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Research Article

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Posted Date: February 8th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1339631/v1

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Evolutionary analysis of Japan’s nuclear wastewater discharge events considering the impact of participants’ emotions

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Research Highlights

- Regardless of the mood of Japanese fishermen, the decision of the Japanese government is closely related to its own interests.

- The emotions of players not only affect their own strategy choices but also affect the strategy choices of other players.

- Optimism will make fishermen blindly trust the government, which will lead to worse outcomes for Japanese fishermen in the game with the Japanese government.

- The influence of key parameters on the evolution trajectories and results are simulated.

- Useful political insights for the Japanese government and Japanese fishermen are given.
Evolutionary analysis of Japan’s nuclear wastewater discharge events considering the impact of participants’ emotions

The Japanese government’s decision on April 13, 2021 to discharge nuclear wastewater from the Fukushima Daiichi Nuclear Power Plant into the sea has aroused widespread concern around the world. People in Japan, especially fishermen, have expressed strong opposition to this decision. In this paper, we discuss an evolutionary game considering the impact of participants’ emotions to explore the evolutionarily stable strategies of both the Japanese government and Japanese fishermen. The results show the following: i) For the sake of interest, no matter what mood the fishermen are in, the Japanese government will choose to discharge nuclear wastewater. ii) The emotions of players not only affect their own strategy choices but also affect the strategy choices of other players. The emotional changes of Japanese fishermen not only affect the changes of their own strategies but also change the evolutionary trajectory of the Japanese government. iii) When both parties are rational, the impact of each key parameter on the evolution results and trajectories of both parties is closely related to the interests of both parties. When the fishermen are pessimistic, the changes in each parameter will not change their willingness to choose the opposition strategy but will affect the change in the Japanese government’s initial willingness to choose the discharge strategy. When the fishermen are optimistic, the cost of nuclear wastewater treatment and financial subsidies will slow down the evolution speed of the Japanese government to choose to discharge and Japanese fishermen to accept discharge policy. This paper also puts forward policy implications for the Japanese government and suggestions for Japanese fishermen to provide necessary support for the government to formulate pollution control policies and the people to protect their own rights and interests.

Keywords: nuclear wastewater discharge; marine pollution protection; evolutionary game model; rank-dependent expected utility; public emotion

1. Introduction

On March 12, 2011, the Japanese government announced a leak of radioactive material from the Fukushima Daiichi Nuclear Power Plant (FDNPP) as a result of the earthquake (Amano 2015). On April 11 of the same year, another 7.1 magnitude earthquake struck Fukushima, and Japan issued another tsunami warning and nuclear leak alert (Ethel et al. 2011). Due to
the abovementioned successive earthquakes and tsunamis, the cores of FDNPP units 1 to 3 melted down. To cool the reactor cores, Tokyo Electric Power Company (TEPCO) continues to inject water into the containment of units 1 to 3. As of April 2021, 1.25 million tons of nuclear wastewater has been stored in the plant and is still increasing at a rate of 140 tons per day (Liu, Lyu, et al. 2021). TEPCO claimed that the wastewater storage tanks in the FDNPP will be fully filled in the fall of 2022 and that there is no more land available for the construction of large numbers of storage tanks. According to Buesseler (2014) and Steinhauser, Brandl, and Johnson (2014), this is the worst and most damaging nuclear accident worldwide since the Chernobyl nuclear disaster in 1986. Therefore, it is not surprising that how to deal with the huge amount of nuclear wastewater has always been the focus of governments and people around the world (Liu, Wang, et al. 2021; Yang et al. 2022).

Ten years after the earthquake, the Japanese government has ‘basically’ decided to discharge nuclear wastewater from the FDNPP into the sea. On April 13, 2021, the Japanese government held a cabinet meeting and formally decided to discharge millions of tons of nuclear wastewater from the FDNPP into the sea after filtering and diluting it. Discharge activity is expected to begin in 2023. The Japanese government promises that discharged wastewater will meet international standards and will not negatively affect human health or the marine ecosystem. However, there are still considerable studies in which the radionuclides contained in wastewater will spread to most of the Pacific Ocean within 57 days and to global waters with ocean currents within 10 years. In particular, radioisotopes with long half-lives in wastewater, such as $^3$H, $^{14}$C, $^{106}$Ru, $^{60}$Co, and $^{90}$Sr, will continue to pose a potential threat to the environment and public health (Okamura et al. 2016; Gallardo and Marui 2016; Iwasa et al. 2020; Shozugawa et al. 2020).
When news broke that the Japanese government had decided to discharge nuclear wastewater, Fukushima fishermen, who had been plagued by the nuclear leak, were in an uproar. When fishing resumed in the limited area of Fukushima Prefecture in June 2012, some Fukushima fishermen set out to try to expand their fishing business. After ten years of efforts, the sales channels of Fukushima fisheries were restored to some extent, and the radiation test pass rate of the products was close to 100%. However, once nuclear wastewater is discharged into the sea by the government, these hard-earned achievements will be ruined. Therefore, the Japanese people have launched several large protests. One can see that the public’s reaction to the proposal of discharging nuclear wastewater into the ocean was far from just opposition; it was more of an outrage. Although the Japanese government and TEPCO have provided explanations for the discharge of nuclear wastewater, they have never been accepted by the majority of the public.

Under this background, it is particularly important to explore the evolutionary stable strategies (ESSs) between the Japanese government and fishermen considering emotional factors and to analyze the key factors affecting ESSs. This will help to provide the necessary reference for the Japanese government to make decisions on the discharge of nuclear wastewater, promote the improvement of the relationship between the government and the people, and advance the sustainable development of the ecological environment and human health. To this end, our paper aims to construct an evolutionary game model to answer the following four research questions: (1) How can the benefits and costs of the Japanese government and Japanese fishermen be reasonably determined in the evolutionary game model? How to construct the payoff matrix of both parties? (2) How can the replication dynamic equation of each stakeholder be constructed while considering the emotion factor? (3) How is the asymptotic stability of each stakeholder analyzed? (4) What are the effects of changes in some critical parameters on the evolutionary results between stakeholders?
To answer the abovementioned research questions, we first construct the payoff matrix based on the actual situation of the Japanese government and Japanese fishermen. Then, we introduce emotional factors into the evolutionary game model to construct replicated dynamic equations of stakeholders and discuss the ESSs under different emotions of the Japanese government and fishermen. Finally, by adjusting several key parameters in the game model, we explore the influence of each factor on the game to identify the key factors affecting the ESS. Overall, the contributions of this paper include the following two aspects:

First, we discuss the game relationship between the Japanese government and Japanese fishermen by capturing the research hotspots and applying evolutionary game theory. At present, studies related to the wastewater treatment of FDNPP mainly analyze the current situation of pollution and the ecological impact and less consider the pollution management strategy of the government. Some studies based on game theory mainly discuss the relationship between the Japanese government and neighboring countries and international organizations, and there is a lack of analysis of the relationship between various stakeholders within Japan. This paper fills the abovementioned research gaps and provides necessary decision support for resolving conflicts arising from nuclear wastewater discharge and ensuring environmental sustainability.

Second, considering the actual relationship between the Japanese government and Japanese fishermen, we extend the evolutionary game theory model by introducing the emotion factor. To the best of our knowledge, this is the first paper that considers emotional factors in the discussion of nuclear wastewater treatment decisions in Japan. By analyzing the ESSs between stakeholders under different emotional combinations, we provide effective theoretical guidance to advance the development of a scientifically sound nuclear wastewater treatment strategy in Japan.
The remainder of this paper is organized as follows. Section 2 reviews the literature related to this paper and identifies the research gap. Section 3 proposes the basic assumptions of the evolutionary game model and introduces rank-dependent expected utility (RDEU) theory. Meanwhile, stakeholders’ ESSs under different emotional combinations are analyzed. In Section 4, numerical simulations are carried out, and the key elements affecting the game are discussed through sensitivity analysis. Finally, Section 5 concludes this paper and proposes several policy recommendations for the government.

2. Literature review

The research questions addressed in this paper are closely related to nuclear wastewater management and evolutionary game theory. Therefore, we use two subsections to develop an overview of each of these two topics.

2.1. Nuclear wastewater management

Numerous studies have confirmed that the radioactive substances contained in nuclear wastewater pose a great threat to the natural environment on which humans depend and to their own health (Clifford and Zhang 1994; Dufresne et al. 2018). Normile (2021) stated that unlike other radioisotopes with significant risks, such as $^{131}$I, $^{236}$U, $^{240}$P, $^{137}$Cs (Tims et al. 2016; Cléro et al. 2021; Tsabaris et al. 2021), the large amount of $^3$H contained in nuclear wastewater from the FDNPP is more hazardous. Currently, approximately 1PBq $^3$H is stored in storage tanks at FDNPP (de With et al. 2021). $^3$H has a half-life of 12.43 years and is highly cyclic in the biosphere. Once $^3$H enters the human body, it may cause radiation damage to humans, leading to cell death. $^3$H may also be enriched in marine organisms, affecting species throughout the food chain (Yankovich et al. 2011; de With et al. 2021).

Through the Advanced Liquid Processing System (ALPS) developed in 2012, TEPCO claims to have filtered out radioisotopes other than $^3$H after treatment of nuclear wastewater.
However, reports still indicate that 73% of nuclear wastewater treated with ALPS still exceeds Japan’s discharge standards as of the end of 2019. According to Shozugawa et al. (2020) and Zhao et al. (2021), some other radioisotopes with longer half-lives (e.g., $^{60}$Co, $^{90}$Sr, $^{106}$Ru) also frequently escape from ALPS. Among them, $^{60}$Co can cause cell damage; $^{90}$Sr greatly increases the risk of leukemia in humans; and $^{106}$Ru has a long-term radiation risk to the environment (Khani, Pahlavanzadeh, and Alizadeh 2012; Khajeh, Sarafraz-Yazdi, and Moghadam 2017). These substances can pose a potential threat to humans and the environment through complex pathways. In addition to the discussion of the impacts caused by discharges from life science and chemical perspectives, some scholars have recently assessed the negative impacts of Fukushima nuclear wastewater discharges from the perspectives of ecosystems (Tanaka et al. 2016), health literacy of Fukushima residents (Moriyama et al. 2020), and food safety perceptions of the Japanese population (Kuroda et al. 2021). The abovementioned literature shows that the Japanese public still has doubts about whether wastewater treated with ALPS can meet discharge standards and is pessimistic about the safety of Fukushima seafood.

2.2. Evolutionary game theory

Evolutionary game theory originated in the 1990s (Liu, Wang, et al. 2021). Unlike traditional static game theory, evolutionary games take inspiration from biological evolution theory and consider that the game equilibrium between players is formed through repeated participation in the game and trial and error (Weibull 1997). Therefore, unlike traditional games that consider each player to be perfectly rational, evolutionary game theory considers each player to have limited rationality. Each player maximizes utility by repeatedly learning and adjusting its own strategy (Von Neumann and Morgenstern 2007). Therefore, the equilibrium state formed by evolutionary games is also called dynamic equilibrium (Gallardo and Marui...
In recent years, evolutionary games have played a pivotal role in disciplines such as economics, finance, and environmental science (Hanley and Folmer 1998) and are seen as an effective tool for exploring the interconnections between individuals in complex systems and the evolutionary trajectories of individual strategies (Coninx, Deconinck, and Holvoet 2018).

In recent years, evolutionary game theory has been widely used in the game analysis of stakeholders, especially in research on the government’s management of pollution activities of enterprises. For example, Xu, Di, and Chen (2021) analyzed the game relationships among stakeholders related to inland waterway navigation pollution. A three-party evolutionary game model was constructed based on prospect theory, and numerical simulation experiments were carried out through system dynamics simulation methods. The simulation results show that to ensure that inland waterway shipping pollution is effectively managed, both upstream and downstream governments should actively implement supervision and ensure the use of clean energy by shipping companies through institutions and policies. For public–private partnership (PPP) projects in wastewater treatment, Estalaki, Abed-Elmdoust, and Kerachian (2015) and Lv, Lin, and Zhou (2021) constructed different evolutionary game models to analyze the dynamic game of stakeholders, respectively. Wang et al. (2021) discussed how energy investment companies promote the development of solar thermal power and nuclear power in the context of carbon neutrality. An evolutionary game model was constructed to analyze the cooperative game among energy investment companies, solar thermal power plants and nuclear power plants. The authors found that energy investment companies are the most willing to participate when all three stakeholders choose to cooperate. In the field of construction waste resource utilization, a multi-intelligent evolutionary game model was developed by Su (2020). The authors found that regulatory costs that were too high reduced the government’s willingness to regulate, and penalties and subsidies that were too low were detrimental to the evolution of optimal strategies among
stakeholders. Similar research has been expanded in research areas such as supply chain
management (Sun et al. 2019), manufacturing (Chen and Hu 2018), marine environmental
governance (Hujainah et al. 2018; Penz and Polsa 2018), marine environmental improvement
across regions (Smythe and McCann 2018; Smith 2018), and marine environmental legal
systems (Cullen-Knox et al. 2017).

There are relatively few policy-oriented studies on the Japanese government’s
discharge of nuclear wastewater into the sea. Very recently, Liu, Lyu, et al. (2021) analyzed
the wastewater discharge equilibrium strategies of discharging countries and other countries
of interest using static game, RDEU game, and sequential game, respectively. In particular,
the authors included emotional factors in the RDEU game model framework. The results
show that the most likely emotional state for countries of interest to prevent emitters from
discharging nuclear wastewater is to remain pessimistic. Liu, Wang, et al. (2021) constructed
a tripartite evolutionary game model to explore the ESSs of Japan, other countries, and
international environmental protection organization (IEPO). It is shown that the cost of
nuclear wastewater treatment, negative externalities of the marine environment, litigation
compensation, international assistance from the IEPO, and the proximity coefficient between
Japan and other countries are all the key factors affecting the ESSs. Yang et al. (2022)
proposed a grey and unknown preference framework of the graph model for conflict
resolution. The proposed method can more comprehensively reflect the decision-making
uncertainty caused by stakeholders’ incomplete cognition of objective things.

2.3. Research gap

Based on the review of the abovementioned literature, it can be found that the vast majority
of studies have discussed the ecological risks involved in the discharge of nuclear wastewater
in the context of governmental decision making in considering the discharge of nuclear
wastewater. The few studies on Japan’s policy of discharging nuclear wastewater also start from international relations and discuss the game relationship among countries or among countries and international organizations. Few studies have included public emotions in the modeling framework and discussed the relationship between the government and the public. However, the impact of emotions on the management of public emergencies has received widespread attention since the outbreak of COVID-19 (Liu, Lyu, et al. 2021). In recent years, some scholars have carried out game analysis considering public emotions around areas such as land acquisition (Hong et al. 2020), environmental pollution (Hao, Yan, and De Qing 2019), and emergency management (Xiong and Hou 2012). To the best of our knowledge, only Liu, Lyu, et al. (2021) constructed an RDEU game model considering public emotions to analyze the impact of Japan’s nuclear wastewater discharge policy on stakeholders. However, the authors assumed that the stakeholders are perfectly rational and construct a static game model without taking into account the dynamics of the game process. Therefore, to fill the abovementioned research gap, we first make several assumptions and construct the payoff matrix. Then, RDEU theory is introduced into the evolutionary game, and replication dynamic equations considering the public emotion factor are constructed for different stakeholders. Next, we determine the key parameters that affect evolutionary equilibrium through numerical simulation. Finally, policy recommendations for the Japanese government and Japanese fishermen are provided to promote the change of the Japanese government’s nuclear wastewater discharge policy and help Japanese fishermen insist on defending their interests to minimize their losses.

3. Methodology

3.1. Basic assumptions

To abstract the problem and construct the game model, we first introduce the following
assumptions.

**Assumption 1.** The most immediate victims of Japan’s nuclear waste discharges are Japanese fishermen. In the evolutionary game of Japanese nuclear wastewater discharge, the Japanese government and Japanese fishermen are involved. In the process of game playing, they constantly modify and improve their behaviors to pursue the maximization of their own utility; that is, they both satisfy the assumption of bounded rational stakeholders (Friedman 1998).

**Assumption 2.** The Japanese government has two strategies: discharge or nondischarge. The probability that the Japanese government chooses the discharge strategy is \( p \) \( (p \in [0,1]) \), and the probability that the Japanese government chooses the nondischarge strategy is \( 1 - p \). The probability that Japanese fishermen choose to accept the discharge strategy is \( q \) \( (q \in [0,1]) \), and the probability that they choose to oppose the discharge strategy is \( 1 - q \).

**Assumption 3.** The cost of the discharge strategy chosen by the Japanese government is set as \( C_d \), which is relatively small but still cannot be ignored. Since the discharge of nuclear wastewater will produce negative externalities to the marine environment (e.g., the deterioration of the marine environment, the destruction of residents’ living environment and the threat to people’s life and health), the negative externalities of the marine environment suffered by Japan are set as \( NE \).

**Assumption 4.** When the Japanese government chooses the discharge strategy and Japanese fishermen accept the nuclear wastewater discharge policy, Japanese fishermen are indifferent to the discharge of nuclear wastewater. They need to bear the negative impact \( B \) of nuclear wastewater discharge on fisheries alone, including the damaged image of Japanese fisheries and the decline in demand, sales and price of seafood. As a result, the Japanese
government’s benefit is \(-C_d - NE\), and the Japanese fishermen’s benefit is \(-B\). If the
Japanese government chooses the discharge policy and the Japanese fishermen oppose the
strategy, the Japanese government will have to bear the discharge cost \(C_d\) and the negative
externality loss \(NE\) of the marine environment. Despite the opposition of the public, the
Japanese government made a behavior contrary to public sentiment, resulting in damage to its
reputation \(R_r\). After nuclear wastewater is discharged into the ocean, it will bring a series of
negative effects to fishermen, which will make their lives poor. To appease the fishermen, the
Japanese government needs to provide a subsidy \(S\) for them. However, in real life, the
subsidy \(S\) is far less than the negative impact \(B\) \((S < B)\). Therefore, the benefits for the
Japanese government are \(-C_d - NE - S - R_r\), while the opposition activities of fishermen,
such as demonstrations and other protests, cost the fishermen \(A\), so the benefit for the
Japanese fishermen is \(-B - A + S\).

Assumption 5. When the Japanese government chooses the nondischarge strategy, it
will bear a huge cost of nuclear wastewater treatment \(C_n\) \((C_n > C_d)\). When the Japanese
government chooses not to discharge nuclear wastewater and Japanese fishermen choose to
accept its strategy, Japanese fishermen will have neither loss nor benefit, so the payoff is 0,
and the Japanese government gains \(-C_n\). When the Japanese government chooses not to
discharge nuclear wastewater and Japanese fishermen choose to oppose the strategy, the
Japanese government and fishermen stand in the same position. At this time, the Japanese
government’s action is popular and gains reputation benefits \(R_r\). Therefore, the payoffs for
the Japanese government and fishermen are \(-A\) and \(-C_n + R_r\), respectively.

For the convenience of the reader, the related parameters and variables are
summarized in Table 1.
Table 1 Model parameters and variable descriptions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$</td>
<td>The cost of nuclear waste water discharge</td>
</tr>
<tr>
<td>$C_n$</td>
<td>Nuclear wastewater treatment costs</td>
</tr>
<tr>
<td>$NE$</td>
<td>The negative externalities of marine environment faced by the Japanese government</td>
</tr>
<tr>
<td>$R_j$</td>
<td>The Japanese government reputation losses</td>
</tr>
<tr>
<td>$R_e$</td>
<td>Reputational gains for the Japanese government</td>
</tr>
<tr>
<td>$A$</td>
<td>The cost of Japanese fishermen’s protests</td>
</tr>
<tr>
<td>$B$</td>
<td>The negative impact of nuclear wastewater discharges on the lives of Japanese fishermen</td>
</tr>
<tr>
<td>$S$</td>
<td>The living allowance given by the Japanese government to Japanese fishermen</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>Probability of Japanese government choosing the discharge strategy</td>
</tr>
<tr>
<td>$q$</td>
<td>Probability of Japanese fishermen choosing the acceptance strategy</td>
</tr>
</tbody>
</table>

3.2. The RDEU game model

RDEU game theory was first proposed by Quiggin (1982) in 1982 and is a utility theory that takes into account the emotional factors of participants. It was later refined by Yaari (1987).

RDEU models, like earlier models, are based on probability weight functions, but their weights are not applied to the probabilities of individual events but to cumulative probabilities. Here, we first present the basic definition of the RDEU model below.

**Definition 1.** If a random variable, say $X$, takes the value in set $\{x_i, i=1,2,\ldots,n\}$, $x_i$ satisfies the order $x_1 > x_2 > \cdots > x_n$, and $X$ obeys the probability distribution of

$$P_r \{X = x_i\} = p_i, \ i = 1,2,\ldots,n,$$

which satisfies $p_i \geq 0$, $p_1 + p_2 + \cdots + p_n = 1$, then the rank of $x_i$ can be defined as Equation (1). The higher the rank of $x_i$ is, the higher the priority in decision-making.

$$RP_r = P\{X \leq x_i\} = p_1 + p_{i+1} + \cdots + p_n \quad i = 1,2,\ldots,n \tag{1}$$

**Definition 2.** The decision maker’s preference can be represented by a real-valued function $V$, which can be defined by the utility function $u(\bullet)$ and the weight function $\pi(\bullet)$,
i.e., $V = (X, u, \pi) = \sum_{i=1}^{n} u(x_i)\pi(x_i)$, where $\pi(x_i)$ represents the decision weight for $x_i$ and can be expressed by Equation (2).

$$\pi(x_i) = W(p_i + 1 - RP_i) - W(1 - RP_i) \quad i = 1, 2, \ldots, n$$ (2)

The function $W(\cdot)$ represents the emotion function of the decision maker, and $W_i(x) = x^{r_i}, \ r_i > 0, \ i = 1, 2$. Here, $r_i$ is called the emotion index of decision maker $i$. If $r_i > 1$, $W_i(x)$ is a pessimistic emotion function; if $0 < r_i < 1$, $W_i(x)$ is an optimistic emotion function; if $r_i = 1$, $W_i(x)$ is a no emotion function, and the decision maker is completely rational (Quiggin 1990; Starmer 2000).

### 3.3. The RDED evolutionary game model

Suppose the mixed strategy of the Japanese government is $(p, 1 - p)$, that is, the Japanese government chooses ‘Discharge’ with probability $p$ and ‘Nondischarge’ with probability $1 - p$; the mixed strategy of Japanese fishermen is $(q, 1 - q)$, i.e., the Japanese fishermen choose ‘Accept discharge’ with probability $q$ and choose ‘Oppose discharge’ with probability $1 - q$. Since nuclear wastewater discharge is a public emergency, it is a more realistic consideration for us to introduce emotional factors into the game analysis. Let the emotional function of the Japanese government be $w_1(p) = p^{r_1}$ and the emotional function of Japanese fishermen be $w_2(q) = q^{r_2}$, where $r_1$ and $r_2 > 0$ are the emotion indices of the Japanese government and Japanese fishermen, respectively. Based on the above discussion, the payoff matrix of the Japanese government and Japanese fishermen is shown in Table 2. The table shows that there are four strategy combinations (Discharge, Accept discharge), (Discharge, Oppose discharge), (Nondischarge, Accept discharge), (Nondischarge, Oppose discharge).
discharge) in the game between the Japanese government and Japanese fishermen, and each player has four possible payoffs. The game process between the Japanese government and fishermen is illustrated in Fig. 1.

<table>
<thead>
<tr>
<th>Japanese Government ($G$)</th>
<th>Japanese Fishermen ($F$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accept discharge ($q$)</td>
<td>Oppose discharge ($1-q$)</td>
</tr>
<tr>
<td>Discharge ($p$)</td>
<td>$-C_d - NE, -B$</td>
</tr>
<tr>
<td>Nondischarge ($1-p$)</td>
<td>$-C_n, 0$</td>
</tr>
</tbody>
</table>

**Table 2** Payoff matrix of Japanese government and Japanese fishermen

According to the definition of rank and decision weight in RDEU theory, the probability distribution, rank and decision weight of the Japanese government ($G$) and Japanese fishermen ($F$), and the corresponding benefits can be obtained, as shown in Tables 3 and 4. Based on the numerical values of nuclear wastewater treatment cost, nuclear wastewater discharge cost and the negative externalities of marine environment that the Japanese government will face after nuclear wastewater discharge, the ranking of strategic benefits of the Japanese government is explained as follows.
After the Fukushima nuclear accident, the Japanese government proposed five kinds of nuclear wastewater treatment solutions, i.e., discharge nuclear wastewater into the sea, turn nuclear wastewater into water vapor and discharge it into the atmosphere, discharge nuclear wastewater into the depths of the ground along underground pipes, electrolytic treatment of nuclear wastewater, and solidification of nuclear wastewater into the ground. Among these options, the cost of discharging the treated water of nuclear wastewater into the sea is the lowest, while the treatment cost of other methods is dozens or even hundreds of times that of discharging it into the sea. From the perspective of cost and technical feasibility, the Japanese government has chosen to discharge nuclear wastewater into the sea among five options. Therefore, the benefit of the Japanese government from not discharging nuclear wastewater should be much smaller than the cost of discharging nuclear wastewater into the sea, so the order of benefits should be 

\[ -C_d - NE > -C_d - NE -S -R_i > -C_n + R_e > -C_n . \]

### Table 3 Probability distribution, rank, and decision weight corresponding to Japanese government income value

<table>
<thead>
<tr>
<th>Japanese government income value</th>
<th>Probability (p_i)</th>
<th>Rank Position (R_{P_i})</th>
<th>Decision Weight (\pi(x_i))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-C_d - NE)</td>
<td>(pq)</td>
<td>1</td>
<td>(W_i(pq))</td>
</tr>
<tr>
<td>(-C_d - NE - S - R_i)</td>
<td>(p(1-q))</td>
<td>1- (pq)</td>
<td>(W_i(p) - W_i(pq))</td>
</tr>
<tr>
<td>(-C_n + R_e)</td>
<td>((1-p)(1-q))</td>
<td>1- (p)</td>
<td>(W_i(1-q + pq) - W_i(p))</td>
</tr>
<tr>
<td>(-C_n)</td>
<td>((1-p)q)</td>
<td>(q-pq)</td>
<td>(1 - W_i(1-q + pq))</td>
</tr>
</tbody>
</table>

### Table 4 Probability distribution, rank, and decision weight corresponding to Japanese fishermen’s income value

<table>
<thead>
<tr>
<th>Japanese fishermen’s income value</th>
<th>Probability (p_i)</th>
<th>Rank Position (R_{P_i})</th>
<th>Decision Weight (\pi(x_i))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>((1-p)q)</td>
<td>1</td>
<td>(W_i(q-pq))</td>
</tr>
<tr>
<td>(-A)</td>
<td>((1-p)(1-q))</td>
<td>1- (q+pq)</td>
<td>(W_i(1-p) - W_i(q-pq))</td>
</tr>
<tr>
<td>(-B - A + S)</td>
<td>(p(1-q))</td>
<td>(p)</td>
<td>(W_i(1-p) - W_i(1-p))</td>
</tr>
<tr>
<td>(-B)</td>
<td>(pq)</td>
<td>(pq)</td>
<td>(1 - W_i(1-pq))</td>
</tr>
</tbody>
</table>

According to the decision weights obtained in Tables 3 and 4, the RDEU expected utility function of the participants can be calculated, and the evolutionary game model with
emotional parameters can be obtained. Let \( U_{GD} \) represent the expected utility of the Japanese government adopting the strategy of discharging nuclear wastewater; \( U_{GN} \) denote the expected utility of the nondischarge strategy; and \( U_G \) is the average expected utility. We can obtain the following relationships.

\[
U_{GD} = (-C_d - NE)q^\gamma + (-C_d - NE - S - R_i)(1 - q^\gamma)
\]

(3)

\[
U_{GN} = -C_nq^\gamma + (-C_n + R_c)(1 - q^\gamma)
\]

(4)

\[
U_G = (-C_n + R_c)[W_1(1 - q + pq) - W_i(p)] + (-C_n)[1 - W_1(1 - q + pq)] + (-C_d - NE)W_i(pq) + (-C_d - NE - S - R_i)[W_i(p) - W_i(pq)]
\]

(5)

Moreover, we let \( U_{FA} \) represent the expected utility of Japanese fishermen choosing to accept the discharge strategy; \( U_{FO} \) denote the expected utility of the opposing discharge strategy; and \( U_F \) is the average expected utility. The following equations can be obtained.

\[
U_{FA} = -Bp^\gamma
\]

(6)

\[
U_{FO} = (S - B - A)p^\gamma + (-A)(1 - p^\gamma) = (-B + S)p^\gamma - A
\]

(7)

\[
U_F = 0W_2(q - pq) + (-A)[W_2(1 - p) - W_2(q - pq)] + (-B)[1 - W_2(1 - pq)]
\]

(8)

According to the basic method of the Nash equilibrium solution, when both sides of the game involved in the Japanese government’s discharge of nuclear wastewater adopt mixed strategies, we take partial derivatives of \( p \) and \( q \) of the RDEU expected utility function Equations (4) and (5). Thus, the replicated dynamic equation can be written as follows.

\[
G(p) = \frac{dp}{dt} = p^\gamma (U_{GD} - U_G)
\]

(9)
\[ F(q) = \frac{dq}{dt} = q^2 (U_{r-A} - U_p) \]
\[ = q^2 \left[ -Bp^r - A(q - pq)^r + (A - S)(1 - pq)^r - (B - S)(1 - p)^r + B \right] \]  

(10)

Let \( G(p) = 0, F(q) = 0 \); five system equilibrium points can be obtained, i.e., \((0,0), (0,1), (1,0), (1,1)\), and the mixed equilibrium point \((p^*, q^*)\). The stability of the equilibrium points can be analyzed using a standard Jacobian matrix \( J \), see Equation (11) (Friedman 1998). The Japanese government and fishermen are both players in the game.

However, unlike the rationality of the Japanese government in the decision-making process, fishermen are easily affected by subjective emotions during the game. Therefore, under the rational decision-making of the Japanese government, we consider the three emotions of Japanese fishermen: completely rational, emotionally pessimistic and emotionally optimistic.

The following sections discuss the stability of the equilibrium point according to the different emotional states of the fishermen.

\[
\text{Jacobian Matrix} = \begin{bmatrix} \frac{\partial G(p)}{\partial p} & \frac{\partial G(p)}{\partial q} \\ \frac{\partial F(q)}{\partial p} & \frac{\partial F(q)}{\partial q} \end{bmatrix}
\]  

(11)

3.3.1. System stability analysis when both sides of the game are rational

This situation means that the participants do not have emotions in the game process, and their behavioral strategies are not affected by any personal emotions. At this time, we set the parameter of the emotion function to be \( r_1 = r_2 = 1 \). Bringing the emotion parameter into each replicated dynamic equation, the stability of each equilibrium point is shown in Table 5. It can be seen from Table 5 that when both sides of the game are rational, the equilibrium point \((0,0)\) is an instability point. The points \((0,1)\) and \((1,1)\) are saddle points. \((p^*, q^*)\) exists only under certain conditions, and \((1,0)\) is the evolutionarily stable point. These results show
that when there is no emotional intervention between the Japanese government and Japanese fishermen, the Japanese government will definitely choose the discharge strategy, while Japanese fishermen will choose to oppose the discharge of nuclear wastewater, (Discharge, Oppose discharge) is the ESS.

<table>
<thead>
<tr>
<th>Equilibrium points</th>
<th>$\text{tr}(J)$</th>
<th>$\text{det}(J)$</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0, 0)</td>
<td>+</td>
<td>+</td>
<td>Instability point</td>
</tr>
<tr>
<td>(0, 1)</td>
<td>+</td>
<td>–</td>
<td>Saddle point</td>
</tr>
<tr>
<td>(1, 0)</td>
<td>–</td>
<td>+</td>
<td>ESS</td>
</tr>
<tr>
<td>(1, 1)</td>
<td>–</td>
<td>–</td>
<td>Saddle point</td>
</tr>
<tr>
<td>$(p^<em>, q^</em>)$</td>
<td></td>
<td></td>
<td>There is no stable solution, depending on the specific situation.</td>
</tr>
</tbody>
</table>

### 3.3.2. System stability analysis when the fisherman is pessimistic

This situation shows that the Japanese government is a rational participant in the game process, and Japanese fishermen are pessimistic in the game process of the nuclear wastewater discharge strategy. For the convenience of analysis, it is assumed that the parameters of the emotion function in this case are $r_1 = 1$ and $r_2 = \frac{1}{3}$, bringing the emotional parameters of the players into each replicated dynamic equation. The stability of each equilibrium point is shown in Table 6. One can see that $(0, 0)$ is an instability point, $(0, 1)$ and $(1, 1)$ are saddle points, $(1, 0)$ is an evolutionarily stable point, and $(p^*, q^*)$ only exists in certain circumstances in a stable solution. This shows that when the Japanese government is rational and the fishermen are pessimistic, the fishermen will inevitably choose to rise up and defend their interests, while the Japanese government will still choose to discharge nuclear wastewater into the sea, (Discharge, Oppose discharge) is the ESS.
Table 6 Asymptotic stability analysis of the equilibrium point of the replicated dynamic system when the fisherman is pessimistic

<table>
<thead>
<tr>
<th>Equilibrium points</th>
<th>$\text{tr} (J)$</th>
<th>$\text{det} (J)$</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(0,0)$</td>
<td>$+$</td>
<td>$+$</td>
<td>Instability point</td>
</tr>
<tr>
<td>$(0,1)$</td>
<td>$+$</td>
<td>$-$</td>
<td>Saddle point</td>
</tr>
<tr>
<td>$(1,0)$</td>
<td>$-$</td>
<td>$+$</td>
<td>$\text{ESS}$</td>
</tr>
<tr>
<td>$(1,1)$</td>
<td>$+$</td>
<td>$-$</td>
<td>Saddle point</td>
</tr>
<tr>
<td>$(p^<em>, q^</em>)$</td>
<td></td>
<td></td>
<td>There is no stable solution, depending on the specific situation.</td>
</tr>
</tbody>
</table>

3.3.3. System stability analysis when the fisherman is optimistic

This situation shows that the Japanese government is a rational participant in the game process, and Japanese fishermen are optimistic in the game of nuclear wastewater discharge. For convenience, we assume that the parameters of the emotion function in this case are $r_1 = 1$ and $r_2 = 2$. Then, the emotional parameters of the players are introduced into each replication dynamic equation, and the stability of each equilibrium point is shown in Table 7. In the table, one can see that the obtained points $(0,0)$ and $(1,0)$ are instability points, $(0,1)$ is a saddle point, $(1,1)$ is an evolutionarily stable point, and $(p^*, q^*)$ can only be obtained under certain circumstances. The abovementioned results show that when the Japanese government is rational and the fishermen are optimistic, although the Japanese government chooses the discharge policy, the optimistic Japanese fishermen choose to accept the government’s move. Even if this policy greatly harms their interests, strategy (Discharge, Accept discharge) is $\text{ESS}$.
### Table 7 Asymptotic stability analysis of the equilibrium point of the replicated dynamic system when the fisherman is optimistic

<table>
<thead>
<tr>
<th>Equilibrium points</th>
<th>$\text{tr}(J)$</th>
<th>$\text{det}(J)$</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0,0)</td>
<td>+</td>
<td>0</td>
<td>Instability point</td>
</tr>
<tr>
<td>(0,1)</td>
<td>-</td>
<td>-</td>
<td>Saddle point</td>
</tr>
<tr>
<td>(1,0)</td>
<td>-, +</td>
<td>0</td>
<td>ESS</td>
</tr>
<tr>
<td>(1,1)</td>
<td>-</td>
<td>+</td>
<td>Saddle point</td>
</tr>
<tr>
<td>$(p^<em>, q^</em>)$</td>
<td></td>
<td></td>
<td>There is no stable solution, depending on the specific situation.</td>
</tr>
</tbody>
</table>

### 4. Numerical simulation

With the continuous fermentation of Japan’s nuclear wastewater discharge event, the conflict of interest between the Japanese government and Japanese fishermen is becoming increasingly tense. Based on the RDEU evolutionary game model between the Japanese government and Japanese fishermen, this section analyzes the corresponding path evolution and the influence of key parameters considering the different emotions of fishermen. In addition to simulating the evolution results of two players in different emotional combinations, we will discuss the influence of different parameters on the evolutionary equilibrium, e.g., nuclear wastewater discharge costs, nuclear wastewater treatment costs, reputation losses, reputational gains, the negative externalities of marine environment, Japanese fishermen’s protests costs, the negative impact on the lives of Japanese fishermen, and living allowance.

#### 4.1. Evolution trajectories and numerical value simulation in three scenarios

Based on the RDEU replicated dynamic equation and stability conditions, the ESSs under each scenario in Section 3.3 are simulated through MATLAB R2019b. According to the constraints of the model parameters and Liu, Wang, et al. (2021), the parameters are set as follows: $C_d = 3$, $NE = 12$, $C_w = 25$, $R_c = 2$, $R_i = 4$, $S = 2.5$, $A = 1$, and $B = 5$. 

4.1.1. Both sides of the game are rational

The probability $p$ that the Japanese government chooses to discharge nuclear wastewater and the probability $q$ that Japanese fishermen choose to accept the strategy are both constantly changing in $(0,1)$. When both parties are rational game subjects, according to the replicated dynamic equation and the dynamic differential equation, the evolutionary trajectory and the numerical change diagram of the dynamic evolution of the Japanese government and Japanese fishermen can be obtained, as shown in Fig. 2(a) and Figs. 2(b)-2(c), respectively.

![Evolutionary trajectory and changes in numerical values when both sides of the game are rational](image)

**Fig. 2** Evolutionary trajectory and changes in numerical values when both sides of the game are rational

Taking the initial willingness $p = 0.5, q = 0.2$, when $r_1 = r_2 = 1$, the evolutionary trajectory of $(1,0)$ is shown in Fig. 2(a). As shown in Fig. 2(a), the Japanese government, as a powerful political party, has absolute control and initiative in the process of nuclear wastewater discharge. After learning that fishermen are opposed to nuclear wastewater discharge, the Japanese government quickly adjusted its strategy to make the nuclear wastewater discharge strategy more effective. The probability that the Japanese government chooses the strategy of discharging is gradually approaching 1. To seek compensation for their own losses, the probability of rational fishermen choosing to accept the nuclear wastewater discharge policy is gradually approaching 0, and they all choose to oppose the policy to obtain compensation for their losses through protests and other forms. The
The probability of opposing the discharge strategy approaches 1. The final result of the evolutionary game is stable at \((1,0)\), when the Japanese government and the fishermen are both rational game players.

The dynamic differential equation of the Japanese government is

\[
G(p, q) = 1.1p + 8.5pq - 8.5p^2q - 1.1p^2. 
\]

It can be seen from Fig. 2(b) that this function is convex, i.e., the second derivative value is negative, indicating that \(p = 1\) is the stable strategy. Thus, the Japanese government will choose the discharge strategy. Meanwhile, the dynamic differential equation of the Japanese government is

\[
F(p, q) = 1.1p + 8.5pq - 8.5p^2q - 1.1p^2. 
\]

It can be seen from Fig. 2(c) that \(p = 0.4\) is the critical point; when \(p \in (0,0.4)\), this part is a convex function, i.e., the second derivative is negative, indicating that \(q = 1\) is the stable strategy; when \(p \in (0.4,1)\), this part is a concave function and \(q = 0\) is the stable strategy. Obviously, when both sides are rational, the Japanese government will only choose to discharge nuclear wastewater into the sea for its own benefit. Since the probability of the Japanese government choosing the discharge strategy is 1, which is greater than the critical value of 0.4, Japanese fishermen will choose to oppose the discharge of nuclear wastewater.

4.1.2. The Japanese government is rational, Japanese fishermen are pessimistic

The probability \(p\) that the Japanese government chooses to discharge nuclear wastewater and the probability \(q\) that Japanese fishermen choose to accept the strategy are both constantly changing in \((0,1)\). When the Japanese government is rational and Japanese fishermen are pessimistic, according to the replicated dynamic equation and the dynamic differential equation, the evolutionary trajectory and the numerical change diagram of the dynamic evolution of the Japanese government and Japanese fishermen can be obtained, as
shown in Fig. 3(a) and Figs. 3(b)-2(c), respectively.

![Fig. 3 Evolutionary trajectory and changes in numerical values when the fishermen are pessimistic](image)

Taking the initial willingness \( p = 0.5, q = 0.2 \), when \( r_1 = 1, r_2 = \frac{1}{3} \), the evolutionary trajectory of \((1,0)\) is shown in Fig. 3(a). As shown in Fig. 3(a), when Japanese fishermen are pessimistic, \((1,0)\) becomes the stable equilibrium point. Although Japanese fishermen oppose the discharge of nuclear wastewater into the sea, the Japanese government still ignores the livelihood and safety of Japanese fishermen and chooses to discharge nuclear wastewater into the sea. Compared with the decision in which both parties are rational, when the fishermen are pessimistic, they do not think that the government will take their interests into account, and they will immediately choose the opposition strategy to defend their own interests. The probability of choosing the opposition strategy rapidly evolves from 0.8 to 1 to defend their own rights and interests. The firm opposition of the fishermen only accelerated the Japanese government’s policy of promoting the discharge of nuclear wastewater into the sea. The probability that the Japanese government chooses to discharge nuclear wastewater into the sea first evolved to 0.95. At this time, the probability that the corresponding Japanese fishermen objected to the policy of discharging nuclear wastewater into the sea evolves to 1, and then the probability that the Japanese government discharges nuclear wastewater into the sea gradually evolves to 1.
The dynamic differential equation of the Japanese government is

\[ G(p, q) = 1.1p + 6.5pq^3 - 8.5p^2q + 2pq - 1.1p^2. \]

It can be seen from Fig. 3(b) that this function is convex, that is, the second derivative value is negative, indicating that \( p = 1 \) is the stable strategy, and the Japanese government will definitely choose the discharge strategy.

The dynamic differential equation of the Japanese government is

\[ F(p, q) = \frac{1}{q} \left[ -5p - (q - pq)^3 - 1.5(1 - pq)^3 - 2.5(1 - p)^3 + 5 \right]. \]

Figure 3(c) shows that \( p = 0.19 \) is the critical point. When \( p \in (0, 0.19) \), this part is a convex function, indicating that \( q = 1 \) is the stable strategy. However, when \( p \in (0.19, 1) \), this part is a concave function, and \( q = 0 \) is the stable strategy. Fishermen under pessimism tend to choose confrontational strategies of struggle, so when the rational Japanese government chooses the discharge strategy, the fishermen will definitely choose the opposition strategy.

4.1.3. The Japanese government is rational, Japanese fishermen are optimistic

The probability \( p \) that the Japanese government chooses to discharge nuclear wastewater and the probability \( q \) that Japanese fishermen choose to accept the strategy are both constantly changing in \((0, 1)\). When the Japanese government is rational and Japanese fishermen are optimistic, according to the replicated dynamic equation and the dynamic differential equation, the evolutionary trajectory and the numerical change diagram of the dynamic evolution of the Japanese government and Japanese fishermen can be obtained, as shown in Fig. 4(a) and Figs. 4(b)-4(c), respectively.
Fig. 4 Evolutionary trajectory and changes in numerical values when the fishermen are optimistic

Taking the initial willingness \( p = 0.5, q = 0.2 \), when \( r_1 = 1, r_2 = 2 \), the evolutionary trajectory of \((1,1)\) is shown in Fig. 4(a). When Japanese fishermen are optimistic, \((1,1)\) becomes the stable equilibrium point, and the Japanese government finally chooses the discharge strategy, while accepting the Japanese government’s nuclear wastewater discharge policy becomes the evolutionarily stable strategy for the fishermen. With the increasing probability that fishermen choose to accept the nuclear wastewater discharge policy, the probability that the Japanese government chooses to discharge nuclear wastewater into the sea increases sharply from 0.5 to 0.6 at first. After gaining the belief that weak fishermen choose to accept the discharge policy, the government quickly adjusts its own strategy and makes the probability of the nuclear wastewater discharge strategy close to 1. Surprisingly, when the fishermen are optimistic, their strategic choices will make their situation worse than in the first two cases. When the fishermen are optimistic, they often show a kind of self-confidence, which is reflected in more trust in the decision-making of the Japanese government. However, the blind trust under this optimism has caused them to suffer a greater loss of interest.

The dynamic differential equation of the Japanese government is

\[
G(p, q) = 1.1p + 2pq + 6.5pq^2 - 8.5p^2q - 1.1p^3.
\]

It can be seen from Fig. 4(b) that this function is convex, that is, the second derivative value is negative, indicating that \( p = 1 \) is the stable strategy, and the Japanese government will choose the discharge strategy. The dynamic
differential equation of the Japanese government is
\[
F(p, q) = q^2 \left[ -5p - (q - pq)^2 - 1.5(1 - pq)^2 - 2.5(1 - p)^2 + 5 \right].
\]
Figure 4(c) shows that \( p = 0.19 \) is the critical point. When \( p \in (0, 0.12) \), this part is a convex function, indicating that \( q = 1 \) is the stable strategy; when \( p \in (0.12, 1) \), this part is a concave function; and \( q = 0 \) is the stable strategy. In other words, if the fishermen are rational, choosing to fight back is their best strategy when the Japanese government chooses the discharge strategy. However, in an optimistic mood, fishermen themselves will have a kind of trust in the government. Such blind trust in an optimistic mood leads fishermen to think that the Japanese government will consider their livelihood and interests. Finally, \( q = 1 \) becomes a stable strategy for fishermen in an optimistic mood. Combined with Figures 2-4, we can obtain the following conclusions.

1. When the Japanese government and Japanese fishermen are rational players, the process of the whole evolutionary game will be relatively calm and slow. However, when the game participants are emotional, the evolution trajectory shows that the process of the evolution of both sides will be relatively intense and rapid.

2. When both sides are rational game players, the dynamic differential equation is a function combining concave and convex, and the critical surface is the critical value of the transformation strategy. In the concave function part, the dynamic evolution value of the Japanese government and fishermen is negative, and the evolution strategy evolves toward ‘struggle’, i.e., the Japanese government will not choose the nuclear wastewater discharge strategy, while the fishermen will choose to oppose the nuclear wastewater discharge policy. In the convex function part, the values of dynamic evolution of both sides are positive, and the evolution strategy is to ‘peaceful’ evolution. The Japanese government will choose to discharge nuclear
wastewater, while Japanese fishermen will choose to accept this policy. The same
conclusion applies when fishermen are pessimistic.

(3) When fishermen are optimistic, the game results of both sides of the game no longer
meet the optimal solution shown by the dynamic differential equation. For Japanese
fishermen, choosing to rebel is the best option to safeguard their own interests, but
they choose to accept the discharge policy of the Japanese government. This shows
once again that blind optimism is not good for Japanese fishermen and the Japanese
government in the nuclear waste discharge game.

4.2. Impacts of key parameters on evolutionary trajectories and result

Considering that each key parameter will also have an impact on the decisions of the
Japanese government and fishermen, we examine the evolution of ESSs using sensitivity
analyses. To carry out numerical experiments, the initial probability is set as (0.5, 0.2), and
the initial parameter is set as $C_d = 3$, $NE = 12$, $C_n = 24.6$, $R_c = 2$, $R_f = 4$, $S = 2.5$, $A = 1$,
$B = 5$ to meet the constraint conditions. The influence of these parameter changes on the
evolutionary trajectories and results of both sides of the game is discussed in the following
subsections.

4.2.1. Impact of $C_d$

Let $C_d = 3, 3.2, 3.4, 3.6$ and $3.8$ while keeping the other parameters unchanged. The impact
of $C_d$ on evolutionary trajectories in three different combinations of emotions is depicted in
Figs. 5(a)-5(f).
The increase in the cost of nuclear wastewater discharge by the Japanese government has no effect on the decision-making results of the rational Japanese government and Japanese fishermen. However, it slows down the speed of the Japanese government’s promotion of the discharge policy, which makes the evolution of the Japanese fishermen’s opposition strategy first slow down and then accelerate. This is because when both parties are
rational, the rise in discharge costs will increase its fiscal expenditure for the Japanese
government, thus slowing down the evolution speed of its evolution to stabilize the
‘Discharge’ strategy. When the fishermen are in a pessimistic mood, the increase in the cost
of nuclear wastewater discharge reduces the probability that the Japanese government
chooses to discharge nuclear wastewater into the sea but has no impact on the fishermen’s
decision-making. Differently, when fishermen are optimistic, the higher cost of nuclear
wastewater discharge will accelerate the evolution of both sides but does not substantially
change the final evolution result. The probability that the Japanese government chooses the
discharge strategy first decreases with the rise of discharge costs and then accelerates to the
stable point. For fishermen, the increase in discharge cost accelerates their choice of the
‘Accept discharge’ strategy, which may be because the blind trust of optimistic fishermen in
the government makes them believe that when the discharge cost rises, the Japanese
government will reduce the probability of their choice of discharge strategy.

4.2.2. Impact of $C_n$

Let $C_n = 24.6, 24.7, 24.8, 24.9$ and 25 while keeping other parameters unchanged. The
impact of $C_n$ on evolutionary trajectories in three different combinations of emotions is
depicted in Figs. 6(a)-6(f).
Fig. 6 Impact of $C_n$ on evolutionary trajectories and results when fishermen are rational, pessimistic and optimistic

The increase in the cost of nuclear wastewater treatment will accelerate the Japanese government’s nuclear wastewater discharge policy and slow down the evolution of fishermen’s opposition strategy under the condition that both sides are rational. This is because the higher cost of nuclear wastewater treatment will definitely force the Japanese government back and accelerate the Japanese government’s choice of nuclear wastewater discharge strategy. In this case, Japanese fishermen will also have a certain degree of ‘understanding’ of the government’s discharge behavior, thus slowing down its evolution to stabilize at $q = 0$. Under the pessimism of the fishermen, as the cost of nuclear wastewater treatment increases, the fishermen’s strategy of insisting on resistance will remain basically unchanged, and the Japanese government will also be more resolute to push ahead the nuclear wastewater discharge policy. When the fishermen are optimistic, the increase in the cost of
nuclear wastewater treatment will lead to a slowdown in the evolution of both sides of the game. For the Japanese government, the increase in the cost of nuclear wastewater treatment will first increase the probability that the Japanese government chooses the discharge strategy and then will slow its evolution speed to the stable equilibrium point. Surprisingly, for Japanese fishermen, the increase in the cost of nuclear wastewater treatment will slow the rate at which they reach the stable equilibrium point \( q = 1 \). This may be because, under the optimistic mood, although the fishermen trust the Japanese government, they also understand that the high cost of nuclear wastewater treatment will force the Japanese government to retreat, thus slowing down the speed of its evolution to stabilize at the stable equilibrium point.

4.2.3. Impact of NE

Let \( NE = 12, 12.1, 12.2, 12.3 \) and \( 12.4 \) while keeping other parameters unchanged. The impact of \( NE \) on evolutionary trajectories in three different combinations of emotions is depicted in Figs. 7(a)-7(f).
Fig. 7 Impact of $NE$ on evolutionary trajectories and results when fishermen are rational, pessimistic and optimistic

One can see that when the fishermen are rational, with the increase in the negative externalities brought by the discharge of nuclear wastewater to the Japanese government’s marine environment, the evolution speed of the Japanese government’s choice of discharge strategy will slow down, but the determination will not be shaken. This will speed up the evolution of Japanese fishermen’s choice of opposing strategies. When the fishermen are pessimistic, the increase in the negative externalities of the Japanese government’s marine environment caused by the discharge of nuclear wastewater will slightly shake Japan’s determination to discharge nuclear wastewater into the sea, but it will not affect the final evolution result. The Japanese government will still choose the discharge policy, and Japanese fishermen will also choose to resolutely resist it. When the fishermen are optimistic, for the Japanese government, the increase in the negative externality cost of the marine environment brought about by the discharge of nuclear wastewater will first slow down its
evolution and then speed up its evolution to the stable point. For Japanese fishermen, the
growth of the negative externalities of the marine environment will accelerate the evolution
of their ‘Accept discharge’ strategy; that is, the higher the negative externality of the marine
environment is, the faster the choice of the ‘Accept discharge’ strategy.

4.2.4. Impact of $R_e$

Let $R_e = 2, 2.1, 2.2, 2.3$ and $2.4$ while keeping other parameters unchanged. The impact of
$R_e$ on evolutionary trajectories in three different combinations of emotions is depicted in
Figs. 8(a)-8(f).
Fig. 8 Impact of $R_e$ on evolutionary trajectories and results when fishermen are rational, pessimistic and optimistic

With the increase in reputation gains, the Japanese government will slow down the speed of its ‘Discharge’ policy when both parties are rational players, which will in turn prompt Japanese fishermen to speed up their choice to oppose the discharge policy. When the fishermen are pessimistic, for the Japanese government, the increase of reputation benefit will first reduce the probability of its choice of discharge and then gradually evolve to the evolutionarily stable strategy. However, the increase in reputation benefit will have no significant effect on the choice of opposition strategy by Japanese fishermen. When the fishermen are optimistic, the increase in reputation gains will initially slow down the evolution of the Japanese government’s choice of the ‘Discharge’ policy, and as an increasing number of Japanese fishermen choose to accept the discharge policy, it will accelerate and stabilize at the evolutionarily stable point $p = 1$. Nevertheless, the increase in reputation gains will prompt Japanese fishermen to choose the strategy of accepting discharge more quickly. This is because the optimistic fishermen will have a blind trust in the government, and when the reputational benefits of ‘Nondischarge’ increase, this kind of blind trust can lead them to believe that the government will consider them and change their strategic choices, so the increase in reputation gains will accelerate fishermen’s choice to accept the discharge policy.
4.2.5. Impact of $R_i$

Let $R_i = 3.5$, 3.6, 3.7, 3.8 and 3.9 while keeping other parameters unchanged. The impact of $R_i$ on evolutionary trajectories in three different combinations of emotions is depicted in Figs. 9(a)-9(f).

Fig. 9 Impact of $R_i$ on evolutionary trajectories and results when fisherman are rational, pessimistic and optimistic.
In the case that both sides are rational, with the increase in reputation loss, the evolution speed of the Japanese government’s choice of discharge policy will slow down, and the speed of Japanese fishermen’s choice of opposition strategy will accelerate. Under the pessimistic mood of fishermen, the increase in reputation loss will increase the determination of the Japanese government to promote the discharge of nuclear wastewater and will have no obvious influence on the decision of Japanese fishermen to oppose discharge. When fishermen are optimistic, the increase in reputation loss will first reduce the probability that the Japanese government will promote the discharge policy and then accelerate to the evolutionarily stable point with the Japanese government sensing the increasing probability that fishermen choose to accept the ‘Discharge’ strategy. For Japanese fishermen, the increase in reputation loss will not prompt them to change their ‘Accept discharge’ strategy but will accelerate the evolution of their ‘Accept discharge’ strategy. This may be because optimistic Japanese fishermen will tend to trust the government. They will think that when the discharge strategy brings more reputation damage to the Japanese government, the government will definitely choose not to discharge nuclear wastewater into the sea. This overconfident speculation makes them choose the ‘Accept discharge’ strategy at an accelerated rate.

4.2.6. Impact of A

Let $A = 0.95, 0.96, 0.97, 0.98$ and $0.99$ while keeping the other parameters unchanged. The impact of $A$ on evolutionary trajectories in three different combinations of emotions is depicted in Figs. 10(a)-10(f).
Fig. 10 Impact of $A$ on evolutionary trajectories and results when fishermen are rational, pessimistic and optimistic

When both the Japanese government and fishermen are rational, the increase in the cost of Japanese fishermen’s protest will have no influence on the Japanese government’s decision-making but will slow down the evolution of Japanese fishermen to reach the stable point. When fishermen are in a pessimistic mood, the increase in protest costs will have no impact on Japanese fishermen’s protest response but will increase the probability that the
Japanese government will promote the policy of nuclear wastewater discharge. This is because in a pessimistic mood, fishermen tend to choose combative strategies to protect themselves, even at greater cost. However, the Japanese government believes that the higher the resistance cost is, the lower the probability that fishermen will choose to rebel. When fishermen are optimistic, the increase in protest cost will slow down the evolution speed of both sides of the game, but it will have no impact on the evolution result. Japanese fishermen tend to trust the government when they are optimistic, so when the cost of choosing the opposition strategy increases, they are more inclined to choose to accept the government’s policies.

4.2.7. Impact of $B$

Let $B = 5, 5.1, 5.2, 5.3$ and $5.4$ while keeping the other parameters unchanged. The impact of $B$ on evolutionary trajectories in three different combinations of emotions is depicted in Figs. 11(a)-11(f).
When both the Japanese government and the fishermen are in a rational state, the increase in the negative impact on the fishermen’s life brought about by the discharge of nuclear wastewater will basically have no effect on the choice and decision-making of the Japanese government and the fishermen. In the pessimistic mood of fishermen, fishermen will firmly push forward the resistance strategy, and the probability that the Japanese government will adopt the discharge policy will first decrease and then will gradually reach the evolutionarily stable point. When the fishermen are optimistic, the increase in the negative impact of the discharge of nuclear wastewater on the fishermen’s life will accelerate the speed at which both sides of the game reach the evolutionarily stable point at the same time. However, it will not have a significant impact on the evolutionary results. The blind optimism and self-confidence of the fishermen will only make their situation more difficult, and the Japanese government will still choose the discharge policy.
4.2.8. Impact of $S$

Let $S = 2.5, 2.6, 2.7, 2.8$ and $2.9$ while keeping other parameters unchanged. The impact of
$S$ on evolutionary trajectories and results in three different combinations of emotions is
depicted in Figs. 12(a)-12(f).

![Graphs showing evolutionary trajectories and results for different S values.](image)

**Fig. 12** Impact of $S$ on evolutionary trajectories and results when fishermen are rational,
pessimistic and optimistic
One can see that when both the Japanese government and fishermen are in a rational state, the increase in government subsidies will slow down the speed of the Japanese government’s promotion of discharge policy. In contrast, it will accelerate the evolution of Japanese fishermen’s choice of opposition strategy. Under the pessimism of fishermen, the increase in government subsidies will initially reduce the probability of the Japanese government choosing the discharge policy. Then, the government finds that the fishermen firmly choose the opposition strategy and will gradually evolve and stabilize at the evolutionarily stable point. When the fishermen are optimistic, the increase in subsidies will slow down the evolution of the Japanese government’s choice of discharge strategies, and it will also slow down the rate at which Japanese fishermen choose the ‘Accept discharge’ strategy. This may be because although optimistic fishermen have great trust in the government, when they find that they can obtain more subsidies by choosing to oppose, the fishermen’s determination will be shaken.

4.3. Policy inspirations

Based on the sensitivity analysis of different parameters, we can obtain the following policy implications.

(1) When the government formulates policies, such as policies for compensation for land acquisition, it should fully consider the emotions of the participating people. To resolve unnecessary struggles caused by negative emotions, it is recommended to establish special emotional channeling mechanisms to avoid the negative impact of emotions on social order and political stability. As the representative of a country’s regime, ensuring the political stability of the government is the basis for the country’s good operation and social stability.
In the process of policy formulation and implementation or in the negotiation and game with the relevant people, the government should be open to the public and establish a fair and open information mechanism and compensation mechanism. Providing open information and compensation mechanisms can enhance the confidence of the masses in the negotiation and game and the trust of the government. Meanwhile, the government can also understand the psychology of the surrounding masses in a timely manner, and to a certain extent, extreme pessimism can be avoided to make the event deteriorate.

4.4. Limitations and future work

In this paper, RDEU theory and evolutionary game theory are combined to study the effect of Japanese fishermen’s emotions on the Japanese government’s nuclear wastewater discharge event. The effect mechanism of fishermen’s emotions on the Japanese government’s attitude toward nuclear wastewater discharge is also explained. However, there are still some limitations.

(1) The players in the RDEU evolutionary game need to be carefully screened. In this paper, the subjects of the RDEU evolutionary game of Japan’s nuclear wastewater discharge event are the Japanese government and Japanese fishermen. However, in reality, the participants are not limited to them but may also involve many stakeholders, such as political parties of other countries, the United Nations and other international organizations. How to select participants and construct a new RDEU model is worth considering in the future.

(2) Emotional changes on both sides can be incorporated into the model framework at the same time. This paper constructs three situations in which the Japanese government is rational and Japanese fishermen are rational, pessimistic and optimistic. However, the
decision of the Japanese government is likely to be emotional, and future research can consider the situation in which both sides of the game are emotional. It would be difficult to define the behavior of the Japanese government in times of optimism or pessimism.

5. Conclusions and policy implications

5.1. Conclusions

In this paper, RDEU theory and the game model are combined to construct the RDEU evolutionary game model of the Japanese government and fishermen on nuclear wastewater discharge to depict the practical issue of the game between Japanese fishermen under different emotions and the rational Japanese government. By analyzing the asymptotic stability and the stability of the evolutionary game system of the two sides when the fishermen are in rational, pessimistic and optimistic moods, the ESSs in three situations are determined. Then, numerical simulations are carried out to illustrate the evolutionary stabilization strategies in the three cases and the influence of some key parameters on the evolutionary stability strategies of both parties. Overall, we can draw the following conclusions.

First, for the sake of interests, no matter what mood the fishermen are in, the Japanese government’s strategic choice is ‘Discharge’. When Japanese fishermen are rational, they will choose to oppose the nuclear wastewater discharge strategy. When Japanese fishermen are in a pessimistic mood, they are more inclined to choose the strategy of resistance to protect themselves. Thus, they will decisively choose to oppose the strategy of discharging nuclear wastewater. When Japanese fishermen are optimistic, they will have blind trust in the government and will choose to accept the government’s nuclear wastewater discharge
strategy. This emotional level of optimism has brought them ‘bad’ results, making their situation even worse.

Second, the emotions of players not only affect their own strategy choices but also affect the strategy choices of other players. The emotional changes of Japanese fishermen not only affect the changes of their own strategies but also change the evolutionary trajectory of the Japanese government, although the strategy of the Japanese government has not undergone substantial changes. This conclusion shows that emotions have a certain degree of infectivity, and the change of strategy caused by one party’s emotional change will also indirectly affect the other party’s strategic choice.

Third, the influence of key parameters on the evolutionary results and trajectories of both parties in different situations is determined. Through comparison, we found that when both parties are rational game subjects, the impact of each key parameter on the evolution results and trajectories of both parties is closely related to the interests of both parties. The cost of nuclear wastewater discharge, nuclear wastewater treatment costs, the negative externalities of the marine environment, reputation gains, reputation losses, and financial subsidies are the key factors that affect the evolutionary trajectory of both parties. When the fishermen are pessimistic, the changes in each parameter will not change their willingness to choose the opposition strategy. Although the changes in the key parameters will affect the change in the Japanese government’s initial willingness to choose the discharge strategy, these changes are positively correlated with the changes in their interests. However, it will not affect the evolution result of its choice of discharge strategy. When the fishermen are optimistic, the increase in the nuclear wastewater discharge cost, the negative marine externalities caused by nuclear wastewater discharge, the reputational gains, the reputation losses, the cost of opposition, and the negative impact of nuclear wastewater discharge on the fishermen’s life all accelerate the evolution speed of the Japanese government’s ‘Discharge’
strategy and the Japanese fishermen’s ‘Accept discharge’ strategy, respectively. The increase in the cost of nuclear wastewater treatment and financial subsidies will slow down the evolution of the Japanese government’s ‘Discharge’ strategy and the Japanese fishermen’s ‘Accept discharge’ strategy.

5.2. Policy implications

Based on the abovementioned conclusions, the following policy implications are proposed from the perspectives of the Japanese government and Japanese fishermen to strengthen the Japanese government’s strategic shift from discharge to nondischarge policy and to minimize the losses of Japanese fishermen under the insistence of the Japanese government.

On the one hand, the Japanese government should intensify its technological research efforts and strive to find better ways to reduce the cost of nuclear wastewater treatment because the discharge of nuclear wastewater will bring huge damage to the marine environment, expensive government subsidies and reputational damage. Alternatively, international assistance could be sought, and alternative approaches could be considered with technical or financial support from other countries; after all, the discharge of nuclear wastewater into the sea is a major issue related to the safety of the global marine environment.

On the other hand, when government subsidies are relatively low or the cost of nuclear wastewater treatment cannot be significantly reduced in a relatively short period of time, Japanese fishermen should choose to rise up and resist the government’s discharge strategy and must not blindly trust the Japanese government. As the first victims of the government’s nuclear wastewater discharge strategy, Japanese fishermen should not have illusions about the government’s ‘people-oriented’ approach and should resolutely protect the oceans on which they depend and plan for their livelihoods. Second, they should expand their
influence as much as possible to let more people know that the discharge of nuclear wastewater into the sea will have a profound and irreversible impact on food safety and human health, to call on more people to join their resistance, increase the reputation loss of the Japanese government, to achieve the goal of restricting the Japanese government’s decision making.

Acknowledgments

The authors would like to express their gratitude for the support provided by the National Natural Science Foundation of China [grant numbers 72071025, 72072097, 72001120 and 72101129], the Social Science Planning Foundation of Liaoning [grant number L19BGL005], the Natural Science Foundation of Liaoning Province [grant number 2020-HYLH-39], the Special Foundation for Basic Scientific Research of the Central Colleges of China [grant number 3132021254] and the School-level Scientific Research Project of Beijing Wuzi University [grant number 2021XJKY10].

Declaration of interest statement

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

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