is not clear-cut, and it is uncertain whether the equilibrium is unique and stable. the process of achieving equilibrium is not clear-cut, and it is uncertain whether the equilibrium is unique and stable. Moreover, even if equilibrium is reached in a particular scenario, external uncertainties can impact the system, potentially disrupting the equilibrium. To address this issue, this paper employs numerical simulations and simulation analysis to characterize the evolutionary decision-making processes of each party in the three-party evolutionary game model under the implementation of ICP. The simulation analysis of the evolutionary game can help us understand how the complex system evolves and changes over time, and its focus is to analyze the impact of key elements on the equilibrium results and explore how to achieve the ideal equilibrium. Based on the research assumptions and game model in this paper, combining real-world scenarios and references from previous literature, this section uses MATLAB 2021b for numerical simulations to analyze the evolutionary processes of enterprises, internal organizations, and the government under predefined probability values for strategies. We also examines the stability of equilibrium points in different situations. We also further explore the effects of internal carbon pricing implementation cost, internal carbon fee rebate ratio, governments' subsidy and internal carbon price on the evolution process and results of the three parties, and explain the micro-mechanisms of the implementation of ICP decision-making by enterprises.

5.1. Basic simulation analysis

First, to validate the accuracy of the model analysis results in section 4 and to provide a more intuitive representation of the impact of different parameter values on the evolution path and stable state of the enterprise's implementation of ICP, this section employs numerical simulations. First, to analyze the impact of the change in the three parties subjects' initial probabilities on the ICP implementation strategy, we analyze the stability of equilibrium strategies for enterprises, internal organizations, and governments under different probability values for strategies. In the value of the initial probability of the three parties' subjects, this study refers to the practice of previous scholars [46], the initial value of x, y, z is 0.1, the step value is 0.2, and the stochastic evolution from 0.1 to 1.0 is conducted. Based on the parameter settings described in the last section and the constraints of stability points, the respective parameters are assigned values. For Scenario 1, there is array 1: $a = 0.2, C_m = 300, \mathrm{M} = 50, P = 30, \mathrm{E} = 5, R_g = 500, f = 0.3, C_z = 100, R_m = 500$. For Scenario 2, there is array 2: $a = 0.2, C_m = 100, \mathrm{M} = 600, P = 50, \mathrm{E} = 5, R_g = 1000, f = 0.3, C_z = 100, R_m = 500$. For Scenario 3, there is array 3: $a = 0.1, C_m = 100, \mathrm{M} = 200, P = 20, \mathrm{E} = 15, R_g = 600, f = 0.7, C_z = 50, R_m = 500$. To enhance the scientific rigor of the simulation, these three sets of arrays undergo 50 iterations, and the results of these iterations are presented in Figs. 5–7.

From Figs. 5–7, it can be observed that under the conditions corresponding to Scenarios 1, 2, and 3, the system exhibits three distinct evolutionarily stable points: $E_4(0,0,1)$, $E_5(1,1,0)$, and $E_8(1,1,1)$. In other words, the combinations of strategies {not implementing the ICP, negatively reducing emissions, positive supervision}, {implementing the ICP, positively reducing emissions,

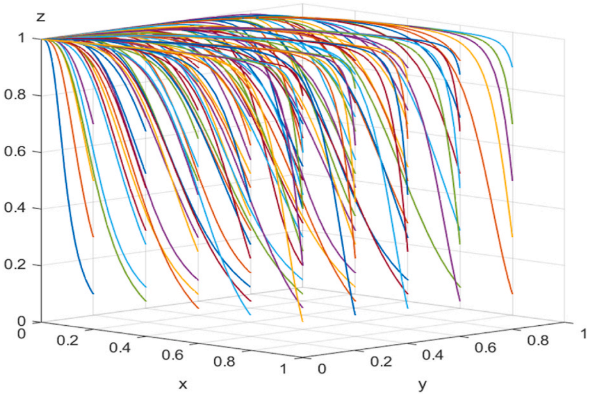

Fig. 5. The evolution result of array 1.

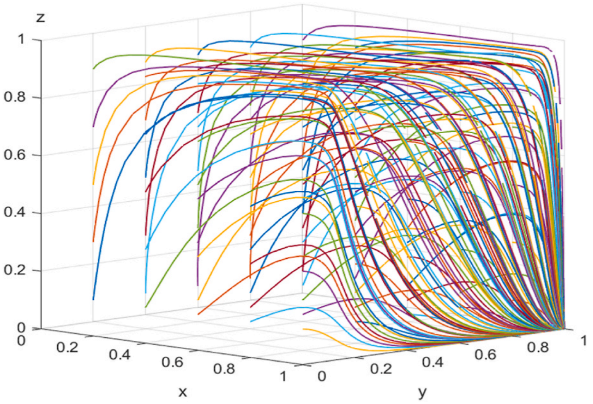

Fig. 6. The evolution result of array 2.

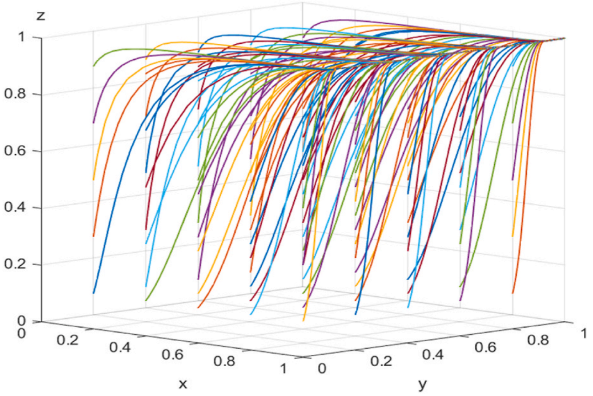

Fig. 7. The Evolution result of array 3.

negative supervision}, and {implementing the ICP, positively reducing emissions, positive supervision} for enterprises, internal organizations, and governments represent three evolutionarily stable strategy combinations. This confirms the consistency and validity of the simulation analysis with the stability analysis of the strategies from different parties. It underscores the practical significance of guiding the implementation of ICP for enterprises.

In the following sections, the main purpose is to discuss the influence of key parameters on the strategy choices of tripartite in the game. When the initial values of decision-making for enterprises, internal organizations, and the government are all pure strategies, they have two choices: 0 and 1. Given the governments' strong commitment to environmental protection and the effective reduction of enterprises' carbon emissions through the implementation of the ICP, as well as the positive effect of governments' positive supervision towards enterprises, we primarily focus on the strategy combination $E_8(1,1,1)$. Then, this paper will in further analyze the evolutionary trends of the relevant factors in the scenarios where enterprises choose to implement ICP, internal organizations choose to actively reduce emissions and governments choose to actively regulate enterprises carbon emissions. Here, we would like to emphasize that the parameter values in Array 3 not only meet the conditions for the stability of $E_8(1,1,1)$ but also, to some extent, draw from previous scholarly research [47–50] and consider certain real-world situations. Therefore, subsequent parameter analyses will be based on Array 3 as the reference point for analysis.

5.2. *Sensitivity analysis of enterprises' ICP implementation cost*

When the initial probabilities x,y and z are at a low level, i.e., $x = y = z = 0.2$, the impact of internal carbon pricing implementation costs on the evolutionary trajectory of enterprises and internal organizations is explored by gradually increasing the cost of internal carbon pricing implementation while keeping other parameters constant. The evolutionary trajectories of the strategies choices of enterprises and internal organizations are presented as Fig. 8.

From Fig. 8, it can be seen that the reduction of the ICP implementation cost C_m can accelerate the evolution of the enterprises' implementation of the ICP and the internal organization's active emissions reduction. This indicates that the reduction in the internal carbon pricing implementation cost has a positive impact on the enterprises' choice of "implementing internal carbon pricing" and the internal organizations' choice of "actively reducing emissions" strategies. In other words, when the initial probabilities of enterprises,

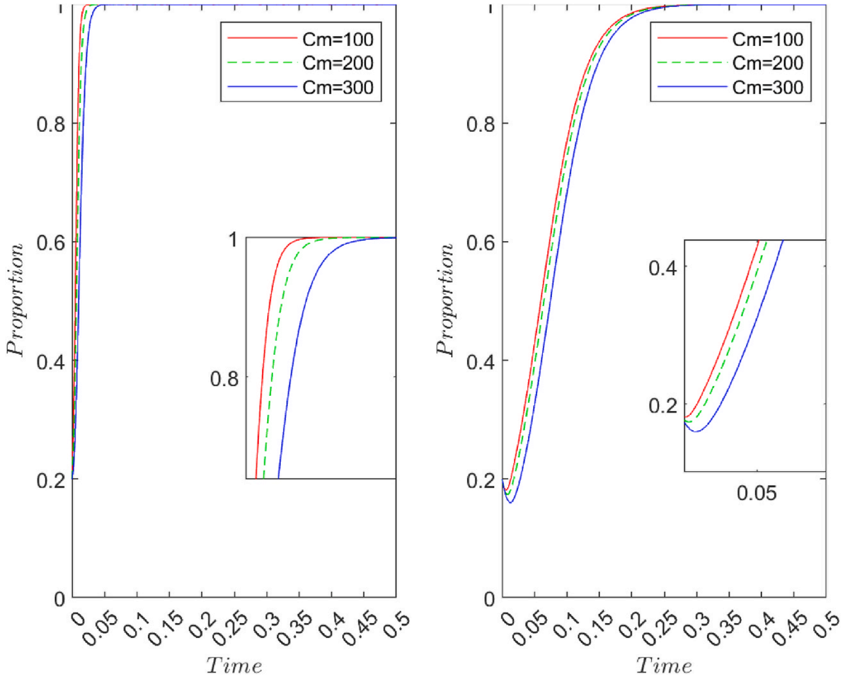

Fig. 8. The evolutionary trajectories of enterprises (left) and internal organizations (right).

internal organizations, and governments are relatively low, continuously lowering the internal carbon pricing implementation cost can expedite the evolution of enterprises and internal organizations toward positive states. When $C_m = 100$, the evolution time required to implement the ICP for enterprises and to actively reduce emissions for the internal organizations is the shortest.

From the right side of the above figure, it becomes evident that, regardless of the cost associated with ICP implementation, internal organizations tend to adopt the passive emissions reduction strategy during the initial short period. Furthermore, within this initial timeframe, the higher the cost of ICP (denoted as C_m), the more likely internal organizations are to be inclined towards passive emissions reduction. However, when a certain threshold in time is surpassed, internal organizations tend to transition towards the active emissions reduction strategy. This phenomenon can be attributed to the following reason. When enterprises first embark on implementing the ICP, they may not have established a fully developed framework, and the regulations initially introduced might not

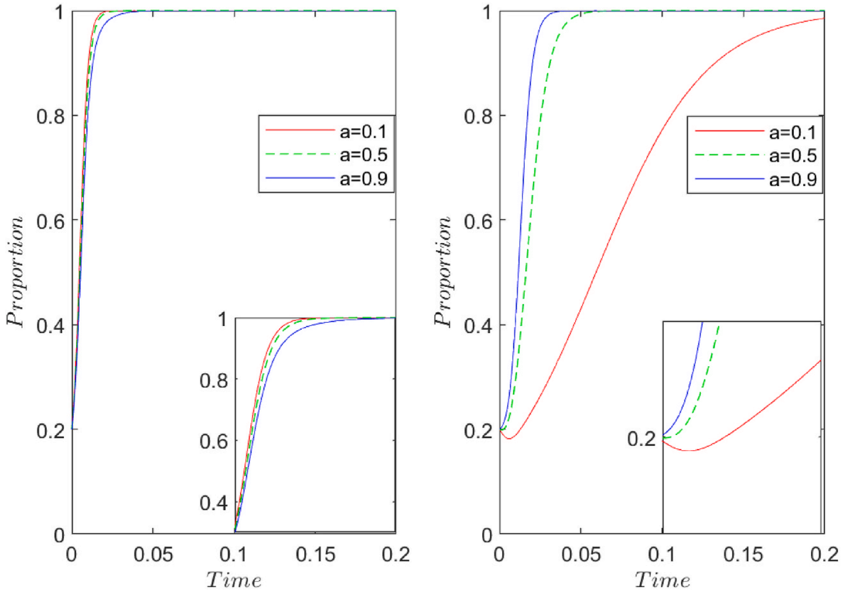

Fig. 9. The evolutionary trajectories of enterprises (left) and internal organizations (right).

be perfectly suited to their specific needs. Consequently, internal organizations might lack confidence in these systems, leading them to initially opt for passive emissions reduction strategies. Nevertheless, with the passage of time, enterprises accumulate knowledge and experience, thereby refining their management systems and enabling the policies they adopt to better align with their internal environment. This progress enhances the confidence of internal organizations, making them more inclined to collaborate with enterprises in actively reducing emissions. In summary, the implementation of the ICP may present initial challenges for enterprises. However, in pursuit of carbon emission reduction objectives, it remains imperative for enterprises to expedite the establishment of the ICP system. During the early stages of ICP system implementation, it is advisable for enterprises to establish scientific and robust management mechanisms, foster enhanced communication with internal organizations, and boost the confidence of these internal entities in actively participating in emissions reduction efforts [51].

5.3. Sensitivity analysis of internal carbon fee return ratio

The impact of internal carbon fee return ratio a on the evolutionary trajectory of enterprises and internal organizations is explored by gradually increasing the internal carbon fee return ratio while keeping other parameters constant, when $x = y = z = 0.2$, The evolutionary trajectories of the strategies choices of enterprises and internal organizations are presented as Fig. 9.

As shown in Fig. 9, regardless of whether the internal carbon fee rebate rate is high or low, enterprises tend to eventually implement ICP. However, the magnitude of the rebate rate determines the duration required for enterprises to evolve into the ESS (Implementing Internal Carbon Pricing Strategy). When the internal carbon fee rebate rate is 0.1, enterprises reach the ESS in the shortest amount of time, displaying the fastest evolution. This can be attributed to the fact that a lower carbon fee rebate rate exerts minimal impact on normal enterprises' operations, thus alleviating financial pressure. The reduced financial burden makes it easier for enterprises to take the necessary steps for implementing the internal carbon pricing strategy within a shorter timeframe. It may also encourage enterprises to participate more actively in internal carbon pricing implementation. However, when the internal carbon fee rebate rate reaches 0.9, the time required for enterprises to achieve ESS (Implementing Internal Carbon Pricing Strategy) is at its longest, and the rate of evolution is significantly reduced. This phenomenon can be attributed to the higher rebate rate imposing excessive costs on enterprises, adversely affecting their regular operations. The high rebate rate implies that enterprises are obligated to refund a larger portion of the carbon fees, which can lead to financial strain, resource shortages, thereby dampening their enthusiasm to actively engage in internal carbon pricing. Furthermore, the substantial carbon fee refunds might leave enterprises with inadequate financial support for implementing internal carbon pricing, making it more challenging to take the necessary steps, resulting in a decelerated evolutionary pace and potentially delaying the attainment of ESS. Thus, the high rebate rate not only increases the financial burden on enterprises but may also hinder the further development of their internal carbon pricing initiatives. Therefore, careful consideration is required when setting the rebate rate to achieve optimal outcomes.

On the other hand, from the right part of Fig. 9, it is evident that for internal organizations, during the early stages of evolution, irrespective of whether the internal carbon fee rebate rate is high or low, they tend to favor the passive emission reduction strategy. Furthermore, the lower the carbon fee rebate rate, the more pronounced the inclination of internal organizations towards passive emission reduction. However, as the carbon fee rebate rate increases, the evolutionary duration of the tendency of internal organizations towards passive emission reduction becomes progressively shorter. Beyond a certain critical time point, regardless of the carbon fee rebate rate set by the enterprise, internal organizations tend to favor active emission reduction strategies. The higher carbon fee rebate rate accentuates the inclination of internal organizations towards active emission reduction, reducing the time needed for them to evolve into the ESS (active emission reduction) state. When the rebate rate is 0.1, internal organizations require the longest time to evolve into the ESS, and their evolutionary pace is the slowest. At a rebate rate of 0.5, internal organizations show a noticeable improvement in evolutionary speed and a significant reduction in the time required for evolution. When the rebate rate is 0.9, although internal organizations evolve into ESS in the shortest time and have the fastest evolution speed, compared to the 0.5 rebate rate, there is no significant increase in the rate of evolution or the time required for evolution. It indicates that the return ratio of 0.5 is already sufficient to encourage active participation of internal organizations in emission reduction. Further increasing the return ratio may not significantly enhance the adoption of proactive emission reduction strategies by internal organizations.

The possible reasons for the observed phenomenon are as follows: First, it is evident that the transition of internal organizations from passive emission reduction strategies to proactive strategies occurs after a certain critical time threshold. This indicates that internal organizations need to undergo a learning and adaptation period before embracing proactive emission reduction. By accumulating experience and learning, internal organizations will be more aware of how to integrate emission reduction measures into their operations, which shortens the time it takes for them to evolve to a positive emission reduction strategy. Second, when the internal carbon fee return ratio is low (e.g., 0.1), internal organizations perceive limited financial incentives for their active participation in emission reduction measures, as the returned amount is insufficient to significantly impact their financial resources. When the carbon fee return ratio is set at 0.5, the returned amount is adequate to incentivize internal organizations to adopt proactive emission reduction measures. This higher return ratio alleviates financial constraints on internal organizations, expedites their evolutionary process, and reduces the time required to reach the proactive emission reduction state.

The above analysis demonstrates a significant relationship between the carbon fee return ratio and the long-term incentives for internal organizations to proactively reduce emissions. This aspect holds paramount importance in the effective implementation of the ICP by enterprises. Therefore, when devising carbon fee return system, enterprises should exercise prudence and refrain from blindly increasing or decreasing the carbon fee return ratio. They should take a comprehensive approach, considering the specific circumstances of both the enterprises and internal organizations. An optimal approach is to allocate half of the carbon fee to internal organizations. This is because a carbon fee return ratio of 0.5 yields the most pronounced incentive effect on internal organizations.

Simultaneously, it provides the greatest motivation for enterprises, without imposing a significant operational burden. In this manner, it effectively encourages internal organizations to actively engage in emission reduction efforts.

5.4. Sensitivity analysis of governments' subsidies

The impact of governments' subsidies M on the evolutionary trajectory of enterprises and internal organizations is explored by gradually increasing the governments' subsidies while keeping other parameters constant, when $x = y = z = 0.2$, The evolutionary trajectories of the strategies choices of enterprises and governments are presented as Fig. 10.

As observed in the left section of Fig. 10, when governments provide subsidies to enterprises for carbon emission reduction – regardless of the subsidy amount – enterprises display a growing inclination towards adopting the ICP. With an increase in subsidies, the time required for enterprises to achieve the ESS shortens, and the rate of evolution accelerates with a decreasing amount. However, the distinction between higher and lower subsidy levels for enterprises during the evolution process is not particularly significant. This implies that it is not the case that the more subsidies the governments give to enterprises to reduce emissions, the greater the incentive for enterprises to evolve to ESS.

The analysis of the right portion of Fig. 10 reveals that the higher the carbon emission reduction subsidies governments provide to enterprises, the longer it takes for governments to evolve into the ESS (active supervision). Furthermore, the longer it takes for governments to evolve into the ESS, and the more unfavorable it is for governments to actively supervise enterprises. When governments establish subsidies for enterprises at half of the benefits derived from their credibility, denoted as $M = \frac{1}{2}R_g$, it presents the most effective incentive for governments to reach the ESS. Conversely, an excess of subsidies fails to significantly motivate enterprises and instead places a financial burden on governments, consequently prolonging their evolution towards actively regulating enterprises.

The reasons for the observed phenomenon are as follows: Higher carbon emission reduction subsidies imply that governments need to allocate more fiscal resources to support enterprises in their emission reduction efforts. This can potentially burden governments financially and consequently extend governments' evolutionary process. However, when governments subsidy to enterprises are set at half of the benefits derived from governments' credibility, that is when $M = \frac{1}{2}R_g$, it provides the most effective incentive. This setting effectively encourages enterprises to engage in active emission reduction while taking into consideration governments' fiscal situation to avoid an excessive financial burden. Therefore, under these circumstances, governments evolve into the active regulatory stage more quickly. In summary, the appropriate level of subsidies is crucial in the interaction between enterprises and businesses, as excessive or insufficient subsidies may lead to unfavorable outcomes.

The analysis above indicates that governments have the capacity to motivate enterprises to adopt the ICP, regardless of the quantity of governments' subsidies for carbon reduction. The magnitude of the subsidy has a negligible impact on enterprises but a more substantial influence on governments. Excessive subsidies result in a considerably longer time for governments to transition to the ESS (Active supervision). Therefore, it is advisable for governments to set the subsidy at half of the income derived from their credibility, as this approach maximizes incentives for both enterprises and governments. Additionally, governments can implement diverse

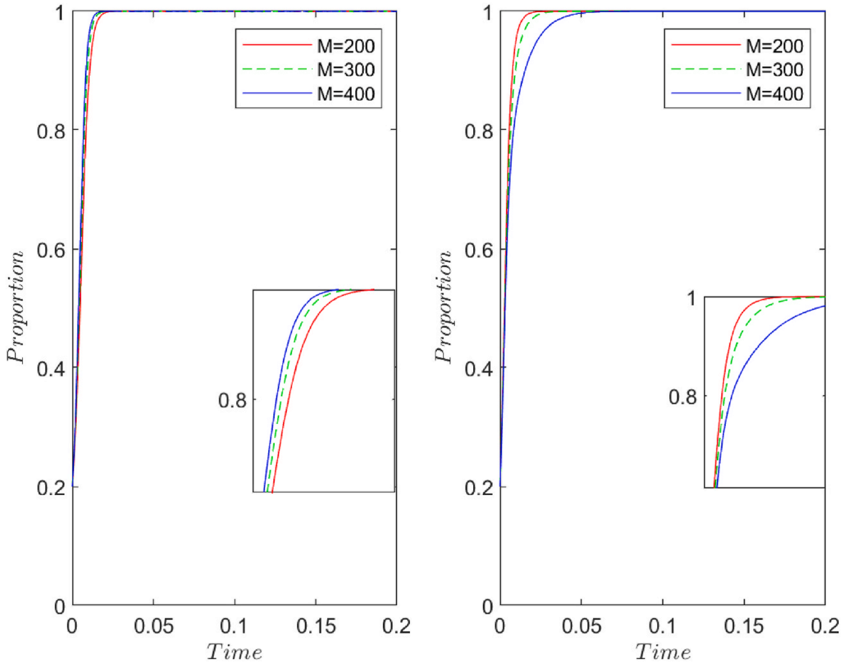

Fig. 10. The evolutionary trajectories of enterprises (left) and governments (right).

innovation incentive policies, reduce material subsidies as necessary, and augment non-material incentives and policy-based incentives to alleviate governments' financial burden while stimulating enterprises to implement the ICP. For example, governments can confer honorary titles upon enterprises to enhance their societal influence and introduce pertinent policies to alleviate the financial challenges faced by enterprises in terms of securing funding [52].

5.5. Sensitivity analysis of internal carbon price

The impact of internal carbon price P on the evolutionary trajectory of enterprises and internal organizations is explored by gradually increasing the internal carbon price while keeping other parameters constant, when $x = y = z = 0.2$, The evolutionary trajectories of the strategies choices of enterprises and internal organizations are presented as Fig. 11.

As shown in the left part of Fig. 11, regardless of whether the internal carbon price is high or low, enterprises eventually tend to implement the Internal Carbon Pricing (ICP). However, the internal carbon price determines the length of time for enterprises to reach the ESS (Implementing the ICP). When the internal carbon price is 40, the evolution time required to reach the ESS is the shortest, and the rate of evolution is the fastest. As the internal carbon price decreases, it takes longer for enterprises to evolve towards the ESS. This is because when internal organizations emit a certain amount of carbon, the higher the carbon price set by enterprises, the higher the carbon fees charged by enterprises. The higher carbon fees have several advantages. On one hand, it encourages internal organizations to better conserve energy and reduce carbon emissions, thereby enhancing the corporate image of social responsibility and sustainable business practices, which can attract more customers, investors, and employees. On the other hand, the increased internal carbon price signifies higher environmental revenue generated by enterprises, indicating a stronger commitment to environmental protection. Therefore, regardless of the specific level of the internal carbon price, enterprises are inclined to implement the ICP.

In the case of internal organizations (as shown in the right part of Fig. 11), during the early stages of evolution, regardless of whether the internal carbon price is high or low, internal organizations lean towards adopting the negative emission reduction strategy. The lower the internal carbon price, the more pronounced their inclination towards negative emission reduction. However, as the internal carbon price increases, the evolution time of their negative emission reduction tendency becomes progressively shorter. Once a certain time threshold is reached, internal organizations tend to shift towards active emission reduction. A higher internal carbon price results in a quicker transition. When the internal carbon price is set at $P = 20$, it takes the longest time for internal organizations to reach the ESS (Actively reducing emissions). With $P = 30$, the rate of internal organizations' evolution significantly increases, and the stabilization time for this evolution is considerably shortened. When $P = 40$, the time required for evolution is at its minimum, and the rate is at its highest. This indicates that a higher internal carbon price imposes more stringent carbon emission reduction requirements on internal organizations, increasing their motivation for active emission reduction. As a result, internal organizations are inclined to actively reduce emissions. Therefore, when establishing the internal carbon price, enterprises should strive to set the internal carbon price as high as possible, while also considering the specific circumstances of both the enterprises and their internal organizations to encourage active emission reduction.

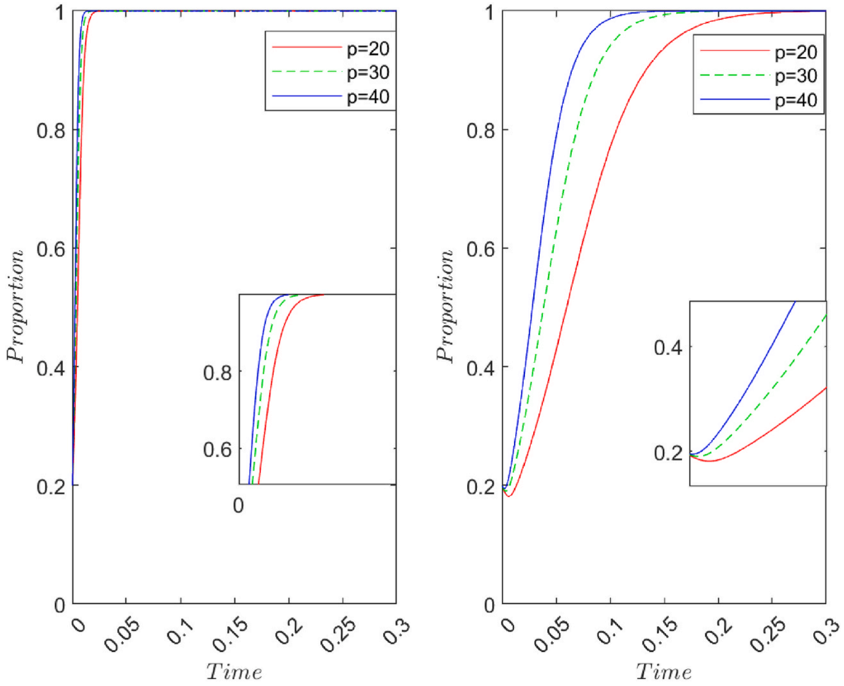

Fig. 11. The evolutionary trajectories of enterprises (left) and internal organizations (right).

6. Conclusions

6.1. Conclusions

The evolutionary game of implementing ICP is an emerging area of enterprises' carbon emission reduction. Firstly, under the premise of bounded rationality among participants, this paper calculates the expected payoffs for enterprises, internal organizations, and governments, constructing the expected payoff matrix for the entire system. Subsequently, this paper delves into the analysis of the conditions required for the system to evolve into the stable state and the various stable states that the system might reach. Furthermore, an in-depth analysis is conducted on relevant parameters, including the implementation costs of internal carbon pricing and the internal carbon fee return ratio, examining their impact on the evolutionary processes of the involved game participants. Following this, the paper provides key findings based on the aforementioned analysis and offers specific recommendations for the relevant stakeholders.

The main conclusions of this paper are as follows.

(1) When the relevant parameters satisfy the following conditions: $-M - Pe + aPe + C_m < 0$, and $M - R_m < 0$ (namely, the sum of carbon fee Pe and governments subsidies M is more than the sum of carbon fee returned to the internal organizations aPe and ICP implementation costs C_m, and enterprises' production and operation R_m is more than the governments' subsidies M), the entire system will evolve to the optimal state, where the corresponding ESS is $E_8(1,1,1)$, and the strategic choices for the enterprise, internal organizations, and government are represented as {implementing the ICP, positively reducing emissions, positive supervision}. It means enterprises tend to implement the ICP, internal organizations tend to actively reduce emissions, and governments also tend to actively supervise enterprises. At this point, the whole system can achieve the Pareto optimum. Therefore, to achieve carbon emission reduction targets and successfully implement the ICP within enterprises, governments should consider providing appropriate carbon emission reduction subsidies for enterprises. The allocation of these subsidies will help ensure that enterprises have sufficient financial incentives to implement ICP. However, the subsidy amount should not be excessive, as excessively high subsidies do not significantly increase the willingness of enterprises to implement ICP. Moreover, more subsidies place an additional financial burden on governments, which is not conducive to governments' evolution toward the stable state of active regulation. Simultaneously, enterprises should formulate clear carbon pricing strategies and plans to anticipate potential costs and challenges in advance, with the aim of minimizing the implementation costs of ICP wherever possible.

(2) For enterprises, the implementation cost of Internal Carbon Pricing (ICP), internal carbon fee return ratio, governments' subsidies, and internal carbon price are critical factors influencing the outcome of their evolutionary game. When the initial evolutionary probabilities of enterprises, internal organizations, and governments, along with relevant parameters, meet the conditions for the optimal equilibrium point $E_8(1,1,1)$, lowering the implementation cost and carbon fee return ratio, as well as increasing governments' subsidies and the internal carbon price, will expedite the evolution of enterprises into the active stable state ("Implementing an internal carbon pricing" strategy). The lower the implementation cost of ICP, the shorter the time required for enterprises to evolve into the active stable state, and the faster the rate of evolution. Therefore, enterprises should focus on reducing the implementation cost of ICP, for example, by adopting more efficient technologies, improving resource utilization, saving energy and materials, and optimizing internal processes. The internal carbon fee return ratio represents the proportion of carbon fees returned by enterprises to internal organizations. A lower internal carbon fee return ratio motivates enterprises to evolve into the stable state ("Implementing an internal carbon pricing" strategy), while a higher return ratio inhibits their motivation to reach the stable state. However, in terms of the magnitude of increased incentive effect, the carbon fee return ratio of 0.5 results in the greatest incremental motivation for enterprises. Therefore, enterprises can use 0.5 as a reference when setting carbon fee return ratios. Governments' subsidies can incentivize enterprises to evolve to the stable state, however, it is not the case that the more governments' subsidies, the greater the incentive effect on enterprises. The increase in the amount of governments' subsidies does not have a significant incentive effect on the increase in the evolutionary speed of enterprises. Therefore, enterprises should ensure compliance and transparency of emission reduction measures. This can increase the governments' trust in the enterprises and help ensure the governments' long-term subsidy support to the enterprises. Regarding internal carbon price, irrespective of the specific internal carbon price, under the conditions of meeting system evolution criteria, enterprises will ultimately choose "Implementing an internal carbon pricing" strategy. The higher the internal carbon price, the shorter the time for enterprises to evolve into the stable state, and the faster the rate of evolution. As the internal carbon price decreases, the time required for enterprises to evolve to the stable point increases. Therefore, when setting internal carbon prices, enterprises can maximize the internal carbon price without compromising the enthusiasm of internal organizations for emissions reduction.

(3) For internal organizations, the key factors influencing their evolutionary outcomes are the implementation cost of ICP, the carbon fee return ratio, and the internal carbon price. Overall, in the early stages of implementing the ICP, internal organizations tend to choose the "passive emission reduction" strategy. However, as time evolves, internal organizations will ultimately opt for the "active emission reduction" strategy. From the perspective of the impact of relevant parameters, the lower the implementation cost of ICP, the shorter the time it takes for internal organizations to evolve toward the "active emission reduction" strategy. Therefore, enterprises should minimize the implementation cost of ICP and optimize the design system of ICP, so as to motivate internal organizations to cooperate with enterprises. Regarding the carbon fee rebate ratio, when it is at a lower level, the initial tendency of internal organizations to "reduce emissions negatively" is the most obvious, and the time it

takes for them to evolve towards the “active emission reduction” strategy is the longest, with the slowest evolutionary pace. However, when the internal carbon fee rebate ratio is set at 0.5, the initial “passive emission reduction” inclination of internal organizations significantly shortens in time, and the pace of evolution towards the “active emission reduction” strategy experiences a substantial acceleration, indicating that this carbon fee rebate ratio has the most significant motivational impact on internal organizations. When the rebate ratio is at a higher level, although the speed at which internal organizations evolve towards the “active emission reduction” strategy is further enhanced, the motivation is not as pronounced as that achieved with the rebate ratio of 0.5. Therefore, it is advisable for internal organizations to engage in productive negotiations with enterprises and consider setting the carbon fee rebate ratio at 0.5 or close to that level to maximize the motivation for active emission reduction. Lastly, concerning internal carbon price, the higher the internal carbon price set by enterprises, the more pronounced the tendency of internal organizations to choose the “active emission reduction” strategy, with the fastest evolutionary pace. Therefore, internal organizations can actively support enterprises in establishing an appropriate internal carbon price, ensuring that this price aligns with the enterprises’ emission reduction strategy while maximizing the motivation for internal organizations to actively reduce emissions.

(4) For governments, in the game model presented in this paper, governments oversee enterprises’ carbon emissions. When governments choose the " positive regulation” strategy, they provide subsidies to enterprises actively implementing ICP, thereby enhancing their credibility. Conversely, when governments choose the “passive regulation” strategy, no subsidies are provided to any enterprises, and their credibility remains unaffected. Therefore, governments’ subsidies are a key factor influencing their evolutionary trajectory and outcomes in this context. The results from the simulation analysis indicate that when governments’ subsidies account for half of the benefits in terms of credibility, the speed at which governments evolve into the " positive regulation” strategy experiences the most significant improvement, resulting in a notably shortened evolution process. In addition, excessive government subsidies can reduce the government’s enthusiasm for regulating enterprises and prolong the time for the government to evolve into the stable state. Therefore, governments should exercise prudence in determining the subsidy amount. It should ensure that the subsidy is not too high, as this might diminish enterprises’ motivation, while also ensuring that the incentive is sufficient for enterprises to implement ICP. The subsidy amount should be set at half of the benefits gained in terms of governments’ credibility, i.e., $= \frac{1}{2}R_g$, which will provide the maximum incentive while mitigating the governments’ financial burden.

6.2. Managerial recommendations

With the continuous improvement of various low-carbon emission reduction regulations in alignment with China’s “double carbon” objective, it is imperative for enterprises to shift away from a “profits-first” mindset and adopt a more proactive approach in implementing Internal Carbon Pricing (ICP) systems [53]. In the course of ICP system implementation, enterprises should emphasize the importance of scientific and technological innovation while striving to continually reduce the costs associated with ICP implementation. Moreover, fostering open lines of communication with governmental bodies and actively embracing social responsibilities are pivotal for securing government support. Furthermore, in determining the internal carbon price and the internal carbon fee return ratio, enterprises should engage in constructive negotiations with their internal organizations. It is essential to take into full consideration the practical circumstances of internal organizations to formulate carbon pricing and fee return ratios that are mutually advantageous. Internal organizations, on their part, should actively collaborate with enterprises in the implementation of the ICP system, thereby aiding enterprises in improving their social reputation. Additionally, governments have the option to amplify emissions reduction subsidies for enterprises, yet these subsidies should not surpass the regular operational revenue of enterprises nor exceed half of the benefits derived from the government’s credibility. Furthermore, governments can explore avenues to expand green financial resources and augment financial support for enterprises engaged in carbon emissions reduction efforts.

6.3. Limitations and research directions

This study analyses the behaviors strategy for implementing the internal carbon pricing system composed of enterprises, internal organizations, and governments, as well as the influence of relevant factors on the equilibrium of the system. However, this study has the following limitations. First, even though the simulation results align with the model analysis in this paper, the parameter values chosen are relatively abstract. To make it more realistic, future research needs to gather more real-world data, and with an ample amount of data, empirical research can be conducted. Second, this paper’s evolutionary game model mainly focuses on enterprises, internal organizations, and governments, while overlooking other relevant entities associated with enterprises, such as consumers and environmental organizations. These entities evaluate enterprises based on their carbon reduction performance, indirectly impacting the implementation of the internal carbon pricing system. Future research should aim to construct a more realistic model by considering a broader range of entities and their relationships. Last, this paper only considers internal factors within enterprises, such as the implementation cost of internal carbon pricing and the internal carbon price, in addition to certain external factors, such as governments’ subsidies’ impact on the ICP. It does not delve into the obstacles or challenges ICP may encounter in the real world. For instance, leadership support is crucial for the success of internal carbon pricing, and without it, implementation may be restricted. Furthermore, accurately measuring greenhouse gas emissions within enterprises is a complex task. Enterprises need to establish effective data collection and monitoring systems to identify and quantify emissions, often requiring substantial resource investment. In addition, internal carbon pricing may necessitate enterprises to provide more data and information to meet transparency and reporting requirements, potentially demanding changes in existing enterprises and data collection processes. These challenges represent real-world obstacles that ICP may encounter during implementation. Future research can parameterize the above issues to create a model that better reflects real-world scenarios.

Funding statement

This paper is supported by Harbin Science and Technology Innovation Talents Research Fund (No. 2022CXRCCG015); State Grid Heilongjiang Electric Power Co., Ltd. Technology Project No. SGHL0000FZJS2202122 (Analysis of Provincial Economic Operation and Policy Effectiveness Evaluation Based on Power Big Data and Blockchain Technology under the Dual Carbon Target).

Data availability statement

All data in this article are included in the paper.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Kai Wu: Project administration, Supervision. **E. Bai:** Conceptualization, Formal analysis, Investigation, Software, Writing – original draft, Writing – review & editing. **Hejie Zhu:** Methodology, Resources, Validation. **Zhijiang Lu:** Software, Validation, Visualization, Writing – review & editing. **Hongxin Zhu:** Data curation, Software, Visualization, 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.

References

[1] C. Fu, W. He, "Ecological overload" as a "civilizational variable":A historical view of ecological civilization [J], Theory Monthly (9) (2023) 142–152. http://10.14180/j.cnki.1004-0544.2023.09.015.

[2] J. Jewell, A. Cherp, On the political feasibility of climate change mitigation pathways: is it too late to keep warming below 1.5° C? [J], Wiley Interdiscipl. Rev.: Clim. Change 11 (1) (2020), e621.

[3] X. Peng, B. Li, P. Jin, Are informal culture institutions good for low-carbon economic transformation in China? A threshold regression analysis from a perspective of competition between local governments, J. Finance Econ. 39 (7) (2013) 110–121. http://10.16538/j.cnki.jfe.2013.07.007.

[4] K. Harpankar, Internal carbon pricing: rationale, promise and limitations, Carbon Manag. 10 (2) (2019) 219–225. http://10.1080/17583004.2019.1577178.

[5] T. Abe, S. Goodrich, S. Lavos, A. Leiser, Emerging Practices in Internal Carbon Pricing. A Practical Guide [J], World Business Council for Sustainable Development, 2015. Retrieved from.

[6] N. Bartlett, H. Cushing, S. Law, Putting a Price on Carbon: Integrating Climate Risk into Business Planning [J]. Carbon Disclosure Project, CDP) North America, New York, NY, USA, 2017.

[7] P. Ducret, B. Leguet, J.-D. Senard, S. Fischer, P. Canfin, A. Grandjean, et al., Internal Carbon Pricing. A Growing Corporate Practice [J], 2016.

[8] O.G. Gorbach, N.S. Hussein, J. Thomsen, Impact of internal carbon prices on the energy system of an organisation's facilities in Germany, Japan and the United Kingdom compared to potential external carbon prices, Energies 14 (14) (2021). http://10.3390/en14144094.

[9] M. Liu, Achievements, deficiencies and countermeasures of China's carbon emission trading practice [J], J. Anhui Normal Univ. (Humanties Soc. Sci.) 49 (3) (2021) 119–124. http://10.14182/j.cnki.j.anu.2021.03.014.

[10] P.Y. Nie, C. Wang, H.X. Wen, Optimal tax selection under monopoly: emission tax vs carbon tax [J], Environ. Sci. Pollut. Control Ser. 29 (8) (2022) 12157–12163. http://10.1007/s11356-021-16519-1.

[11] N. Bento, G. Gianfrate, J.E. Aldy, National climate policies and corporate internal carbon pricing [J], Energy J. 42 (5) (2021) 89–100. http://10.5547/01956574.42.5.nben.

[12] J.L. Ma, J. Kuo, Environmental self-regulation for sustainable development: can internal carbon pricing enhance financial performance? Bus. Strat. Environ. 30 (8) (2021) 3517–3527. http://10.1002/bse.2817.

[13] N. Bento, G. Gianfrate, Determinants of internal carbon pricing [J], Energy Pol. 143 (2020). http://10.1016/j.enpol.2020.111499.

[14] F. Riedel, G. Gorbach, C. Kost, Barriers to internal carbon pricing in German companies [J], Energy Pol. 159 (2021). http://10.1016/j.enpol.2021.112654.

[15] O.G. Gorbach, C. Kost, C. Pickett, Review of Internal Carbon Pricing and the Development of a Decision Process for the Identification of Promising Internal Pricing Methods for an Organisation [J], vol. 154, Renewable & Sustainable Energy Reviews, 2022. http://10.1016/j.rser.2021.111745.

[16] O.G. Gorbach, J. Thomsen, Comparing the energy system of a facility with uncertainty about future internal carbon prices and energy carrier costs using deterministic optimisation and two-stage stochastic programming [J], Energies 15 (10) (2022). http://10.3390/en15103836.

[17] A. Trinks, M. Mulder, B. Scholtens, External Carbon Costs and Internal Carbon Pricing [J], vol. 168, Renewable & Sustainable Energy Reviews, 2022. http://10.1016/j.rser.2022.112780.

[18] W. Ben-Amar, M. Gomes, H. Khursheed, S. Marsat, Climate change exposure and internal carbon pricing adoption, Bus. Strat. Environ. 31 (7) (2022) 2854–2870. http://10.1002/bse.3051.

[19] L.P. Kuo, B.G. Chang, Ambitious corporate climate action: impacts of science-based target and internal carbon pricing on carbon management reputation-Evidence from Japan [J], Sustain. Prod. Consum. 27 (2021) 1830–1840. http://10.1016/j.spc.2021.04.025.

[20] J.I.A.N.G. Jinhe, Analysis of carbon pricing mechanism and proposals on the improvement of China's carbon market under carbon neutralization [J], Price: Theory & Practice (2) (2022) 26–30+90. http://10.19851/j.cnki.cn11-1010/f.2022.02.039.

[21] Z. Bangzhu, X. Chenxin, W. Ping, Z. Chong, W. Zhanchi, S. Luyang, Does internal carbon pricing scheme achieve a win-win carbon emission reduction and revenue increase? [J], Account. Res. (4) (2021) 178–192.

[22] J.F. Shi, Y.Q. Su, Behavioural strategies of manufacturing firms for high-quality development from the perspective of government participation: a three-part evolutionary game analysis [J], Heliyon 9 (4) (2023). http://10.1016/j.heliyon.2023.e14982.
[23] K. Sigmund, M.A. Nowak, Evolutionary game theory [J], Curr. Biol. 9 (14) (1999) R503–R505.
[24] L. Samuelson, Game theory in economics and beyond [J], J. Econ. Perspect. 30 (4) (2016) 107–130. http://10.1257/jep.30.4.107.
[25] G.L. Munck, Game theory and comparative politics: new perspectives, old interests, Dados - Rev. Ciências Sociais 43 (3) (2000) 559–600. http://10.1590/s0011-52582000000300005.
[26] A.V. Thakor, GAME-THEORY in finance [J], Financ. Manag. 20 (1) (1991) 71–94. http://10.2307/3666098.
[27] Y. Shoham, Computer science and game theory [J], Commun. ACM 51 (8) (2008) 74–79. http://10.1145/1378704.1378721.
[28] Z. Ernst, Game Theory in Evolutionary Biology [M], 2007.
[29] M. Voorneveld, An introductory course on mathematical game theory [J], Game. Econ. Behav. 71 (2) (2011) 534–538. http://10.1016/j.geb.2010.12.006.
[30] T.L. Vincent, J.S. Brown, Evolutionary Game Theory, Natural Selection, and Darwinian Dynamics [M], Cambridge University Press, 2005.
[31] J.S. Brown, T.L. Vincent, A theory for the evolutionary game [J], Theor. Popul. Biol. 31 (1) (1987) 140–166. http://10.1016/0040-5809(87)90026-8.
[32] J.M. Alexander, Evolutionary Game Theory [J], Elements in Decision Theory and Philosophy, 2009.
[33] C. Adami, J. Schossau, A. Hintze, Evolutionary game theory using agent-based methods [J], Phys. Life Rev. 19 (2016) 1–26.
[34] Yang J, Wang F, Zhang W, An B. Research on the Influence Mechanism of Charitable Donation on Company Loss Reversal: Baed on the Perspective of Organizational Legitmacy [J] J. Syst. Manag.: 1-24, https://kns.cnki.net/kcms/detail/31.1977.N.20231030.1649.002.html.
[35] S. Li, Research on the construction of intelligent management accounting system for energy enterprises under the "dual carbon", Goal [J]. Fin. & Account. (19) (2022) 55–60.
[36] Liu, WU, Zhang. Evolutionary Game of Value Co-Destruction of the Ecosystem of Live Commerce Platform [J]. Chin. J. Manag. Sci.: 1–13.http://10.16381/j.cnki.issn1003-207x.2022.0951.
[37] J. Sun, L. Yang, C. Teng, Decision and Coordination of low-carbon closed-loop supply chain considering government subsidies and equity cooperation [J], J. Syst. Eng. 38 (4) (2023) 540–554. http://10.13383/j.cnki.jse.2023.04.008.
[38] Bai Y, Zhao X, Ding L. Research on Chinese Emission Allowances Storage and Lending Mechanism Considering Enterprise Time Preference [J]. Chin. J. Manag. Sci.: 1-13.http://10.16381/j.cnki.issn1003-207x.2022.1151.
[39] H. Wen, Z. Zhang, X. Zou, An evolution game analysis of farmers' participation in E-commerce behavior driven by policies [J], J. Jilin Bus. Technol. College 39 (4) (2023) 13–20. http://10.19520/j.cnki.issn1674-3288.2023.04.015.
[40] J. Yang, Research on carbon asset management, exploitation and utilization of coal mine gas [J], Shanxi Coking Coal Sci. & Technol. 41 (Z1) (2017) 109–112.
[41] R. Sun, D. He, H. Su, Application of blockchain technology to preventing supply chain finance based on evolutionary game [J], Chin. J. Manag. Sci. (2022) 1–18. http://10.16381/j.cnki.issn1003-207x.2021.1538.
[42] J.L. Luo, M.J. Hu, M.M. Huang, Y.H. Bai, How does innovation consortium promote low-carbon agricultural technology innovation: an evolutionary game analysis [J], J. Clean. Prod. (2023) 384. http://10.1016/j.jclepro.2022.135564.
[43] L. Zhu, J. Rong, S. Zhang, Three-party evolutionary game and simulation analysis of drug quality supervision under the goernment reward and punishment mechanism [J], Chin. J. Manag. Sci. 29 (11) (2021) 55–67. http://10.16381/j.cnki.issn1003-207x.2019.0481.
[44] D. Friedman, Evolutionary games in economics [J], Econometrica: J. Econom. Soc. (1991) 637–666.
[45] R.O.N.G. Zhu, Zhang, Three-party evolutionary game and simulation analysis of drug quality supervision under the government reward and punishment mechanism [J], Chin. J. Manag. Sci. 29 (11) (2021) 55–67. http://10.16381/j.cnki.issn1003-207x.2019.0481.
[46] L. Zhu, J. Rong, S. Zhang, Three-party evolutionary game and simulation analysis of drug quality supervision under the government reward and punishment mechanism [J], Chin. J. Manag. Sci. 29 (11) (2021) 55–67. http://10.16381/j.cnki.issn1003-207x.2019.0481.
[47] W.Q. Guo, S.Q. Chen, M. Lei, Evolutionary game and strategy analysis of carbon emission reduction in supply chain based on system dynamic model [J], Sustainability 15 (11) (2023). http://10.3390/su15118933.
[48] T. Tang, Y. Chen, Exploration of carbon tax tools based on green tax experience [J], China Financ. (20) (2021) 71–72.
[49] S. Huang, Good practice of TCFD framework——a case study of microsoft's climate-related information disclosure [J], Finance Res. (3) (2022) 10–18. http://10.14115/j.cnki.10-1242/f.2022.03.001.
[50] M. Hu, H. Gao, J. Liao, J. Liu, Q. Jiang, Research on refining and chemical enterprise respond to "dual control" policy [J], Green Petrol. & Petrochem. 8 (2) (2023) 10–14+27.
[51] Q.I. Chen, Technical Route,System Innovation,and system guarantee for achieving carbon peak and carbon neutrality [J], Soc. Sci. Guangdong (2) (2022) 15–23 +286. https://kns.cnki.net/kcms/detail/44.1067.C.20220301.1035.006.html.
[52] J. Wei, C. Wang, Improving interaction mechanism of carbon reduction technology innovation between supply chain enterprises and government by means of differential game [J], J. Clean. Prod. 296 (2021). http://10.1016/j.jclepro.2021.126578.
[53] Yang, The time value and practical approach of bringing carbon peak and carbon neutralization into the overall layout of ecological civilization construction [J], Leading J. Ideol. & Theoretical Educ. (10) (2022) 147–153. http://10.16580/j.sxlljydk.2022.10.007.