Evolutionary game analysis of enterprise carbon emission regulation based on prospect theory

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Abstract
With the continuous development of a low-carbon economy, the issue of carbon emission regulation has attracted extensive attention. Considering the characteristics of bounded rationality and difference of risk perception in government and enterprises in the carbon emission regulation process, we construct an evolutionary game model based on prospect theory. Using this model, we analyze the evolutionary stability strategies of government and enterprises under the low, medium, and high risk of air quality deterioration. The results show that the cost-benefit ratio of government and enterprise is the threshold to distinguish the grade of air quality deterioration risk. When the risk of air quality deterioration is low, the government tends to be passive regulation and enterprises tend to traditional production. In the situation of medium risk, the strategy choice of government and enterprise is in a circular state. In the situation of high risk, the government tends to be passive supervision, while enterprises tend to choose low-carbon production. At the same time, there is an incentive paradox in the process of regulation of carbon emissions, but in the long run, it is more effective to strengthen the punishment of local governments’ passive regulation than to increase the punishment of enterprises.

Keywords Carbon regulation · Risk of air quality · Prospect theory · Evolutionary game · Incentive paradox

1 Introduction
With the rapid development of industrialization, people’s living standards have greatly improved; however, the massive consumption of fossil fuels has led to the rapid increase of greenhouse gas emissions in the process of industrialization, such as carbon dioxide (Yang et al. 2022a). The Intergovernmental Panel on Climate Change (IPCC) points out that carbon emissions from human activities are the main cause of global warming and frequent extreme weather (Edenhofer and Seyboth 2013). To restrain carbon emissions, the governments have promulgated various regulatory policies, for example, carbon tax, carbon cap-and-trade, carbon legislation, and so on (Chang et al. 2022).

Among the many factors affecting carbon emission, enterprise emission is the primary one. In the long term, low-carbon production can help enterprises avoid the risk of environmental penalties and offset the input cost, and finally achieve a win–win situation between environmental protection and profit targets (Porter and Van der Linde 1995). However, in the short term, the low-carbon investment of enterprises will increase the production cost of enterprises. Due to enterprises being more inclined to pursue certain economic benefits, it is difficult for enterprises to actively carry out a low-carbon investment with low short-term economic benefits and uncertain future returns (Hasan et al. 2021; Zhao et al. 2021). Enterprises will weigh whether to invest in low carbon according to the principle of maximum revenue, and they are possible to give up environmental protection for economic benefits (Clarkson et al. 2004; Zhang et al. 2021). As the main body of carbon emission supervision, the local government should actively supervise the carbon emission of enterprises in the region, however, the supervision requires more manpower, material resources, and financial costs, meanwhile, the production activities of enterprises play an...
important role in the growth of the local economy, and the growth of the local economy is conducive to the realization of local government performance. From this perspective, local governments also lack sufficient incentives to urge companies to engage in low-carbon production. Therefore, local governments may have an incomplete or distorted implementation of central government policies (Chen et al. 2020; Hu and Shi 2021).

Thus, we can see that carbon emission regulation is a game process between government and enterprises. Research on the dynamic relationship between government and enterprises in the regulatory process is crucial to improving the regulatory level and controlling carbon emissions.

In recent years, many scholars have studied the regulation of carbon emission from different aspects (Zhu et al. 2021; Yang et al. 2022b; Dong et al. 2022), but they did not take into account the bounded rationality and the dynamic relationship of the participants. In the process of carbon emission regulation, both the government and enterprises show the characteristics of bounded rationality. The evolutionary game can relax the rational assumption of game participants and effectively make up for the deficiency of traditional game theory. Based on this, Wang et al. (2020) studied the regulation of carbon emissions under the dual governance system of China by constructing an evolutionary game model between the central government, local government, and emission enterprises. Song et al. (2021) studied the government’s carbon emission supervision strategy for the construction industry based on the evolutionary game model. To improve the atmospheric environment of coastal areas, Jiang et al. (2020) studied the government’s supervision of shipping companies in carbon emission control areas by constructing an evolutionary game model. Kang et al. (2019) analyzed the impact of the government’s supervision policies on the emission reduction strategies of members in the supply chain. Deng et al. (2022) used the evolutionary game model to analyze the influence of government carbon emission regulation on the strategic choice of port enterprises and transportation enterprises.

Though the evolutionary game model can effectively relax the rational assumption of game players, however, there are subjective cognition biases of profit and loss in the evolutionary game between government and enterprise, this kind of cognition bias will affect the evolution trend of the game between government and enterprise. Prospect theory is the research achievement of psychology and behavioral science (Edwards 1996); it can effectively describe the different risk attitudes of decision makers toward the gains and losses in uncertain environments. Scholars have applied prospect theory to many fields, such as management science (Su et al. 2022; Liao et al. 2022) and economics (Barberis et al. 2021; Su et al. 2022). Some scholars have combined prospect theory and evolutionary game theory for research, for example (Shen et al. 2021; Xu et al. 2021), but there is less research on carbon regulation. Meanwhile, the strategies of the two players will change with the change of the environment during the game, the strategy choice between government and enterprise is different under different environmental quality, and this paper considers the strategic choices of government and enterprises under different circumstances. We summarize the differences between this study and existing literature in Table 1.

In addition, paradox often exists in management, and some scholars have studied the incentive paradox in the management process (Najm 2019; Kober and Thambur 2021; De Angelis 2021). Song et al. (2021) found that government increased interventions, such as penalties, subsidies, and public scrutiny, are more effective than improved carbon monitoring in controlling carbon emissions.

Therefore, based on previous studies, we use the prospect theory to modify the payment matrix in the traditional evolutionary game model and construct an evolutionary game model based on the prospect theory. Considering the impact of air quality on the strategic choice of government and enterprise in the game, we divide the risk of air quality deterioration into three levels. Using the game model analyzed the strategic choice of government and enterprises at different levels. At the same time, we combine the incentive paradox to analyze the problem of regulating emissions from the perspective of long term and short term. Finally, numerical simulation is used to describe the dynamic evolution strategies of government and enterprise in a different situation.

This paper has three main contributions.

(1) In this paper, the prospect theory is introduced into the carbon emission regulation game, and the payment matrix of the traditional evolutionary game is modified by the prospect theory, eliminating the subjective perception bias caused by the profit and loss of the government and enterprises in the uncertain environment. This research method is more consistent with the real situation.

(2) Considering the impact of environmental quality changes on government and enterprise strategy choices, we derive a threshold function, which divides the risk of air quality deterioration into three levels, and each level connects dynamically. Finally, we use the game model to analyze the strategic choices of the government and enterprises at each risk level. This method provides a theoretical basis for dynamic supervision in different states.
(3) We consider the incentive paradox that may occur in the regulatory process, and analyze the mode of regulation for government and enterprises from the perspective of long term and short term. This provides a new perspective for improving the efficiency of carbon emission regulation.

The rest of this paper is organized as follows. The second part is the construction of the dynamic game model. In the third part, we analyze the game model and the incentive paradox in supervision. In the fourth part, numerical simulation is carried out and the simulation results are described. In the fifth part, we summarize the whole paper and put forward the future research direction.

2 Dynamic game of carbon emission regulation

Government and enterprise are bounded rational subjects, they have their own strategic choices in terms of the perception of gains and losses, and therefore, this paper analyzes the strategic choice of government and enterprise by constructing an evolutionary game model based on prospect theory.

2.1 Prospect theory

The decision maker’s attitude toward risk is determined by the value function and the weight function. The prospect value $V$ represents the judgment made by decision makers based on their psychological feelings, as shown below:

$$V = \sum_{i=1}^{n} w(p_i)v(\Delta x_i) \quad (1)$$

where $w(p_i)$ represents decision weight; $v(\Delta x_i)$ represents the subjective perceived value of decision makers.

The subjective perceived value function proposed by Kahneman (1979) is a power function, the expression as:

$$v(\Delta x) = \begin{cases} \Delta x^{a_1}, & x \geq 0 \\ -\lambda(-\Delta x)^{a_2}, & x < 0 \end{cases} \quad (2)$$

The decision weight is the subjective judgment of the decision maker, according to the probability of the occurrence of the event, the expression as:

$$w(p_i) = \frac{p_i^a}{[p_i^a + (1 - p_i)^a]^r} \quad (3)$$

where $a_1$ and $a_2$ represent the sensitivity coefficient of decision makers to risks. $\lambda$ represents the risk aversion coefficient. Using the experimental method of Tversky, it can be concluded that $a = a_1 = a_2$ is approximately 0.88, $\lambda$ is approximately 2, and $r$ is approximately 0.61.

2.2 Model assumptions and construction

Hypothesis 1 There are only two parties in the game, government and carbon emission enterprises, both of them are bounded rational. Both sides do not have the optimal strategy at the beginning; they reach the optimal strategies through constant learning, trial and adjust in the game process.

Hypothesis 2 Government and enterprises have two choice strategies: positive regulation and passive regulation, low-carbon production and traditional production. As long as either the government or enterprises adopt a positive strategy, there is no possibility of air quality deterioration.

Hypothesis 3 Enterprises and government are more sensitive to local air quality and the strategies of the other side. In order to maximize profits, both the government and enterprises may engage in opportunistic behavior.
Hypothesis 4 The strategic choice of the two sides is based on the perception of their respective returns in the game. Both sides have the same risk avoidance coefficient and sensitivity. When the air quality does not deteriorate, both sides can obtain normal returns. The notations throughout this study are summarized in Table 2.

Based on the above assumptions, we can construct the perceived benefits of matrix of the government and enterprises as shown in Table 3.

When the government chooses positive regulation, enterprises choose low-carbon production. The total revenue of government is \( V_1 - C_1 \); \( V_1 \) represents the revenue perceived by government. The total revenue of the enterprise is \( V_2 - C_2 \). \( V_2 \) represents the revenue perceived by the enterprise. In this case, the possibility of air quality deterioration is 0. Therefore, we are taking 0 as the reference point; according to (1), \( V_1 \) and \( V_2 \) can be expressed as:

\[
V_1 = w (1 - p) \times v (\pi_1 - 0) + w (p) \times v (0 - m) \\
= v (\pi_1) > C_1
\]

\[
V_2 = w (1 - p) \times v (\pi_2 - 0) + w (p) \times v (0 - t) \\
= v (\pi_2) > C_2
\]

When the government chooses passive regulation and enterprises choose low-carbon production, the air quality deterioration will also not occur. Since the government does not pay regulatory costs, the total revenue of government is \( V_1 \), while the total revenue of enterprise is \( V_2 - C_2 \).

When the government chooses positive regulation and enterprises choose traditional production, the enterprise’s behavior will be quickly discovered and stopped by the government. Therefore, the air quality deterioration does not occur. After the production behavior of the enterprise is discovered by the government, the enterprise cannot obtain the expected revenue \( \pi_2 \) and needs to pay a fine \( D \). In this case, the revenue of the enterprise is \( V_3 \), while the revenue of the government is social revenue, because the fines collected are not treated as revenue, so the total revenue of the government is still \( V_1 - C_1 \). According to (1), \( V_3 \) can be expressed as:

\[
V_3 = w (1 - p) \times v (-D - 0) + w (p) \times v (0 - t) \\
= v (-D) > C_2
\]

When the government chooses passive regulation and enterprises choose traditional production, the possibility of air quality deterioration is \( p \). In the case of air quality deterioration, social benefits will be greatly reduced. At this point, the revenue of government is \( V_4 \). The government will also increase penalties on enterprises; the revenue of enterprise is \( V_5 \). Taking 0 as the reference point, according to (1), \( V_4 \) and \( V_5 \) can be expressed as:

\[
V_4 = w (1 - p) \cdot v (\pi_1 - 0) + w (p) \cdot v (0 - m) \\
= w (1 - p) \cdot v (\pi_1) + w (p) \cdot v (-m)
\]

\[
V_5 = w (1 - p) \cdot v (\pi_2 - 0) + w (p) \cdot v (0 - t) \\
= w (1 - p) \cdot v (\pi_2) + w (p) \cdot v (-t)
\]

3 Analysis of evolutionary game based on prospect theory

Because the difference between \( w(1 - p) \) and \( 1 - w(p) \) is small, for the convenience of subsequent calculation, we assume \( w(1 - p) = 1 - w(p) \). According to Table 3, we can get the replication dynamic equation of enterprise and government as follows:

\[
F(x) = x \left(1 - x\right) \{ y \left[-w (p) \cdot v (\pi_1) - v (-m)\right] - C_1 \\
+ w (p) \cdot v (\pi_1) - v (-m)\}
\]

(4)

\[
F(y) = y \left(1 - y\right) \{ x \cdot v (-D) \\
+ v (\pi_2) + w (p) \cdot v (-t) - v (\pi_2)\} - C_2 \\
+ w (p) \cdot v (\pi_2) - v (-t)\}
\]

(5)

3.1 Strategy analysis of government

According to evolutionary game theory, when \( F(x) \) satisfies \( F(x) = 0 \) and \( F'(x) < 0, \) \( x \) is an evolutionary

Table 2 Model parameter description

| Notation | Meaning |
|----------|---------|
| \( \pi_1 \) | Represents the revenue of government regulation when air quality does not deteriorate |
| \( C_1 \) | Represents the cost of government positive regulation |
| \( \pi_2 \) | Represents the revenue of enterprise when air quality does not deteriorate |
| \( C_2 \) | Represents the low carbon investment cost of enterprises |
| \( D \) | Represents the fine paid by an enterprise when its traditional production is discovered |
| \( -m \) | Represents the government’s loss when the air quality deteriorates |
| \( -t \) | Represents the loss of the enterprise when the air quality deteriorates |
| \( p \) | Represents the probability of air quality deterioration |
stable strategy. Taking the derivative of \( F(x) \) with respect to \( x \), we have:

\[
F'(x) = (1 - 2x) \{ y [ -w(p)(v(x) - v(m))] - C_1 + w(p) [v(x) - v(-m)] \}
\]

When \( F(x) = 0 \), we can get:

\[
x_1 = 0, \ x_2 = 1, y^* = \frac{C_1 + w(p)[v(x) - v(-m)]}{w(p)[v(x) - v(-m)]}.
\]

The evolution strategy of government can be discussed in the following.

1. In situation \( y^* < 0 \), namely

\[
\frac{-C_1 + w(p)[v(x) - v(-m)]}{w(p)[v(x) - v(-m)]} < 0
\]

Due to \( w(p)[v(x) - v(-m)] > 0 \), we have \( -C_1 + w(p)[v(x) - v(-m)] < 0 \), so we can get \( w(p) \in (0, \frac{C_1}{v(x) - v(-m)}). \) At this point, \( y > y^* \), from \( F(0) = 0 \) and \( F'(0) < 0 \), we have \( x_1 = 0 \) is an evolutionary stability strategy. It shows that if the probability of enterprises choosing low-carbon production is greater than \( \frac{-C_1 + w(p)[v(x) - v(-m)]}{w(p)[v(x) - v(-m)]} \), the government tends to choose passive regulation.

2. In situation \( 0 \leq y^* < 1 \), namely \( 0 < \frac{-C_1 + w(p)[v(x) - v(-m)]}{w(p)[v(x) - v(-m)]} < 1 \)

From \( w(p)[v(x) - v(-m)] > 0 \), we have \( -C_1 + w(p)[v(x) - v(-m)] > 0 \), so we get \( w(p) \in \left( \frac{C_1}{v(x) - v(-m)}, 1 \right) \). When \( y < y^* \), from \( F(1) = 0 \) and \( F'(1) < 0 \), we have \( x_1 = 1 \) is an evolution stable strategy. It shows that if the probability of enterprises choosing low-carbon production is lower than \( \frac{-C_1 + w(p)[v(x) - v(-m)]}{w(p)[v(x) - v(-m)]} \), the government tends to choose positive regulation strategy.

When \( y = y^* \), from \( F(0) = 0 \) and \( F'(0) = 0 \), we have that all the \( x \) are in equilibrium. It shows that the revenue of government is the same whether the government choose positive regulation or passive regulation. When \( y > y^* \), from \( F(0) = 0 \) and \( F'(0) > 0 \), we have \( x_1 = 0 \) is an evolutionary stability strategy. It shows that if the probability of enterprises choosing low-carbon production is higher than \( \frac{-C_1 + w(p)[v(x) - v(-m)]}{w(p)[v(x) - v(-m)]} \), the government tends to choose passive regulation strategy.

3. In situation \( y^* > 1 \), namely \( \frac{-C_1 + w(p)[v(x) - v(-m)]}{w(p)[v(x) - v(-m)]} > 1 \)

From \( w(p)[v(x) - v(-m)] > 0, -C_1 + w(p)[v(x) - v(-m)] > w(p)[v(x) - v(-m)] \), we get \( C_1 < 0 \), so this situation does not exist.

To sum up, when \( w(p) \in (0, \frac{C_1}{v(x) - v(-m)}) \), \( x = 0 \) is the evolutionary stability strategy of government; when \( w(p) \in \left( \frac{C_1}{v(x) - v(-m)}, 1 \right) \), if \( y > y^* \), \( x = 0 \) is the stable strategies of government; if \( y < y^* \), \( x = 1 \) is the evolution stable strategy of government.

### 3.2 Strategy analysis of enterprises

Similarly, when \( F(y) \) satisfies and \( F'(y) < 0 \), \( y \) is an evolutionary stable strategy. Taking the derivative of \( F(y) \) with respect to \( y \), we have:

\[
F'(y) = (1 - 2y) \{ x [v(w(-D) + v(x_2) + w(p)(v(-t) - v(x_2))] - C_2 + w(p)[v(x_2) - v(-t)] \}
\]

When \( F(y) = 0 \), we can get:

\[
y_1 = 0, \ y_2 = 1, \ y^* = \frac{C_2 - w(p)[v(x_2) - v(-t)]}{v(-D) + v(x_2) + w(p)[v(-t)],}
\]

In the same way, the choice of enterprise strategy can be discussed in the following situations:

1. In situation \( x^* < 0 \), namely \( \frac{C_2 - w(p)[v(x_2) - v(-t)]}{v(-D) + v(x_2) + w(p)[v(-t)]} < 0 \)

(1) When \( v(x_2) - v(-t) > 0, C_2 - w(p)[v(x_2) - v(-t)] \leq 0 \), we have \( C_2 - w(p)[v(x_2) - v(-t)] \leq 0 \); it satisfies to the hypothesis \( v(x_2) > C_2 \).
2. In situation \(0 < x < 1\), namely \(0 < \frac{C_2 - w(p)}{-v(-D) + v(\pi_2) - w(p) [v(\pi_2) - v(\pi_2 )]} < 1\):

\[\begin{align*}
(1) \quad & \text{When } -v(-D) + v(\pi_2) - w(p) [v(\pi_2) - v(\pi_2 )] < 0, C_2 - w(p) [v(\pi_2) - v(\pi_2 )] > 0, \text{ we get } v(\pi_2) < C_2, \text{ it not satisfies to the hypothesis, this situation does not exist.} \\
& \text{Thus, we can get } w(p) \in \left(0, \frac{C_2}{v(\pi_2) - v(\pi_2 )}\right).
\end{align*}\]

\[\begin{align*}
(2) \quad & \text{When } -v(-D) + v(\pi_2) - w(p) [v(\pi_2) - v(\pi_2 )] > 0, \text{ we have } C_2 - w(p) [v(\pi_2) - v(\pi_2 )] > 0, \text{ it not satisfies the hypothesis } v(\pi_2) > C_2, \text{ so this situation does not exist.}
\end{align*}\]

Under \(w(p) \in \left(0, \frac{C_1}{v(\pi_2) - v(\pi_2 )}\right)\), when \(x > x^*\), from \(F(1) = 0, F'(1) < 0\), we have \(y = 1\) is evolution stable strategy of enterprises. It indicates that if the probability of government positive regulation is equal to \(\frac{C_2 - w(p)}{-v(-D) + v(\pi_2) - w(p) [v(\pi_2) - v(\pi_2 )]}\), the enterprises will choose low-carbon production strategies.

3. In situation \(x^* > 1\), namely \(\frac{C_2 - w(p)}{-v(-D) + v(\pi_2) - w(p) [v(\pi_2) - v(\pi_2 )]} > 1\):

\[\begin{align*}
(1) \quad & \text{When } -v(-D) + v(\pi_2) - w(p) [v(\pi_2) - v(\pi_2 )] > 0, \text{ we have } C_2 - w(p) [v(\pi_2) - v(\pi_2 )] > 0, \text{ so the hypothesis } v(\pi_2) > C_2, \text{ this situation not exist.}
\end{align*}\]

3.3 Analysis of evolution strategies

Using \(w_1(p) = \frac{C_1}{v(\pi_2) - v(\pi_2 )}\) and \(w_2(p) = \frac{C_2}{v(\pi_2) - v(\pi_2 )}\) to divide the risk of air quality deterioration into low, medium, and high three levels. The evolution strategies of government and enterprise at each level are analyzed in the following two situations:

1. The first situation: \(0 < \frac{C_1}{v(\pi_2) - v(\pi_2 )} < \frac{C_2}{v(\pi_2) - v(\pi_2 )}\)

\[\begin{align*}
(1) \quad & \text{When } w(p) \in \left(0, \frac{C_1}{v(\pi_2) - v(\pi_2 )}\right), \text{ the production strategy of enterprises depends on the government’s regulatory strategy, namely } x > x^*, y = 1 \text{ and } x < x^*, y = 0, \text{ from the above analysis. At this point, we can get the government will choose passive regulation, that is } x = 0. \text{ Due to } x > 0, \text{ we have } x < x^*, \text{ so the enterprise will choose traditional production strategy; therefore, the evolutionary strategy of government and enterprise is } x = 0, y = 0.
\end{align*}\]

\[\begin{align*}
(2) \quad & \text{When } w(p) \in \left(\frac{C_1}{v(\pi_2) - v(\pi_2 )}, \frac{C_2}{v(\pi_2) - v(\pi_2 )}\right), \text{ the production strategy of enterprises depends on the government’s regulatory strategy, namely } x > x^*, y = 1 \text{ and } x < x^*, y = 0. \text{ At this time, the government’s regulatory strategy also changes with the production strategy of enterprises, that is } y = y^*, x = 1 \text{ and } y > y^*, x = 0. \text{ Therefore, at this time, the strategic choice of the government and enterprises is infinite cycle.}
\end{align*}\]

(3) When \(w(p) \in \left(\frac{C_2}{v(\pi_2) - v(\pi_2 )}, 1\right)\), we can get enterprise will choose low-carbon production strategies, namely \(y = 1\). The regulatory strategy of government depends on the production strategy of enterprises, namely \(y > y^*, x = 0\) and \(y < y^*, x = 1\). From \(y = 1\), we can get \(y > y^*, so
we have \( x = 0 \) is an evolutionary stability strategy of government, that is government will choose the passive regulation strategy. Therefore, the evolution strategy of government and enterprise is \( x = 0, y = 1 \).

2. The second situation: \( 0 < \frac{C_1}{\sqrt{v(x_1) - v(-1)}} < \frac{C_1}{\sqrt{v(x_1) - v(-m)}} < 1 \)

(1) When \( w(p) \in \left(0, \frac{C_2}{\sqrt{v(x_1) - v(-1)}}\right)\), the production strategies of enterprises according to the regulation strategies of government, namely \( x > x^*\), \( y = 1 \) and \( x < x^*\), \( y = 0 \). From above analysis, at this point, the government will choose the strategy of passive regulation, namely \( x = 0 \). From \( x < x^*\), we have enterprises that will choose the traditional production strategy. Therefore, \( x = 0, y = 0 \) is the evolutionary stable point.

(2) When \( w(p) \in \left(-\frac{C_2}{v(x_1) - v(-1)}, \frac{C_1}{\sqrt{v(x_1) - v(-m)}}\right)\), enterprises will choose low-carbon production strategy, namely \( y = 1 \), while the government’s strategy is passive regulation, namely \( x = 0 \). Therefore, \( x = 0, y = 1 \) is the evolutionary stable point.

(3) When \( w(p) \in \left(-\frac{C_1}{\sqrt{v(x_1) - v(-m)}}, 1\right)\), enterprises will choose low-carbon production, namely \( y = 1 \). The strategy regulation of government depends on the production strategy of enterprise, namely \( y > y^*, x = 0 \) and \( y < y^*, x = 1 \). Due to \( y = 1 > y^* \), we can get \( x = 0 \). Therefore, \( x = 0, y = 1 \) is the evolutionary stable points.

To sum up, dynamic evolution strategy of enterprises and government in the above two situations is shown in Fig. 1. In Fig. 1, horizontal axis represents the probability that the government chooses the positive regulation strategy (Unit: percentage). Vertical axis represents the probability that the enterprise chooses the low-carbon production strategy (Unit: percentage).

(a) When the possibility of air quality deterioration is low, enterprises will choose traditional production methods, and government will choose passive regulation.

(b) When the possibility of air quality deterioration is at a middle level, if the possibility of air quality deterioration is enough to promote the transformation of government to positive regulation, but not enough to promote the transformation of enterprises to low-carbon production, the evolution strategy of government and enterprise will cycle indefinitely. When the probability of air quality deterioration reaches a level that prompts enterprises to transform to low-carbon production, it is not enough to prompt government to change existing regulatory strategies. Enterprises will choose low-carbon production, while government will choose passive regulation.

(c) When the probability of air quality deterioration is high, enterprises choose low-carbon production and the government chooses positive regulation in order to avoid huge losses. However, when the government realizes the transformation of enterprises to low-carbon production, they will change to passive regulation.

3.4 Evolutionary game analysis under incentive paradox

Although the risk of air quality deterioration will affect the results of the game between government and enterprises, the change of other parameters will also affect the results of the game between government and enterprises. Therefore, we analyze the impact of the government’s punishment of traditional production and the loss of social benefits on the game results.

In Fig. 2, horizontal axis represents the probability of traditional production by enterprises (Unit: percentage).
Vertical axis represents the revenue of government under passive regulation (Unit: Ten thousand Yuan). If the probability of enterprise traditional production is greater than $x_0$, the revenue of government is negative, so the government will choose positive regulation. Therefore, in order to ensure the maximization of revenue, the probability of enterprises’ traditional production tends to $x_0$ rather than higher than $x_0$.

In Fig. 3, horizontal axis represents the probability of positive regulation by government (Unit: percentage). Vertical axis represents the revenue of enterprise under traditional production (Unit: Ten thousand Yuan). The government increased penalties for traditional production of enterprises, namely the amounts of fines from $D$ to $D'$ as shown in Fig. 3; the enterprise’s revenues will become negative under the same government regulatory probability. In order to obtain positive revenue, enterprises must reduce the behavior of traditional production. However, with the decrease in traditional production probability of enterprises, the government will gradually reduce the probability of positive regulation. Similarly, with the decrease in the probability of government positive regulation, the behavior of traditional production of enterprises will return to the original level.

On the other hand, if it increases the punishment for passive regulation of government, namely the penalties from $t$ to $t_1$ as shown in Fig. 2, this means that with the same probability of regulation, the revenue of government become negative. In order to keep its original revenue level, the government will increase the probability of regulation, and then, enterprise will decrease the probability of traditional production with the increase in probability of government regulation.

Therefore, increasing the penalty on enterprises’ traditional production behavior can promote enterprises to transform to low-carbon production in the short term, but in the long run, it will only indirectly increase the probability of passive regulation of government. Eventually, the enterprise reverts to its original behavior of production. However, if increasing the punishment for passive regulation of government can make the government adopt positive regulation strategies, thus it reduces the traditional production behavior of enterprises.

### 4 Numerical simulation and result analysis

#### 4.1 Carbon emission regulation case description

In this section, we carry out numerical simulation analysis. We selected the carbon emission regulation in a region in western China as a case to analyze the strategic choices of the government and enterprises. The following parameters are set according to the website of environment and Statistics department of local government, China Energy Statistical Yearbook, China Environmental Statistical Yearbook, and the statistical data of the third party. The specific data are as follows.

The revenue of government chooses positive supervision is 80, and the cost of positive regulation is 33. The revenue of enterprise that chooses traditional production is 125; the cost of low-carbon production is 60. When the traditional production of the enterprise is found by the government, the fine is 70. When the air quality deteriorates, the social benefit loss of government is 60, and the loss of enterprise is 96 (Table 4).

Based on the above basic parameters, we can obtain:

$$w_1(p) = \frac{C_1}{v(\pi_1) + v(t)} = \frac{33}{47.28 + 73.42} \approx 0.27$$

$$w_2(p) = \frac{C_2}{v(\pi_2) + v(m)} = \frac{60}{70.03 - 111.03} \approx 0.33$$
Due to $w_1(p) < w_2(p)$, it satisfies the second situation in evolutionary game analysis. Therefore, we assume that: when $w(p) \in (0, 0.27)$, it belongs to the situation of low risk of air quality deterioration; when $w(p) \in (0.27, 0.33)$, it belongs to the situation of medium risk of air quality deterioration; when $w(p) \in (0.33, 1)$, it belongs to the situation of high risk of air quality deterioration.

4.2 Analysis of government and revenue evolutionary results

1. Low risk of air quality deterioration

Suppose the probability of air quality deterioration is $p = 0.1$, we have $w(p) = 0.19 \in (0, 0.27)$, it belongs to the game strategy under low risk of air quality deterioration. In this situation, the replication dynamic equation of the government and enterprise is:

\[
F(x) = x(1 - x)(-22.49y - 10.51), \\
F(y) = y(1 - y)(120.38x - 26.27).
\]

Through MATLAB software simulation, we can get the evolution trend of government and enterprises, as shown in Fig. 4.

We can see from Fig. 4 that (0,0) is the evolutionary stable point; it indicated that under low risk of air quality deterioration, government tend to choose passive regulation and enterprises tend to choose traditional production.

2. Medium risk of air quality deterioration

Suppose the probability of air quality deterioration is $p = 0.3$, we have $w(p) = 0.32 \in (0.27, 0.33)$; it belongs to the game strategy under medium risk of air quality deterioration. In this situation, the replication dynamic equation of the government and enterprise is:

\[
F(x) = x(1 - x)(-57.2y + 24.2), \\
F(y) = y(1 - y)(68.32x + 25.79).
\]

In this case, we can get the evolution strategy trend between the government and enterprises, as shown in Fig. 5.

We can see from Fig. 5 that the strategies of government and enterprise are determined to the strategies of the other side; their strategy has an infinite loop.

3. High risk of air quality deterioration

Suppose the probability of air quality deterioration is $p = 0.6$, we have $w(p) = 0.47 \in (0.33, 1)$; it belongs to the game strategy under high risk of air quality deterioration. In this situation, the replication dynamic equation of the government and enterprise is:

\[
F(x) = x(1 - x)(-35.09y + 2.09), \\
F(y) = y(1 - y)(101.47x - 7.36).
\]

Through MATLAB simulation, we have the evolution trend of government and enterprises, as shown in Fig. 5.

We can see from Fig. 5 that the strategies of government and enterprise are determined to the strategies of the other side; their strategy has an infinite loop.

From Fig. 6, we have that (0,1) is the final evolutionary stable point. When faced the high risk of air quality deterioration, both government and enterprise will attach great importance to it. At this time, enterprises will choose low-carbon production strategy and the government will choose positive regulation. However, when the government realize the behavior of low-carbon production of enterprises, they will turn to passive regulation.
5 Conclusion

This paper analyzes the strategy choice of government and enterprises under different circumstances and the incentive paradox in the process of carbon emission regulation. The main conclusions are as follows.

First, when the risk of air quality deterioration is lower, the enterprises tend to choose the traditional of production, and the government in the face of the enterprise’s traditional production behavior tend to choose passive regulation.

Second, when the risk of air quality deterioration is medium, the government and the enterprise will choose the opposite strategy, namely the enterprise’s production strategy changes with the regulation strategy of the government department.

Third, when the enterprise’s production strategy changes, the government’s regulation strategy will also change. When the risk of air quality deterioration is high,
Enterprises will choose low-carbon production and government will choose positive regulation at first. However, with the continuous low-carbon production of enterprises, government regulation gradually changes from positive regulation to passive regulation.

Fourth, the government increases the fine on traditional production of enterprise, which can change the production behavior of enterprises in a short period, but in the long run, it will make the government more passive regulation, and the enterprise back to the original production status. If the punishment for ineffective regulation of government is increased, the regulation of government will become more positive, which can effectively promote enterprises’ low-carbon production behaviors in the long run.

Through the above analysis, we propose the following management insights. (1) The central government strengthens the supervision and assessment of local governments, increasing the weight of environmental protection in the performance assessment of local governments. (2) Local governments have increased penalties for illegal emissions and raised the expectation of environmental risk losses of enterprises, so as to reduce illegal emissions behaviors of enterprises. (3) Strengthen the publicity of low carbon, cultivate the public’s awareness of low carbon and environmental protection, and form a social supervision mechanism, so as to reduce enterprises’ expectation of traditional production benefits.

This study has the following limitations. This paper only considers the game between government and enterprises, without considering the influence of external factors on decision making. In addition, through evolutionary game analysis, we determined the evolutionary trend of the game between the government and enterprises, but did not calculate the specific profit value.

In future research, we will consider the influence of external factors, such as consumer preferences, third-party supervision, and subsidy policies on the strategic choices of governments and enterprises. Through further analysis, the specific value of the game subject in the evolution process and the value of the stable state are determined.

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**Data availability**  Enquiries about data availability should be directed to the authors.  

**Declarations**

**Conflict of interest**  The authors declare that they have no conflict of interest.
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