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Original Research

The Behavioral Economics of Water Pollution Supervision: An Evolutionary Game Analysis with Prospect Theory and Mental Accounting

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Abstract

In contemporary society, water pollution has emerged as a critical environmental challenge, necessitating effective strategies for its control. This paper examines the strategic interactions involved in water pollution control, focusing particularly on the behavioral choices and influencing factors of governmental bodies and industrial stakeholders. By integrating psychological accounting theory into an evolutionary game model, we comprehensively analyze the decision-making processes of both government entities and industrial polluters. We simulate the trade-offs and choices between active pollution control measures and laissez-faire approaches. Our findings reveal that psychological value perceptions play a crucial role in shaping all stakeholders' behavioral decisions and strategy evolution. The effectiveness of water pollution control is influenced by a range of factors, including treatment costs, decision-making influence coefficients, and risk preferences. The study underscores the importance of acknowledging the impact of psychological value perceptions, reducing treatment costs, and enhancing environmental awareness among participants as an effective means to promote water pollution control behaviors. Based on our game-theoretic analysis and simulation results, we propose specific policy recommendations and theoretical insights aimed at enhancing the efficiency of water pollution control efforts, with the ultimate goal of promoting the protection and sustainable utilization of water resources and raising public awareness of environmental protection.

Keywords: water pollution control, evolutionary game, prospect theory, mental accounting, environmental awareness

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Introduction

A healthy ecological environment is essential for human survival and well-being [1]. With the rapid advancement of industrialization and urbanization, the problem of water pollution has become increasingly serious. It has become one of the environmental challenges that need to be solved urgently in the world [2-6]. Despite stringent regulations and enforcement efforts, instances of non-compliance continue to occur, often due to complex behavioral factors. This paper integrates insights from behavioral economics, particularly prospect theory and mental accounting, into an evolutionary game framework to better understand the dynamics of water pollution supervision.

Prospect theory suggests that individuals' decisions are influenced not only by objective outcomes but also by how these outcomes are framed relative to a reference point. Mental accounting further posits that people organize, evaluate, and manage their financial activities through a series of cognitive accounts, which can lead to systematic biases in decision-making.

In the context of environmental regulation, these theories help explain why firms may deviate from regulatory compliance even when penalties for non-compliance exist. For example, firms might underweight the probability of detection or overestimate the benefits of non-compliance due to framing effects or biases in mental accounting. Similarly, regulators may be influenced by similar cognitive biases in their strategies for detecting and penalizing non-compliance.

This study employs an evolutionary game model to simulate the strategic interactions between polluting firms and regulatory agencies over time. By incorporating prospect theory and mental accounting into the model, we aim to uncover the underlying behavioral mechanisms that drive compliance and non-compliance behaviors. The results will provide policymakers with a deeper understanding of how to design more effective regulatory frameworks that account for the behavioral complexities of regulated entities.

The remainder of this paper is organized as follows: next section reviews the relevant literature. The following section presents the methodology and the evolutionary game model. The Results and Discussion section is dedicated to the simulation results, analyzing the implications of the findings. The final section concludes with policy implications and directions for future research.

Theoretical Basis and Literature Review

Evolutionary Game Theory

Evolutionary game theory is an important branch of game theory that combines ideas about evolution and adaptation in biology to study the evolutionary process of interactions between individuals in a group. Unlike classical game theory, bounded rationality is the premise of evolutionary game theory. As a result, researchers are increasingly interested in using evolutionary game theory to deal with numerous projects.

The theory originated from the evolutionary game framework based on the classical game theory established by Smith [7] in 1982. It was first introduced into the field of economics by Friedman [8] in 1991, thus broadening its application. Over the years, evolutionary game theory has been widely used in various fields [9-12], such as coal [13], logistics [14], power generation [15], manufacturing [16], and energy [17, 18], and has been highly praised by industry experts.

In the complex system of water pollution control, evolutionary game theory can provide a framework for simulating and analyzing how bounded rational actors adjust their strategies according to the behavior of other actors [19]. Therefore, using evolutionary game theory to analyze the game problems in water pollution control is helpful in revealing the strategic choices and evolution paths of various stakeholders and provides a scientific basis for formulating effective governance strategies. On the issue of governance supervision, some scholars have used the evolutionary game method to discuss regulatory behavior and strategy choice. For example, Li et al. [20] constructed an asymmetric evolutionary game model to analyze the behavioral evolution of government regulatory authorities and the private sector in water environment governance PPP projects, proposing regulatory suggestions that deepen our understanding of the dynamic game relationship between regulators and the regulated. Similarly, Feng et al. [21] explored the structure of the green supply chain finance credit market under government supervision, constructing an evolutionary game model involving green SMEs, core enterprises, and financial institutions. Wang et al. [22] focused on regional environmental governance, developing a tripartite evolutionary game model encompassing the public, enterprises, and local governments to analyze the behavioral strategies and influencing factors of all parties. The application of evolutionary game theory is increasingly being recognized by scholars [23-26] for its ability to dissect complex regulatory dynamics and strategic interactions within various sectors, highlighting its growing significance in the field of governance research.

Prospect Theory and Mental Accounting

Despite the widespread application of EGT, the benefit matrix based on expected utility theory in the existing literature often overlooks the participants' perception of risk and the impact of psychological accounts. Due to the complexity of regulation, decision-makers' behavior is influenced not only by objective benefits but also by subjective judgments and value perceptions. The prospect theory proposed by Tversky and Kahneman [27] provides a new perspective for understanding decision-makers' behavior in the face of risk and uncertainty. This theory is a supplement and refinement of traditional economic theory, emphasizing people's cognitive biases and irrational behaviors in decision-making.

Some studies have begun to combine prospect theory with evolutionary game theory to analyze decision-making behavior more comprehensively. For example, Shen et al. [28] combined these two theories to study the decision-making behavior of local governments and pollutant dischargers in watershed ecological compensation. This combination provides a new analytical tool for understanding the complex decision-making process in water pollution control. Li et al. [29], based on the prospect theory and under the premise of bounded rationality of decision-makers, constructed a game model for green technology innovation between enterprises and governments to dynamically analyze the decision-making process and optimal strategies in different scenarios. Wang et al. [30] integrated prospect theory into trilateral evolutionary game theory to establish the perceived benefit matrix of local governments, construction enterprises, and the public in the game, analyze the strategic choice and evolution paths of the three participants using the replication dynamic equation, and analyze the process of resource utilization for construction waste. Li et al. [31]. Using the prospect theory, a tripartite game model of low-carbon innovation of power batteries with the participation of government agencies, power battery manufacturers, and recycling enterprises is proposed.

Mental accounting theory, introduced by Thaler [32], complements prospect theory by focusing on how decision-makers evaluate gains and losses based on different sources or uses of funds. This theory reflects the behavioral characteristics of individuals in multi-attribute decision-making situations. Incorporating mental accounting into the analysis of EGT in water pollution control can deepen our understanding of strategy selection and the game processes of different stakeholders, such as governments and enterprises. For example, in water pollution control, the decision-making of governments and industrial polluting enterprises is influenced not only by direct economic interests but also by social, environmental, and policy objectives. By considering mental accounts, it is possible to more accurately model how these decision-makers weigh different goals and respond to each other's strategies.

Summary

The significant contributions of evolutionary game theory (EGT) to the field of water pollution control are noteworthy. However, the existing research predominantly focuses on the objective benefits of different strategies, often overlooking the subjective judgments and value perceptions of decision-makers. These subjective factors can significantly influence stakeholders' strategic choices and evolution paths in water pollution control.

Based on this, this paper aims to integrate mental accounting theory with EGT to deeply explore the game problem in water pollution control. By doing so, it seeks to provide a comprehensive understanding of the strategic interactions among stakeholders, thereby contributing to developing more effective regulatory frameworks and policies.

Materials and Methods

Evolutionary Model Assumptions and Parameter Setting

Model Assumptions

Assumption 1: The game players consist of industrial enterprises and government departments, both of which are characterized by bounded rationality and satisfy the value function constructed by prospect theory and mental accounting theory. The combined value function of prospect theory and mental accounting can be represented as:

$$V(x)=\begin{cases}(x-UV)^{\theta}, & x\geq UV\\ -\lambda(UV-x)^{\tau}, & x<UV\end{cases} \tag{1}$$

$$Z(x)=\begin{cases}\delta(x-UZ)^{\phi}, & x\geq UZ\\ -(UZ-x)^{\sigma}, & x<UZ\end{cases} \tag{2}$$

In this context, V(x) denotes the valuation function of the utility account, which assesses the perceived value of the gains obtained. Z(x) signifies the valuation function of the cost account, which evaluates the perceived value of the costs expended. UV indicates the reference point for gains, while UZ corresponds to the reference point for costs.

The parameter λ quantifies the degree of loss aversion associated with gains, x represents the variation in value, and θ and τ are the risk preference coefficients that reflect the relative weighting of gains against losses. Similarly, ϕ and σ are the risk preference coefficients that pertain to the relative weighting of costs against losses. The parameter δ denotes the degree of loss aversion associated with costs.

The associated decision-making functions are as follows:

$$\pi(\varepsilon)=\frac{\varepsilon^{r}}{[\varepsilon^{r}+(1-\varepsilon)^{r}]^{\frac{1}{r}}} \tag{3}$$

In this context, $\pi(\varepsilon)$ represents the decision weight function, which signifies the decision-maker's subjective assessment of the probability of an event occurring or their inclination towards a particular strategic choice. This function is monotonically increasing and serves as an evaluative measure of probability, with the properties of π (0) = 0 and π (1) = 1. The parameter r denotes the decision impact coefficient; a higher r-value indicates a greater curvature in the decision weight function, implying a lower individual discernment rate of objective probabilities.

Assumption 2: The two sides of the game are industrial enterprises and government regulators, and both sides show bounded rationality in the game process. Decision-making is based on a psychological perception of one's own value, which is influenced by prospect theory and psychological account theory; that is, the decision-maker is more sensitive to the perception of loss than the same order of magnitude of gain and will evaluate the value according to different accounts.

Assumption 3: An industrial company can choose whether to implement strict wastewater treatment and pollution control with a set of strategies such as Strict Wastewater Treatment, Strict Wastewater Treatment, Loose Wastewater Treatment. It can be succinctly referred to as the strategy pair (Active Participation, Passive Participation). Enterprises may neglect environmental protection to maximize short-term benefits when implementing lenient wastewater treatment, thereby reducing costs in the short term. At the same time, companies may also choose to implement strict wastewater treatment to avoid long-term environmental liability and social condemnation.

Assumption 4: Government regulators can choose to implement strict environmental regulations and monitor or enforce lax environmental regulations with a set of strategies for implementing strict environmental regulations, implementing lax environmental regulations. It can be succinctly referred to as the strategy pair (Active Regulation, Passive Regulation). Strict environmental regulations can effectively reduce water pollution, while lax environmental regulations can lead to inadequate pollution control.

Assumption 5: Suppose that the probability of an industrial enterprise adopting a "strict wastewater treatment" strategy is x ($0 \le x \le 1$), and the probability of adopting the "implement loose wastewater treatment" strategy is $1 - x$ ($0 \le x \le 1$); suppose the probability of a government regulator adopting an "enforce stringent environmental regulations" strategy is y ($0 \le y \le 1$), and the probability of adopting the strategy of "implementing loose environmental supervision" is $1 - y$ ($0 \le y \le 1$).

Model Parameter Setting

(1) Industrial enterprises

As the main body of pollution control, the behavior of industrial enterprises is weighed between economic benefits and environmental responsibility. Adopting pollution reduction measures (R1) by industrial companies may lead to an environmentally friendly image and potential government subsidies or tax breaks, which are important factors for companies to consider in their decision-making process. However, these measures may also come with certain costs (W1), such as equipment upgrades and increased operating costs, which may discourage companies from adopting stricter pollution control measures. At the same time, companies may reap excess economic benefits when they do not take emission reduction measures (R2), such as savings in wastewater treatment costs. However, this option also comes with the risk of fines or reputational damage (L1), which can lead to legal action and a loss of trust in the market.

(2) Government regulatory agencies

As another subject to pollution control, government regulators are also subject to the trade-off between costs and benefits. The government's implementation of strict emission standards comes at a cost (G1), including the legislative process, the construction of monitoring facilities, and the investment of law enforcement forces. Governments can lose public trust due to their failure to regulate effectively (L2).

(3) Industrial enterprises and government regulators

The interaction between industrial companies and government regulators constitutes a complex strategy game. When industrial enterprises adopt emission reduction strategies with lax government regulation, it may lead to reduced investment and increased environmental risks. In such cases, not only might the enterprises face additional costs for environmental damage compensation (L3), but the government could also incur corresponding losses. Conversely, under strict government regulation, if industrial companies fail to meet their emission reduction targets, the government will bear higher regulatory costs and the risk of a possible slowdown in economic activity, which is also reflected in the additional regulatory and economic losses that the government may bear due to non-compliance (L4).

Evolutionary Model Building and Analyzing

Evolutionary Model Building

The value account and cost account functions are introduced into the traditional game matrix to obtain the game return matrix based on the psychological account, as shown in Table 1.

On the one hand, the expected return U_x of the enterprise with a strong willingness to participate is given by:

$$U_x = \pi(y)[V(R1) - Z(W1)] + \pi(1-y)[V(R1) - Z(W1 + L3 + L1)] \tag{4}$$

On the other hand, the expected return U_{1-x} of the enterprise with passive participation is given by:

Table 1. The payoff matrix of the model.

Enterprise	Government	
	Active Regulation (*y*)	Passive Regulation (1 – *y*)
Active Participation (*x*)	$V(R1)-Z(W1)$ $V(S)-Z(G1)$	$V(R1)-Z(W1+L3+L1)$ $-Z(L2+L3))$
Passive Participation (1 – *x*)	$V(R2)-Z(L1)$ $V(S)-Z(G1+L4)$	$V(R2)-Z(L1)$ $-Z(L2)$

$$U_{1-x}=\pi(y)[V(R2)-Z(L1)]+\pi(1-y)[V(R2)-Z(L1)] \tag{5}$$

Besides, we assume that the average benefit $\bar{U}_1$ of the enterprise is given by:

$$\overline{U_1}=xU_x+(1-x)U_{1-x} \tag{6}$$

Then, according to Equations (1)-(3), the replicated dynamic equation *F*(*x*) of the enterprise can be obtained as follows:

$$\begin{aligned}F(x)=x(U_x-\overline{U_1})=x(1-x)(\pi(y)[V(R1-R2)\\+Z(L1-W1)]+\pi(1-y)[V(R1-R2)-Z(W1+L3)]\\=x(1-x)(\pi(y)A+\pi(1-y)B)\end{aligned} \tag{7}$$

In the formulation, *A* signifies the differential in the value function for industrial entities that opt for rigorous wastewater management protocols, comparing the scenario where the governmental body enforces stringent environmental regulations against the context of more lenient oversight by the same authority. Conversely, *B* denotes the discrepancy in the value function for industrial entities electing to implement less stringent wastewater treatment practices, juxtaposed against situations where the government either enforces strict environmental policies or adopts a more relaxed regulatory stance.

Moreover, we assume that the expected return U_y of the government with active regulation is given by:

$$U_y=\pi(x)[V(S)-Z(G1)]+\pi(1-x)[V(S)-Z(G1+L4)] \tag{8}$$

On the contrary, we suppose that the expected return U_{1-y} of the government with a negative regulation strategy is given by:

$$U_{1-y}=\pi(x)[-Z(L2+L3)]+\pi(1-x)[-Z(L2)] \tag{9}$$

Besides, we assume that the average benefit $\bar{U}_2$ of the local government is given by:

$$\overline{U_2}=yU_y+\left(1-y\right)U_{1-y} \tag{10}$$

Furthermore, from Equations (5)-(7), we obtain the replicated dynamic equation *F*(*y*) of the local government as follows:

$$\begin{aligned}F(y)=y(U_y-\overline{U_2})=y(1-y)(\pi(x)[V(S)\\+Z(L2+L3-G1)]+\pi(1-x)[V(S)-Z(G1+L4-L2)])\\=y(1-y)(\pi(x)C+\pi(1-x)D)\end{aligned} \tag{11}$$

In the Equation (11), C represents the difference in the value function for industrial entities when they opt for stringent wastewater treatment under conditions where the government enforces strict environmental regulations, as opposed to their value function when they choose less stringent wastewater management practices under the same regulatory environment. D signifies the disparity in the value function for industrial entities choosing rigorous wastewater treatment methods versus those opting for less stringent approaches in scenarios where the government adopts a more lenient regulatory approach toward environmental protection.

Thus, according to Equations (4) and (8), a dynamic system is given by:

$$\begin{cases}F(x)=\dfrac{dx}{dt}=x(1-x)(\pi(y)A+\pi(1-y)B)\\F(y)=\dfrac{dy}{dt}=y(1-y)(\pi(x)C+\pi(1-x)D)\end{cases} \tag{12}$$

Setting the above replicator dynamics equation system equal to zero, we can identify five local equilibrium points. Among these, if *F*(*x*) = 0, then *x* = 0 or *x* = 1 and $y^{*}[B/(B-A)]^{\gamma-1}$, if *F*(*y*) = 0, then *y* = 0 or *y* = 1, $x^{*}[D/(D-C)]^{\gamma-1}$.

Consequently, the four pure strategy Nash equilibrium points are, and a single mixed strategy solution is $E_5([B/(B-A)]^{\gamma-1}, [D/(D-C)]^{\gamma-1})$. Next, the evolutionary stability of the model will be analyzed.

Evolutionary Model Analyzing

According to Friedman [8], we can analyze the local stability of such an equilibrium using the Jacobian matrix of the system, which provides insights into whether the equilibrium is indeed an ESS.

According to the replication dynamic Equation, the system's Jacobian matrix is set as J, and the Jacobian matrix of the system is calculated as follows:

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

$$= \begin{bmatrix} (1-2x)[\pi(y)A+\pi(1-y)B] & x(1-x)[\frac{d\pi(y)}{dy}A+\frac{d\pi(1-y)}{dy}B] \\ y(1-y)(\frac{d\pi(x)}{dx}C+\frac{\pi(1-x)}{dx}D) & (1-2y)[\pi(x)C+\pi(1-x)D] \end{bmatrix} \tag{13}$$

$$\begin{cases} a_{11} = (1-2x)[\pi(y)A+\pi(1-y)B] \\ a_{12} = x(1-x)[\frac{d\pi(y)}{dy}A+\frac{d\pi(1-y)}{dy}B] \\ a_{21} = y(1-y)(\frac{d\pi(x)}{dx}C+\frac{\pi(1-x)}{dx}D) \\ a_{22} = (1-2y)[\pi(x)C+\pi(1-x)D] \end{cases} \tag{14}$$

Then, the value of matrix determinant J is:

$$\det J = a_{11}a_{22} - a_{12}a_{21} \tag{15}$$

The trace of the matrix J is:

$$\mathrm{tr}J = a_{11} + a_{22} \tag{16}$$

According to the Lyapunov stability theorem, when the Jacobian matrix satisfies the condition that the determinant is greater than zero and the trace of the matrix is less than zero, the corresponding equilibrium point is locally asymptotically stable. The corresponding evolution strategy is also stable.

For this system, when $E_4(1,1)$ is the unique stable point, the system evolution reaches an optimal state. Here, we focus particularly on this point, and the stability of the four points is as shown below:

(1) For the equilibrium point $E_1(0,0)$, the determinant of the Jacobian matrix J is given by BD, and the trace of J is $B + D$. Given that det$J$>0 and tr$J$>0, this equilibrium point is identified as an unstable node.

(2) At $E_2(1,0)$, the determinant of J is $-AD$, and its trace is $A - D$ With det$J$>0 and tr$J$<0, this equilibrium point is characterized as a saddle point.

(3) For $E_3(0,1)$, the determinant of J is $-CB$, and the trace is $C - B$. Considering det$J$>0 and tr$J$<0, this equilibrium point also exhibits the properties of a saddle point.

(4) When examining $E_4(1,1)$, the determinant of J is AC, and the trace is $-(A + C)$. Given that det$J$>0 and tr$J$<0, this equilibrium point is classified as an Evolutionarily Stable Strategy (ESS).

Results and Discussion

Numerical Simulation

Based on theoretical analysis, this section utilizes Python to conduct numerical simulations of a two-party water pollution supervision game system involving industrial enterprises and government regulatory agencies.

In this simulation, we set a series of parameter values for use according to the conditions and relevant literature, and the initial parameter values are set according to the most ideal state (1,1) of the evolution results. R1 and R2 are set to 10 and 5, respectively. The value of L1 is 7. W1 is set to 3. S is set to 4. The values of L2, L3, and L4 are 9, 6, and 4, respectively. G1 is set to 8. λ is 1, and δ is 2. In addition, θ is 0.88, τ is 0.88, φ is 0.98, and σ is 0.98. The risk adjustment parameter r is set to 0.5. Finally, the values of UV and UZ are both 1.5.

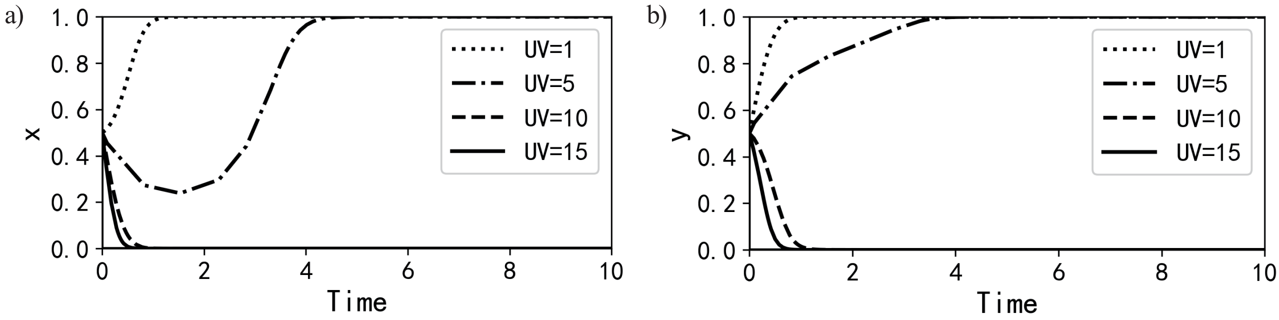

Fig. 1. The evolutionary state of the UV value change. (a) Effect of UV changes on x, (b) Effect of UV changes on y.

The Effect of Changes in UV Reference Points on the Evolution of the System

The reference points of the value account are UV = {1, 5, 10, 15}, and the influence of numerical changes on the choice of system evolution strategy is observed. The evolution process is shown in Fig. 1.

This diagram illustrates governments' and enterprises' strategic choices and dynamic changes under different value reference points under UV water pollution control. The Fig. 1a) depicts the impact of UV on industrial enterprises' choice of water pollution control strategies, while the Fig. 1b) reflects the impact of UV on the government's choice of water pollution control strategies.

As a reference point, UV not only represents the current value judgment criteria of industrial enterprises and governments but also influences their psychological expectations. With the increase of UV, the evolution speed of industrial enterprises choosing to actively participate in the process slows down. The evolution speed of government departments choosing active supervision also slows down, and the evolution results tend to be passive participation and passive supervision. It shows that when the value reference point is high, industrial enterprises are under pressure to take active participation behaviors, and enterprises may focus too much on short-term goals, ignoring the long-term environmental impact and the need for sustainable development, and thus choose to sacrifice environmental protection in exchange for short-term economic benefits. At the same time, regulators are under pressure to implement active regulation. They may focus more on short-term performance than long-term environmental benefits, so they may be more inclined to support economic development than environmental protection in the short term.

The Influence of the Change of the UZ Reference Point on the Evolution of the System

Set the reference points UZ = {1, 5, 10, 15}, and observe the influence of numerical changes on the selection of system evolution strategies, as shown in Fig. 2.

This diagram illustrates the strategy choices and dynamic changes of governments and enterprises in water pollution control under different cost reference points UZ. The Fig. 2a) depicts UZ's impact on industrial enterprises' choice of strategies for water pollution control, while the Fig. 2b) reflects UZ's influence on the government's choice of strategies for water pollution control.

With the increase of UZ, the speed of industrial polluting enterprises to choose to implement active participation slows down, and the change of strategy choice will occur when the UZ is increased to 5-10, from active participation to passive participation. A higher cost reference point means that companies are at greater risk of a margin squeeze. Under fixed income, rising costs directly compress profit margins, and companies may choose to reduce their spending on environmental protection to maintain profitability.

The speed at which government departments choose to strengthen supervision will slow down accordingly, but the strategic choice has stayed the same, and it will remain active supervision. A higher reference point for regulatory costs means governments face tougher regulatory challenges. Under the fixed fiscal budget, the increased regulatory costs directly compress the funding space available for other public service and infrastructure projects, and the government has slowed down the choice of active regulation. The government may take steps to optimize regulatory efficiency and flexibility to ensure environmental objectives in order to maintain overall public service standards and fiscal health.

The Impact of R Changes on the Evolution of the System

Let r = { 0.2, 0.4, 0.6, 0.8}, and observe the influence of numerical changes on the selection of the system evolution strategy and the evolution process is shown in Fig. 3.

Fig. 3 shows governments' and enterprises' strategic choices and dynamic changes under different r-values. The Fig. 3a) depicts the impact of the change in r on the choice of strategies for water pollution control by industrial polluting enterprises, while the Fig. 3b)

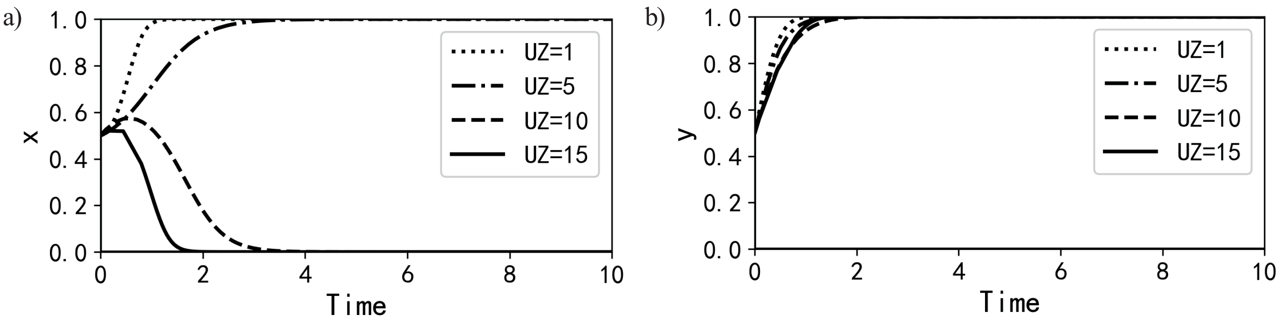

Fig. 2. The evolutionary state of the change in the UZ value. a) Effect of UZ change on x, b) Effect of UZ change on y.

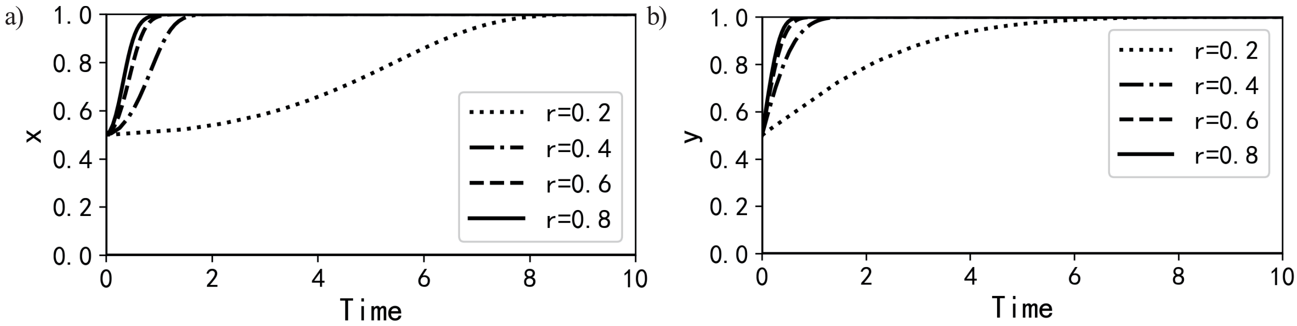

Fig. 3. The evolutionary state of the r-value change. a) Effect of r change on x, b) Effect of r change on y.

reflects the impact of r change on the government's choice of strategies for water pollution control.

First, with an increase in r, the speed at which industrial polluting enterprises tend to pay attention to active participation in water pollution control is accelerating, and the speed at which the government tends to pay attention to active supervision is also faster. When r = 0.2, it is obvious that the rate of evolution is the slowest. r represents the impact coefficient of decision-making, and with the increase of r, decision-makers are more sensitive to the perception of low-probability events, which leads to a more curved decision-making weight function. The rate of active participation and active supervision of industrial polluting enterprises and governments is accelerated.

The Impact of W1 Changes on the Evolution of the System

The cost of active participation of industrial polluting enterprises W1 = {3, 5, 7, 9} is observed. The influence of numerical changes on the choice of system evolution strategy is observed, and the evolution process is shown in Fig. 4.

This Fig. 4 illustrates governments' and enterprises' strategic choices and dynamic changes under different W1 values. The Fig. 4a) depicts the impact of W1 on the choice of water pollution control strategies by industrial polluting enterprises, while the Fig. 4b) reflects the impact of W1 on the government's choice of water pollution control strategies.

It can be seen from the Fig. 4 that the change in W1 value has a greater impact on industrial polluting enterprises and has less impact on the government's choice of strategy. When the W1 value is low, the cost of pollution reduction measures is relatively low. In this case, the industrial polluter may be more likely to accept and implement pollution control measures, and the cost burden is smaller. As the cost of pollution control increases, when it reaches a certain level, industrial polluting enterprises will change their choice strategy and turn to a passive participation strategy, while government regulators will not change their choice strategy if they are less affected by the change of this parameter.

The Impact of G1 Changes on the Evolution of the System

The cost of active government supervision G1 = {4, 8, 12, 16} is observed. The influence of numerical changes on the choice of system evolution strategy is observed, and the evolution process is shown in Fig. 5.

Fig. 5 illustrates governments and enterprises' strategic choices and dynamic changes under different G1 values.

The graph in Fig. 5a) represents the impact of the G1 value on industrial polluting companies, and the graph in Fig. 5b) represents the impact on the government.

As can be seen from the Fig. 5, the change in G1 value has a greater impact on the government and less

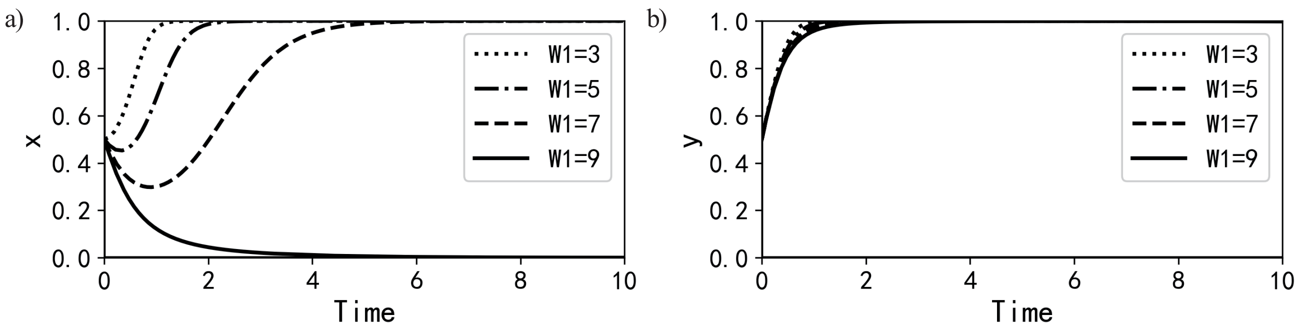

Fig. 4. The evolutionary state of the change in the W1 value. a) Effect of W1 change on x, b) Effect of W1 change on y.

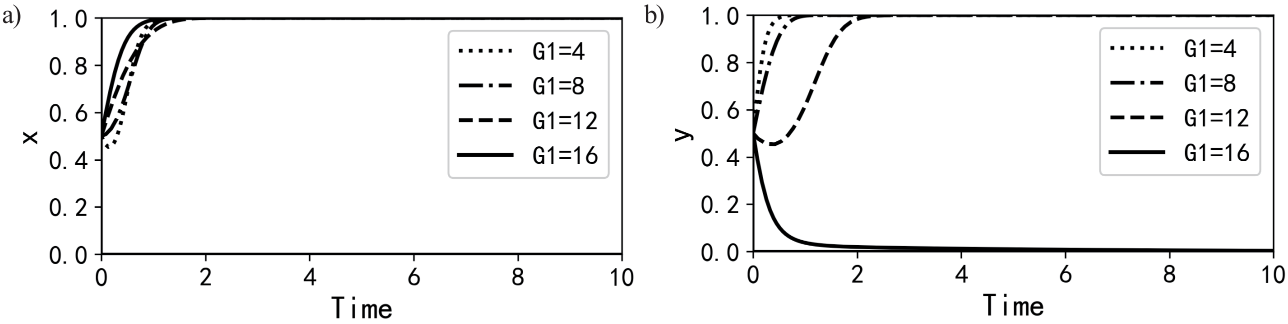

Fig. 5. The evolutionary state of the change in the G1 value. a) Effect of G1 change on x, b) Effect of G1 change on y.

on industrial polluting enterprises. As the G1 value increases, i.e., the government needs to invest more resources to implement active regulatory strategies, governments tend to choose active regulatory strategies at a slower pace and change the implementation strategies from active regulation to passive regulation when the cost value rises to a certain level. Industrial polluting enterprises are less affected by the change in this parameter and will not change their chosen strategy.

Discussion

(1) The impact of reference points on strategic choices is significant. Simulation results indicate that changes in both the value reference point (UV) and the cost reference point (UZ) significantly influence the strategic choices of governments and industrial enterprises in managing water pollution. An increase in the reference point leads to a decrease in the enthusiasm of industrial enterprises to participate, and the enthusiasm for government regulation is also affected. Under high reference points, enterprises and governments may be more inclined towards short-term goals, neglecting long-term environmental benefits and sustainable development.

(2) Variations in the decision-making influence coefficient (r) directly affect the decision-makers' perception of low-probability events, thereby influencing the pace of strategic evolution for industrial enterprises and governments. As the value of r increases, the decision-makers' sensitivity to risk is heightened, promoting the selection of strategies for active participation.

(3) Industrial polluting enterprises exhibit a high-cost sensitivity; an increase in W1 leads to a shift from active to passive participation. Although the government's regulatory cost (G1) also affects its strategic choices, the degree of impact is relatively minor.

(4) With the variation of parameters, the strategic choices of governments and enterprises show a dynamic change trend. This change is not only influenced by a single parameter but is also the result of the combined effects of multiple factors.

Strategic Recommendations

(1) Governments and enterprises should establish mechanisms for dynamically adjusting reference points to adapt to the continuously changing environment and market conditions, ensuring a balance between long-term and short-term goals.

(2) Through training and education, improve decision-makers' ability to perceive low-probability events, enabling them to make more rational strategic choices when facing uncertainty.

(3) Industrial enterprises should reduce pollution control costs through technological innovation and process optimization, while governments should alleviate the environmental protection cost burden on enterprises through policy support and incentive measures.

(4) Governments should improve regulatory efficiency through technological means and management innovation, reducing regulatory costs and ensuring effective environmental regulation within a limited fiscal budget.

(5) Encourage cooperation among governments and enterprises to jointly promote water pollution management, achieving a win-win situation for the environment and the economy.

Conclusions

This paper constructs an evolutionary game model integrated with psychological accounting to explore strategic interactions in water pollution control, particularly focusing on the behavioral choices of governments and industrial polluters. The study finds that perceptions of psychological value significantly influence decision-making processes and strategic evolution, highlighting the central role of psychological factors in water pollution management.

The research results reveal that handling costs, decision impact coefficients, and risk preferences are key factors affecting the effectiveness of water pollution governance. Incorporating psychological accounting theory enables the model to capture how decision-makers weigh gains and losses across different mental accounts, influencing their choices regarding pollution control measures. Furthermore, simulation results indicate that enhancing environmental awareness and acknowledging the influence of psychological values can effectively promote pollution control behaviors.

Based on evolutionary game analysis and simulation outcomes, this paper offers concrete policy recommendations aimed at improving the efficiency of water pollution governance. These recommendations include, but are not limited to, establishing a dynamic reference point adjustment mechanism to enhance the risk perception capabilities of decision-makers, optimizing cost structures, and strengthening regulatory efficiency. This will encourage cooperation among multiple stakeholders, such as governments and enterprises, to jointly advance the process of water pollution control and achieve a win-win situation for the environment and the economy. These suggestions aim to promote the protection and sustainable use of water resources.

This study not only provides a new perspective on understanding the complex decision-making processes in water pollution control but also fills a gap in the existing literature by introducing the concept of mental accounting to explain how psychological factors influence environmental protection decisions. Additionally, the policy recommendations proposed in this study are practical and offer a scientific basis for formulating more effective strategies for water pollution control. Theoretically, this work enriches the knowledge base in environmental economics and public policy. Practically, it offers valuable guidance for addressing real-world water pollution issues.

Future Work

Despite providing new perspectives and valuable insights into water pollution governance, this study also acknowledges some limitations and suggests future research directions. Firstly, while the models and analyses are based on theoretical assumptions and simulated data, future research should consider applying them to real-world case studies to validate their practicality and effectiveness.

Secondly, future research could further investigate the application of psychological accounting theory under different cultural, economic, and policy contexts and how it can be combined with other behavioral economics theories to enrich the strategic options for water pollution control. Additionally, given the long-term nature and complexity of water pollution governance, future research could focus on the dynamic adjustments of policies and the coordination among multiple stakeholders.

Lastly, with the development of big data and artificial intelligence technologies, future research could explore applying these advanced technologies within evolutionary game models to more accurately simulate and predict the evolution of strategies. This would provide a more scientific basis for decision-making in water pollution governance and facilitate the formulation and implementation of environmental policies.

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Conflict of Interest

The authors declare no conflict of interest.

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