# Research on Cooperation Mechanism of Marine Plastic Waste Management Based on Complex Network Evolutionary Game

*Xin Xu[1], Yingying Hou[1], Changping Zhao[2*], Lei Shi[3], Yu Gong[4]*

[1]*College of Maritime Economic and Management, DMU, Dalian 116026, China*

[2]*Changshu Institute of Technology, Changshu 215500, China*

[3]*School of Resources, Environment and Chemical Engineering, Nanchang University, Nanchang 330031, China*

[4]*Southampton Business School, University of Southampton, UK, SO17 1BJ*

**About the Author:**

Dr. Xin Xu:

Assistant Professor, School of Shipping Economics and Management, Dalian Maritime University, Dalian 116026, China

Email: red86933563@dlmu.edu.cn

Miss Yingying Hou:

Master student, Dalian Maritime University, Dalian 116026, China

Main research directions: international economic and political relations

Email: hyy9moon@163.com

Prof. Changping Zhao (corresponding author):

Professor in School of Business, Changshu Institute of Technology, Changshu 215500, China

Email: zhao0037@sina.com

Prof. Shi Lei

Professor in School of Resources, Environment and Chemical Engineering,
Nanchang University, Nanchang 330031, China

Email: shilei@ncu.edu.cn

Dr. Yu Gong:

Assistant Professor, Southampton Business School, University of Southampton, UK,
SO17 1BJ

Email: Y.Gong@soton.ac.uk

**ABSTRACT:**

Marine plastic waste pollution affects the stability of the marine ecosystem, inhibits the sustainable development of the blue economy, and threatens the health of humankind. In order to build a stable and long-term international cooperation mechanism in marine plastic waste, this paper takes the country as the research object and propose an international marine plastic waste cooperation network. We introduce the "Matthew effect" of network connection and relationship cost into the model from the perspective of social relations, and uses the method of the evolutionary game on complex networks to construct the evolutionary game model of marine plastic waste treatment. Through simulation methods, this paper explores the impact of economic factors, relational structure and game structure on the evolution of management cooperation of marine plastic waste. It not only provides a theoretical basis for international cooperation in marine plastic waste management, but also provides a clear direction for its implications in practice. Based on the theoretical analysis and empirical research, this research finds that: First, in management cooperation of marine plastic waste, economic factors are the most direct factor, relational structure plays a regulatory role, and game structure is an intermediary variable. Second, the benefits and costs of governance cooperation in economic factors promote and inhibit the cooperation behavior of group respectively. Relationship structure has a two-way effect on the cooperation behavior of group and network stability. Moreover, the cumulative income weight in the game structure is positively related to the partner density. Finally, the key to the current cooperative governance of marine plastic waste is to build a stable and long-term market mechanism, properly handle the influence of major powers, regulate the governance relationships, and promote international cooperation in marine plastic waste management.

*Keywords: Marine plastic waste; Governance cooperation; Complex network evolutionary game; Prisoner's dilemma*

## 1. Introduction

Marine Plastic Pollution has received great attention from the environment, the economy, the science and technology, the politics, and other fields due to its seriousness [1], and it has become a hot topic of global governance cooperation [2,3]. According to statistics, the total global plastic production is growing at a rate of 200,000 tons per year and it is estimated that the cumulative production will reach 33 billion tons by 2050 [4,5]. The huge amount of plastic production has triggered the emergence that up to 10% of the plastic flows into the ocean [6,7] and enters the human body through the food chain to harm human health [8]. The problems of complex formation mechanism, extensive migration path, indistinct responsibility sharing and obvious inter-generational damage determine that the governance path of marine plastic waste must be global cooperation [9]. At present, both the United Nations and the G20 have discussed cooperation in the management of marine plastic waste as a key issue. Also, the G20 Osaka Summit reached the "Blue Ocean Vision" and promised to achieve "zero-emission" of marine plastic waste by 2050. From the perspective of pollution status, pollution characteristics, and governance goals, marine plastic waste treatment is a heavy and urgent task which requires to balance the participation of all parties and establish a global marine plastic waste management cooperation mechanism [10].

The research on marine plastic waste has become a hot trend and made a few achievements, and it is expected that the scientific literature on marine microplastics will continue increasing over the next years [11]. The characteristics of marine plastic waste pollution also determine that its research needs to take an interdisciplinary research path [11], integrating natural science with management and economics to propose solutions [12]. At present, researches on natural science involve source and gathering place, migration paths, and mechanisms of influence [11], while, researches of economic and management science focus on the treatment, and governance mechanisms of marine plastic waste.

Marine plastic waste is divided into two types: land-sourced and sea-sourced [13,14]. Among them, plastic waste of marine origin includes three scenarios: coastal tourism, shipping transportation, and marine aquaculture and fishing [1]. Through rivers and internal waterways, plastic waste enters the ocean with the help of monsoon, ocean current, tide, etc. [15]. And then it is broken into fragments through radiation, weathering, erosion, scouring, etc., and flows around the world [16-19]. The five major plastic debris (PE,PP, PET, PVC and PS) gathering places in the global ocean coincide with the five major circulation locations (South equatorial current, North equatorial current, Gulf stream, North pacific current, and Kuroshio) on the ocean surface, and the vortex in the circulation center is the sink of plastic waste [18]. Plastic pollution not only has masking effect and phagocytosis effect to marine plants [21,23], but also affects the digestion and propagation of marine animals [3,5,24-25] with the specific impact mechanism is yet to be explored [22]. In addition, plastics are transmitted through the food chain, and ultimately it will have a greater harmful effect on humans under the action of the enrichment effect [1,24,27-28].

Based on the important research results in the field of economics and management, we find that the governance mechanism include four scenarios: the input of land source, coastal tourism, shipping industry, and marine aquaculture and fishing industry [23,30]. The governance bodies cover five categories: international organizations, non-governmental organizations (NGOs), governments, enterprises, and the public. With the participation and collaboration of all entities, a three-dimensional governance system featuring global leadership, regional coordination, and national implementation has formed [9, 12].

At the national implementation level, the central government, local governments, non-governmental organizations, enterprises, and the public are all important participants. The national-level mechanism of marine plastic waste management includes three dimensions: market, society, and government. Specifically, through legislation and policy guidance, the government not only encourages enterprises to accelerate technological innovation and undertake social responsibility but also mobilizes the public to raise environmental awareness and participate in beach-cleaning activities [9,12]. The government and society jointly supervise and manage market behaviors to promote the recycling of plastic waste and develop a circular economy. At the same time, the market also provides financial support for the government and society. In addition, in the entire governance mechanism, NGOs have also played a great role in monitoring government actions and guiding the public to participate in plastic governance activities. The three links at the national level are linked together to jointly promote the treatment of marine plastic waste.

At the regional coordination level, the current management of marine plastic waste is led by regional intergovernmental organizations, represented by the European Union (EU) and Association of Southeast Asian Nations (ASEAN), and carried out through multilateral or bilateral cooperation agreements [9,12]. Existing research results point out that the management of marine plastic waste in Southeast Asia has obvious national subjectivity, external participation, and lack of cooperation networks and its governance is facing the real dilemma of low institutionalization, insufficient governance funds, and weak coordination and leadership. Such governance issues in Southeast Asian partially reflects the current global marine plastic waste problems [25].

At the global level, the governance of marine plastic waste is carried out through three forms of international legislation, soft law (resolutions, declarations, initiatives, guidelines, action plans, etc.) [12], and voluntary commitments [12], among which, soft law that lacks legally binding force is dominant [26]. Overall, it lacks a strong binding force and cannot effectively solve the problem of marine plastic waste pollution [10].

In summary, the sources and sinks, migration paths, and impact mechanisms of marine plastic waste have been explored. The research on the measurement, monitoring, extraction, identification, interception, salvage, and degradation of marine plastic waste has got some achievements [21,24,27], which has laid a technical foundation for its cooperative governance [28]. However, the global and regional coordination mechanism for marine plastic waste management cooperation has not yet been fully established. In addition, the existing governance mechanism has the characteristics of disorder and fragmentation, especially the cooperative fragmentation [23]. A fragmented and inadequate multilateral cooperation system may inhibit strong global governance mechanisms [29]. Therefore, building a multi-participant, long-term and stable governance cooperation mechanism is still a major difficulty in the research of ocean governance. In the research of this problem, the existing literature mainly focuses on qualitative analysis, and the results of simulation research with a quantitative model are relatively rare.

The pollution of marine plastic waste is extremely complex, which is manifested in both complex sources, disorderly distribution and non-linear effects, as well as cross-regional. More importantly, the problem of marine environmental pollution does not exist in isolation, but implies economic, political, cultural and social problems, which often have an inherent causal relationship with marine plastic waste pollution to some extent. Marine plastic pollution management in the above complex context is bound to involve different levels of interests, technology and other sophisticated social issues, which indirectly increases the complexity and difficulty of governance [30]. In addition, the lack of uniform rules and standards at the international level is not conducive to cooperation among countries. More importantly, when choosing a strategy, marine plastic pollution management subjects will weigh their interests through learning mechanisms combined with changes in the real situation, and repeatedly adjust their strategies until they choose the most favorable strategy, which is a dynamic game process, and the network is unstable in the dynamic change process.

Evolutionary game theory is a powerful tool for studying various self-organizing behaviors in natural, social and economic systems [31]. It takes the bounded rationality, learning mechanism and decision-making process into consideration [32], and focuses on the research on the problem of bounded rational individuals to maximize the benefits through repeated games, and is suitable for the research of environmental governance cooperation [33].

In addition, we understand that the complex network method has unique advantages in the study of social relations. On the one hand, complex networks have many nodes with flexible connections, which can represent the heterogeneous characteristics of real networks and are more in line with many real networks in reality; on the other hand, the connection of nodes in a complex network can change over time, which can reflect the evolution of node connections in social networks [32]. At present, these methods have been applied in the supply chain [34], government policy influence [35], as well as in the field of ecological cooperation [36].

As a product of the combination of complex network methods and evolutionary game methods, complex network evolutionary games can better describe the relationship between nodes in reality and the process of making decisions through learning mechanisms. Judging from the search results, no research applies the method of complex network game to the cooperation mechanism of marine plastic waste management. This article aims to apply the method of network game to analyze and deduce it theoretically, trying to provide a new supplement to the research in this field.

Combining the literature and actual governance cases, it is found that as the most important level of the three-dimensional governance mechanism and the most critical category of the five types of governance entities, countries play an extremely important role in the cooperation of marine plastic waste governance and is the core subject and implementer of marine plastic waste governance [12,31]. The relevant countries have formed a relationship network through various economic and political relations such as reverse supply chain of plastic waste, international plastic waste trade, etc., which affects the strategic choice of the stakeholders in the cooperation of marine plastic waste management indirectly. In addition, the existing results prove that the scale-free network is more conducive to the cooperation among subjects [37]. It can be inferred from those findings above that the relationship structure among government entities is an important factor that affects the establishment of their cooperation mechanism.

Marine plastic waste treatment is cost-effective approach, although its economic cost is unknown [10]. Economic feasibility is the most critical factor that affects the decision-making of marine plastic waste management. The treatment of marine plastic waste not only requires relevant countries to invest capital, personnel, technology and other economic factors but also brings benefits to them from the marine fishery, tourism, energy, environment and other industries. The relevant interest countries play games around the benefits and costs of governance. The differences in the income evaluation and accounting methods of the main body and the cost differences of input elements will form different structures of the game and then different game structures will produce different equilibrium states in dynamic evolution [10]. Based on the above analysis, this research attempts to answer the research questions: *How countries can create an effective global marine plastics waste cooperation network?*

In order to answer the question above, we construct an evolutionary game model from the three dimensions of economic factors (intuitive revenue, unit-cost of cooperation, collaboration workload, benefits of separate governance, spillover benefits of governance cooperation, cost of information and supervision and the cost of overcoming barriers to cooperation), the structure of network relationship (the relationship strength), and game structure (cumulative income weights), and use simulation methods to simulate the equilibrium results. On this basis, we discuss the cooperative mechanism of marine plastic waste management, hoping that not only provide a theoretical basis for the international cooperation in the management of marine plastic waste but also provide a clear direction for the practice of it.

Specifically, this paper is organized as follows: the background and literature review is provided in this section. The construction of cooperation network model for marine plastic waste management is provided in Section 2. The simulation experiments and evaluation results are provided in Section 3. Finally, discussion and conclusions are provided in Section 4.

## 2. Construction of cooperation model for marine plastic waste management

### *2.1. Cooperation network model of marine plastic waste treatment*

The "governance cooperation" model appeared as early as the 1990s, aiming to solve the cross-domain and cross-sectoral public governance issues in the post-industrial society. Song [38] pointed out that international cooperation is a better way to realize national interests and Hassan [39] demonstrated the effectiveness of international governance cooperation in the prevention and control of marine debris. International cooperation is affected by national capacity and international relations. The former which determines the overall trend of international relations and runs through all stages of international cooperation is the main variable of international cooperation [38]. The national power and concepts of mainstream countries influence the pattern of Inter-state relations and control the development trend of international cooperation. Conversely, countries with small influence may become more dependent on countries with strong capabilities and gradually lose their independence [36]. At present, the existing forms of cooperation include common response to existing initiatives, joining in strong binding agreements, and forming alliances [36]. Under different forms of cooperation, the strength of relations between countries is different, and the relationship structure of the formed network is also different. Combining existing forms of cooperation, this study regards relationships of alliances and strong binding agreement as strong relationships, while the relationships resulting from joint responses to initiatives are considered as weak relationships.

From the perspective of the evolution of governance cooperation of marine plastic waste in Southeast Asia, the European Union, and other regions, governance cooperation is generally initiated by a few countries, and then neighboring countries carry out substantive cooperation to form cooperative organizations. After this stage, they continue to develop new members and establish new relationships to expand the scale and scope of the network. In reality, 143 countries have participated in the "regional seas" project implemented by the United Nations Environment Programme and some countries (China, the European Union, Japan, the United

States, etc.) successively communicating and cooperating with ASEAN on the issue of marine plastic waste treatment [36]. According to the history and process above, the network of governance cooperation can be constructed according to the generation mechanism of the scale-free network. The model is defined by the following steps.

Step one, in the initial network, m0 countries form a complete connection and a new node with m edges joins the network of governance cooperation at each time.

Step two, nodes newly added to the network are connected in the manner of "preferred connection" that proposed by Barabási and Alber(1999). That is, new countries are more inclined to connect with the nodes with a large degree in the network. This phenomenon is called the "Matthew Effect" [40]. Then, according to the influence of the connected node, the new node decides whether to continue to connect with its neighbors with a specific probability. The method of generating the connection mechanism is as follows.

The player *i* is connected to the existing player *j* with probability $P(k_j)$ according to Equation. 1 firstly, the remaining m-1 edges are connected by the following two ways.

$$P(k_j) = \frac{k_j}{\sum_l k_l} \tag{1}$$

Where $k_j$ is the degree of player *j* and $\sum_l k_l$ is the degree of all nodes in the network.

Firstly, player *i* is randomly connected to m-1 neighbors of player *j* with probability *q*. Player *i* connects all the neighbors of *j* if the neighbor number of player *j* is less than m-1 ($k_j$ <m-1), the remaining $m-1-k_j$ edges are connected to other countries by the mechanism of priority connection in the model.

Secondly, player *i* is connected to other m-1 countries with probability *1-q* according to the mechanism of priority connection in the scale-free model.

It is worth noting that this connection method can produce a scale-free network that conforms to a power-law distribution and can change agglomeration. The probability of *q* reflects the influence of countries with high degrees in the network, and affects the agglomeration of the network indirectly.

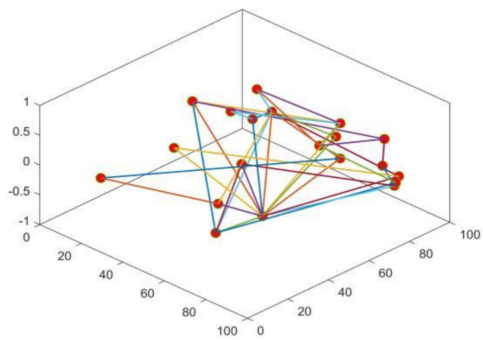

**Figure. 1.** Network structure diagram with 20 players in the management cooperation of marine plastic waste.

Figure.1 shows a network structure of governance cooperation generated by the model when $q = 0$, which composed of countries participating in governance cooperation of marine plastic waste. In the initial state, two nodes are completely connected. To facilitate observation, the Figure above only shows the network connection with 20 nodes. The nodes in the network represent each country, and the connection between the nodes represents the interaction between the two countries.

*2.2. The cooperative game model of marine plastic waste management*

Base on the scale-free agglomeration network model, the evolutionary game model of cooperative management in marine plastic waste is established according to the two person two strategy game behavior of the BA scale-free network studied by Santos et al [41-43].

The choice of management cooperation strategy of marine plastic waste is directly related to the benefits and costs of governance. Therefore, we incorporate these economic factors into the construction of the governance cooperation game model.

*2.2.1. Model assumptions*

Management cooperation of marine plastic waste is carried out between countries, and each country considers the maximization of their interests rather than the interests of the group in the game process [41,42]. Based on this, we make the following assumptions.

Hypothesis 1: Regardless of the scale, strength, and influence of countries in the marine plastic waste management cooperation network, each node is homogeneous, and the predictable intuitive income and costs of countries under the same strategic choice are the same. Each country chooses under the pure strategy of governance cooperation and individual governance, the latter strategy means governance without cooperation.

Hypothesis 2: There are directly foreseeable income and costs under the strategy of governance cooperation. This model assumes that the benefits of a single country that chooses the strategy of governance cooperation are $b$, and the cost is $d$ ($0<d<b$) [44]. When only the methods of physical salvage are considered, the directly foreseeable benefits include the benefits of reusing plastic waste and fish farming from the improvement of marine water quality after salvage. The directly foreseeable costs includes the labor cost of salvage, material cost of trawling nets and fishing boats [24], logistics cost, reprocessing cost etc. The directly foreseeable cost is expressed by multiplying $u$ of the unit-cost by the $v$ of workload of governance cooperation, where the distribution of unit-cost of governance cooperation conforms to the Poisson distribution approximately. Therefore, the direct foreseeable cost $b$ follows Equation. 2 (The parameter $\lambda$ of Poisson distribution is 1 and $u$ is a positive integer).

$$b = (\frac{1}{u!}) * \exp(-1) * u * v \tag{2}$$

Most marine plastic waste is buoyant. Under the influence of ocean dynamics, geomorphology, monsoon, human activities, etc., the spatial distribution and accumulation density of plastic waste are different [45]. At present, marine plastic waste is concentrated in the coastline, sea surface, seabed, water column, and other regions of Europe, Asia, Africa and North America [46-48].The United Nations Environment Program estimates that 15% of marine debris floats on the surface, 15% remains in the water column, and 70% remains on the seabed [24]. Considering the operability of ocean plastic treatment under the existing technology, we ignore the seabed that is inconvenient to salvage and the coastline that is the easiest to operate, and consider the sea surface and water column as areas most in need of treatment.

Existing research on the distribution of marine plastic waste has two angles: horizontal and vertical. From the horizontal perspective, marine plastic waste is concentrated in five major circulations (South Equatorial Current, North Equatorial Current, Gulf Stream, North Pacific Current, and Kuroshio), and the center of the circulation is the sink of plastic waste. In particular, the density of plastic waste is the highest at the vortex center of the circulation and gradually decreases from the vortex to the outside [18,49]. Therefore, from the perspective of the circulation center, the distribution of marine plastic waste is approximately conforms to the Poisson distribution. From a vertical point of view, the monitoring data of some sea areas shows that within a certain range from the sea surface, the density of ocean plastic debris is approximately in line with the Poisson distribution. Therefore, from the perspective of horizontal and vertical perspective, this research assumes that the distribution of marine plastic waste approximately conforms to the Poisson distribution. Considering that plastic density is positively related to the unit-cost of governance, it is assumed that $u$ also conforms to the Poisson distribution.

Hypothesis 3: If both players choose the individual governance strategy in the game, the gains of single country are $e$ ($0<e<b$).

The harm of marine plastic waste pollution radiates the world, and no country can be alone. Therefore, the treatment of marine plastic pollution is necessary for all countries. Obviously, coastal countries with tourism as their main industry have obtained greater benefits in the governance process. Developed countries have relatively high technical level and rich governance experience, and can achieve better governance levels with less treatment cos. However, the entire model considers the general situation, assumes that the national nodes are homogeneous, and the subjects involved are all sovereign countries in the world (including but not limited to developed countries and countries with coastal tourism as the main industry). In order to maintain the consistency of the assumptions, we choose the average level of benefits and costs. Therefore, from the global average level, the benefits of cooperative governance through the sharing of technology and experience in cooperation are greater than the benefits of individual governance ($e<b$).

*2.2.2. Single-game model payment for marine plastic waste management cooperation*

The management of marine plastic pollution is a public product like social security, and there is a free-rider phenomenon in cooperation. If each participant chooses a separate governance strategy, and they can only obtain a small part of the benefits of governance, then it will be detrimental to the entire society. On the contrary, if each participant chooses a cooperative governance strategy, he will obtain greater benefits through the sharing of technology and experience, which is extremely beneficial to the entire environment and society. The result of this strategic choice is similar to the prisoner's dilemma where the individual chooses to confess or not. Prisoner's dilemma games are widely used to study the possibility of cooperative behavior among selfish individuals seeking to maximize their interests [31]. At present, the prisoner's dilemma as a metaphor for the evolution of research cooperation has attracted considerable attention, and studies applying the Prisoner's dilemma to climate and environmental governance have also emerged [50,51]. Therefore, we choose the Prisoner's Dilemma theory to describe the payment of the evolutionary game model based on the scale-free network.

According to the prisoner's dilemma theory and the above assumptions, the single-game payoff matrix for the management cooperation of marine plastic waste can be obtained as shown in Table 1. The benefits and costs in Table 1 are the immediate income and costs that can be directly predicted in a single game. It is noting that the model incorporates all countries in the world into the study, and considers the subject's income under different strategy combinations under average conditions. It is noting that the model incorporates all countries in the world into the study, and considers the subject's income under different strategy combinations under average conditions. In the strategy combination (C, D), on the one hand, the cost of the player *i* who chooses cooperative governance is greater than that in the other strategy combinations, and the income obtained is relatively small. On the other hand, the existence of positive externalities of environmental governance distributes a part of player *i*'s income to player *j*, leaving player *i* with a smaller income. In addition, the proportion of income distribution determines the return of a single game and affects the subsequent strategy adjustment process. The influence mechanism and simulation process of this proportion are relatively complicated, and this proportion is difficult to determine. Therefore, in order to make the simulation process easy to operate, we simplified the individual's income and assumed that the individual's income was zero under the strategy combination of (C,D) [52].

**Table 1**
Single-game payoff matrix.

| Single game between node *i* and node *j* | | The strategy of node *j* | |
|---|---|---|---|
| | | Governance cooperation | Individual governance |
| The strategy of node *i* | Governance cooperation | *b-d*; *b-d* | *-d*; *b* |
| | Individual governance | *b*; *-d* | *e*; *e* |

*2.3. Evolutionary game model of the marine plastic waste management cooperation network*

Combining the established complex network model with the game model, an evolutionary game model of cooperation network for marine plastic waste treatment is constructed.

*2.3.1. Assumptions*

Based on the single-game hypothesis in Section 2.2 and the results of relevant literature we made the following hypotheses.

Hypothesis 1: The strategy of player *i* is $S_i$ ($S_i = \{1,0\}$). Among which, "$S_i = 1$" means that player *i* chooses the strategy of governance cooperation, and "$S_i = 0$" indicates that player *i* chooses the "individual governance" strategy.

Hypothesis 2: Player *i* only plays games with neighboring nodes that establish contact in the network of marine plastic waste management cooperation and it is recorded as a game after player *i* completes the game with all its neighbors. Besides, *t* is used to represent the number of games.

Hypothesis 3: Management cooperation of marine plastic waste has spillover benefits. On the one hand, governance cooperation reduces costs and improves efficiency through technical exchanges and experience sharing, on the other hand, it will produce greater medium and long-term benefits. For example, the improvement of water environment will reduce the risk of disease, prolong life expectancy and increase the happiness of people around the water area. Also, a healthy and stable marine ecosystem will provide regulating services (e.g., carbon sequestration and climate mitigation) [24]. The larger the scale of governance cooperation, the larger the spillover benefit. Therefore, we assume that the spillover benefit is positively related to the number of countries participating in governance cooperation. The benefit obtained by the *t*-th game of player *i* can be written as $\sum_{j=1}^{k_i} S_j * f$ if we use *f* to denote the spillover benefit obtained by governance cooperation between an entity and its neighbors. Among them, $S_j$ ($S_j = \{1,0\}$) is the strategy of country *j* and $k_i$ is the connection of player *i*, which is the number of neighbors that establish contact with player *i*. $\sum_{j=1}^{k_i} S_j$ is the number of countries which choose the cooperation strategy among the neighbors of country *i* in the *t*-th game.

Hypothesis 4: There are information and supervision costs when a single country chooses a governance cooperation strategy. These costs are positively correlated with the number of countries cooperating in governance, and it is positively correlated with the number of countries cooperating in governance. If the information and supervision cost of player i that cooperates with a single neighbor is represented by *g*, then the information and supervision cost of the *t*-th game of player *i* can be written as $\sum_{j=1}^{k_i} S_j * g \quad (S_j = \{1,0\})$.

Hypothesis 5: There are differences in governance experience, technology, laws and regulations, and cultural concepts among different countries and these differences constitute obstacles to unified action. Therefore, cooperation requires a certain cost to overcome these obstacles. Besides, the more countries that influence a particular field, the higher the transaction cost of international cooperation. In this paper, the cost of overcoming these barriers is called "the cost of eliminating barriers to cooperation". When two countries cooperate, the cost of eliminating cooperation obstacles for a single country is expressed by *h*, then the cost of eliminating the obstacle to cooperation in the *t*-th game of player *i* can be written as $\sum_{j=1}^{k_i} S_j * h \quad (S_j = \{1,0\})$.

To sum up, the income that player *i* obtains from the game consists of two parts in the management cooperation network of marine plastic waste. The first part is the immediate income that can be directly foreseen ($\sum_{j}^{k_i}\sum_{S_i}\pi_i(S_i, S_j)$), the second part is the income that cannot be foreseen ($(\sum_{j=1}^{k_i} S_j) f - (\sum_{j=1}^{k_i} S_j) g - (\sum_{j=1}^{k_i} S_j) h$).

The unforeseeable benefits consist of three parts, Spillover benefit ($(\sum_{j=1}^{k_i} S_j) f$), cost of information and supervision ($(\sum_{j=1}^{k_i} S_j) g$), and the cost of removing barriers to cooperation ($(\sum_{j=1}^{k_i} S_j) h$).

Therefore, the total revenue of the t-round game of player *i* can be written as $U_i(t)$.

$$U_i(t) = \begin{cases} P_{S_j} * \sum_{j=1}^{k_i}\sum_{S_i}\pi_i(S_i, S_j) + (\sum_{j=1}^{k_i} S_j) f - (\sum_{j=1}^{k_i} S_j) h - (\sum_{j=1}^{k_i} S_j) g, S_i = 1 \\ P_{S_j} * \sum_{j=1}^{k_i}\sum_{S_i}\pi_i(S_i, S_j), S_i = 0 \end{cases} \tag{3}$$

Where $P_{S_j}$ is the probability of strategy choice of player *j* when player *i* and player *j* play a game. $P_1$ and $P_0$ are the probability that player *j* chooses the cooperative governance strategy and the individual governance strategy respectively ($P_1 + P_0 = 1$).

**Table 2**

Meaning of each symbol involved in the model.

| Symbol | Implication |
|---|---|
| $S_i$ | The strategy of node *i* (Value 1 or 0) |
| $\pi_i(S_i,S_j)$ | Payoffs of country *i* in the game of *i* and *j* |
| $k_i$ | The degree of country *i* (the number of connections with country *i*) |
| *u* | Unit-cost of governance cooperation, which is approximately obeys Poisson distribution |
| *v* | Workload of a country in governance cooperation |
| *b* | The intuitive benefits obtained by a single country when the two entities cooperate in governance |
| *d* | Intuitive cost of a single country when two countries choose cooperation. ($d=(1/u!)exp(-1)uv$) |
| *e* | The respective benefits of the two entities when they choose separate governance strategies |
| *f* | The spillover benefits obtained by a single country when the two countries choose the cooperative governance strategy |
| *g* | Information and supervision costs of a single country in management cooperation |
| *h* | The cost of a single country participating in cooperation to eliminate obstacles to cooperation |
| $P_1$ | Probability of opponents choosing cooperative strategies in the game |
| $P_0$ | The probability that the opponent chooses the strategy of individual governance during the game |
| *f(c)* | Collaborator density |

*2.3.2. Model analysis*

Countries in the network show the characteristics of bounded rationality in the decision-making of complex problems. They often adjust their strategies through learning and comparison during repeated games with their neighbors. Specific steps are as follows.

Step one, choosing the initial strategy. The strategy of governance cooperation is given to the new country with the probability of $P_C = 0.5$.

Step two, calculating the income. The country randomly selects one of its neighbors to play the game and then compares the returns according to the weighted return method. Under the weighted income method, the income function of the *t*-th round of the game of country *i* is as follows [37].

$$U_i(t) = a*(P_{S_j}*(\sum_{j\in\Omega_i}\sum_{S_i}\pi_i(S_i,S_j)) + (\sum_{j=1}^{k_i}S_j)*(f-g-h)) + (1-a)\frac{P_{S_j}*(\sum_{j\in\Omega_i}\sum_{S_i}\pi_i(S_i,S_j)) + (\sum_{j=1}^{k_i}S_j)*(f-g-h)}{k_i} \quad (4)$$

Among them, $\Omega_i$ represents the neighbor set of player *i* determined by the network structure; $S_i$ is the strategy chosen by country *i* in a game; $k_i$ represents the number of neighbors of country *i*; *a* $(0 \le a \le 1)$ is the weight parameter of the cumulative earnings in the utility function; $\pi_i(S_i, S_j)$ is the income obtained by player *i* in the game with player *j*. $(\sum_{j=1}^{k_i} S_j) * (f - g - h)$ is the benefits that cannot be directly foreseen.

Step three, updating the strategy. Each country in the complex network play an evolutionary game with their neighbors and accumulate the payoffs in each round and adjusts its strategy according to the cumulative profits [53]. Player *i* will keep its original strategy unchanged if the benefit of himself is greater than the player j ($U_i > U_j$). On the contrary, player *i* will update its strategy in the next round of the game and adopt the strategy of player *j* with the probability given by Equation. 5 [37,54].

$$P = \frac{U_j - U_i}{(1-a)T + a * T * \max(k_i, k_j)} \tag{5}$$

Where $U_j$ and $U_i$ are the income obtained by *j* and *i* from this game; *T* is the deception temptation parameter in the model of prisoner's dilemma game, that is the income of the country who adopts the non-cooperative strategy in the (non-cooperative, cooperative) strategy combination. Specifically, the parameter *b* in the cooperative game of marine plastic waste management is *T*. $k_i$ and $k_j$ are the connectivity numbers of player *i* and *j*.

Step four, executing the step of two and three in a loop to reach the set number of iterations.

Player *i* is determined to be a country participating in the governance cooperation of marine plastic waste and the number of partners is increased by one if it always chooses the governance cooperation strategy. According to the above logic, the probability that the neighbor *j* of the country *i* is a newly added partner is Equation. 6.

$$P_1 = 0.5 \prod_{l=1}^{k_j} \frac{U_j - U_l}{(1-a) * T + a * T * \max(k_i, k_j)} \tag{6}$$

The probability that the neighbor *j* of player *i* is a non-cooperator can be written as $P_0 = 1 - P_1$.

After completing the above four steps, we analyze the specific effects of variables on the cooperation of marine plastic waste management through simulation. The effect of marine plastic waste management cooperation is measured by *f(c)*, where *f(c)* is expressed by the ratio of the number of countries that choose cooperative governance strategy to the total number of network nodes.

Bringing the initial return matrix of single game into the return formula we can get the Equation. 7.

$$U_i(t)=\begin{cases} P_1(\sum_{j=1}^{k_i}S_j)(b-d)+P_0(k_i-\sum_{j=1}^{k_i}S_j)(-d)+(\sum_{j=1}^{k_i}S_j)f-(\sum_{j=1}^{k_i}S_j)h-(\sum_{j=1}^{k_i}S_j)g, S_i=1 \\ P_1(\sum_{j=1}^{k_i}S_j)b+P_0(k_i-\sum_{j=1}^{k_i}S_j)e, S_i=0 \end{cases} \quad (7)$$

The equilibrium condition for player *i* to choose the governance cooperation strategy is that the benefits of governance cooperation ≥ the benefits of individual governance and it can be written as Equation. 8.

$$P_1(\sum_{j=1}^{k_i}S_j)(b-d)+P_0(k_i-\sum_{j=1}^{k_i}S_j)(-d)+(\sum_{j=1}^{k_i}S_j)f-(\sum_{j=1}^{k_i}S_j)h-(\sum_{j=1}^{k_i}S_j)g \geq P_1(\sum_{j=1}^{k_i}S_j)b+P_0(k_i-\sum_{j=1}^{k_i}S_j)e \quad (8)$$

A simplified version can be obtained by sorting, such as Equation. 9.

$$(\sum_{j=1}^{k_i}S_j)f-(\sum_{j=1}^{k_i}S_j)h-(\sum_{j=1}^{k_i}S_j)g-P_1(\sum_{j=1}^{k_i}S_j)d-(1-P_1)(K_i-\sum_{j=1}^{k_i}S_j)(e+d)\geq 0 \quad (9)$$

It can be seen from the above formula that the strategy choice of a country in the *t*-th game of management cooperation of marine plastic waste is directly related to the probability of the opponent's strategy choice, the number of countries who choose the cooperation strategy in the t-round game, and the economic factors including spillover income, single governance income, intuitive cost, information and supervision cost and the cost of overcoming cooperation obstacles. The greater the unexpected spillover income of governance cooperation, the easier the formula above is to be established, and the more likely countries are to choose governance cooperation; the greater the cost of overcoming cooperation obstacles, the greater the information and supervision cost g of cooperation, the greater the intuitive cost of governance cooperation, and the greater the income *e* of individual governance, the more difficult the formula above is to be established, the less likely it is for countries to adopt the strategy of governance cooperation. Besides, the probability of the opponent's strategy choice in the game also has an important influence on the choice of country strategy.

## 3. Simulation of the evolutionary game of marine plastic waste management cooperation network

### *3.1. Simulation process*

The specific connection relationship in the cooperation network of marine plastic waste treatment is quantified as a 0-1 matrix (*q*=0). The value of different countries with connection relationship in the corresponding position in the table is 1; otherwise, it is 0. Considering the excessive number of countries, only 20 nodes are included in the matrix, as shown in Table 3.

**Table 3**

Network node relation matrix with 20 nodes.

| Nodes | a | b | c | d | e | f | g | h | i | j | k | l | m | n | o | p | q | r | s | t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| b | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| c | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| d | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 |
| e | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| f | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| g | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| h | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| i | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| j | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| k | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| l | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| m | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 |
| n | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| o | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 |
| p | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| q | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| r | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| s | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| t | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| $k_i$ | 4 | 1 | 11 | 10 | 5 | 2 | 4 | 5 | 3 | 3 | 4 | 3 | 5 | 1 | 7 | 2 | 2 | 2 | 2 | 2 |

The letters in the matrix of relationship network represent the countries in the network, $k_i$ represents the number of countries that have established a connection relationship with country *i*, which are: [4,1,11,10,5,2,4,5,3,3,3,4 ,3,5,1,7,2,2,2,2].

Figure 1 and Table 3 show us the connectivity of the 20 nodes of marine plastic waste management under the scale-free network. The number of individuals with a high degree of connectivity in the network is low (Figure. 1), and there are only 2 nodes with a degree exceeding half of the total number of nodes in the network, accounting for 10% of the total number of nodes. The remaining nodes are basically connected with a degree of 5 or less (Table 3). On the whole, the network composed of 20 nodes shows a fragmentation characteristic, which is basically consistent with the real network.

MATLAB is used for simulation, and the simulation process is shown in Figure. 2:

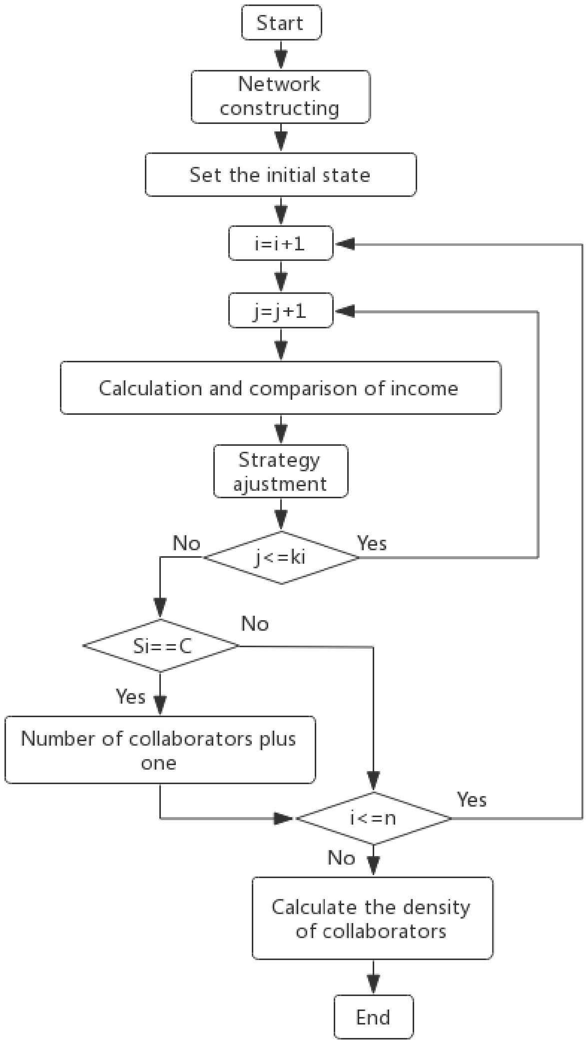


**Figure. 2.** Simulation flow chart of complex network model based on global governance of marine plastic waste.

*3.2. Results and analysis of simulation*

In the initial state, there are two countries in the network to form a complete connection and each country has two edges. The countries newly entered make choices with a probability. In addition, considering that there are 195 sovereign countries in the world, the number of nodes introduced in the model is 195.

*3.2.1. The situation where the relationship strength changes and the cumulative income weight a=0*

According to the weighted utility function and strategy updating rules in the model, the weight parameter of cumulative income is 0, and the calculation method at this time is the average income calculation method. Notably, relational costs are taken into account in this case.

1) The relationship between the intuitive benefits of cooperation and the density of collaborators under different relationship strengths.

It is assumed that the unit-cost of the cooperation is 10, the workload is 10000, the benefit in separate governance of the single country is 20, the spillover benefit is 20, the information and supervision cost is 5, and the cost of the single country to overcome the barriers to cooperation is 10. The simulation results are shown in Figure. 3.

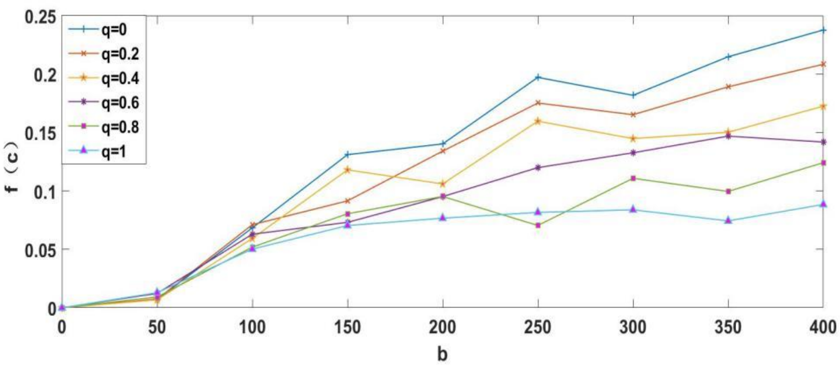


**Figure. 3.** The simulation diagram of the impact of intuitive revenue on density of collaborators under the change of relationship strength.

In Figure. 3, regardless of the value of *q*, the directly foreseeable benefit *b* has weak effect on group cooperation behavior in a lower range but has a promoting effect on it in a higher range. Specifically, in the range of (0, 50), the change of *b* does not have significant impact on *f(c)*, and just few countries in the network choose a cooperation strategy. In the range of *b*>50, *f(c)* increases rapidly in fluctuation with the increase of *b*. Finally, in the range of *b*>250, *f(c)* tends to be stable gradually.

The relationship strength has a negative correlation with the partner density. The larger the value of *q*, the lower the curve position and the smaller the *f(c)*.

From the above analysis, it can be inferred that the predictable direct income and relationship strength affect the equilibrium state of network game by influencing the strategy choice of each node in the network, and only when the economic value of this part exceeds a certain range can it greatly attracts countries and urges them to choose the strategy of governance cooperation. In addition, the greater the relationship strength, the more unfavorable it is for the establishment of cooperation relationship. In other words, the greater the influence of a country in the network, the more unstable the cooperative relationship between countries.

2) The relationship between the unit-cost of cooperation and the density of partners under different relationship strengths.

It is assumed that the direct benefit of the cooperation is 50, the workload of the cooperation is 10000, the benefit in separate management of the single country is 20, the spillover benefit of the cooperation is 20, the information and supervision cost of the cooperation is 5, and the cost of the country to overcome the obstacles in the cooperation is 10. The results are shown in Figure. 4.

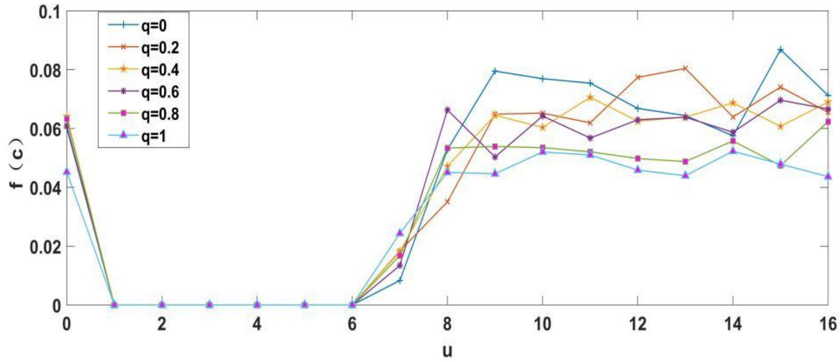


**Figure. 4.** The simulation diagram of the influence of unit cost of cooperation on density of partners under the change of relationship strength.

In Figure. 4, no matter what the value of *q* is, the unit cooperation cost *u* (the value of *u* is a positive integer) has the same influence on the equilibrium density of cooperative governance. In the range of (0,6], *f(c)* drops rapidly from the initial state to 0 and maintains at this level. In the range of (6,9), *f(c)* increases rapidly and tends to be dynamically stable when *u* reaches 9.

Regardless of the value of *u*, the relationship strength is negatively correlated with the partner density. In the initial state, the negative correlation is not obvious. However, in the range of (8, 20), overall, the negative correlation between the value of *q* and the position of the curve is valid. Specifically, the smaller the *q* value is, the higher the position of the curve represented is, and the greater the *f(c)* is although the curves represented by different *q* values fluctuate around the equilibrium value.

In summary, the unit-cost and relationship strength affect governance cooperation of marine plastic waste. The unit-cost of governance cooperation exerts an absolute restraint on the cooperative behavior of the group in a relatively low range and the inhibitory effect disappears in a higher range. Combining with the distribution law of unit-cost of governance cooperation, a higher expected unit-cost inhibits the behavior of governance cooperation when u is lower, while the situation is reversed when u becomes larger. Besides, in the case of changes in the unit-cost of governance cooperation, strong relationships show an inhibitory effect on group cooperation behavior, which is consistent with the message conveyed in Figure 3.

3) The relationship between the workload of cooperation and the density of collaborators under different relationship strengths.

We suppose that the intuitive benefit of governance cooperation of marine plastic waste is 50, the unit-cost of governance cooperation is 10, the benefit of individual governance of a single country is 20, the spillover benefit of governance cooperation is 20, the information and supervision cost of governance cooperation is 5 and the cost that a single country needs to pay to overcome obstacles to cooperation is 10. The simulation results are shown in Figure. 5.

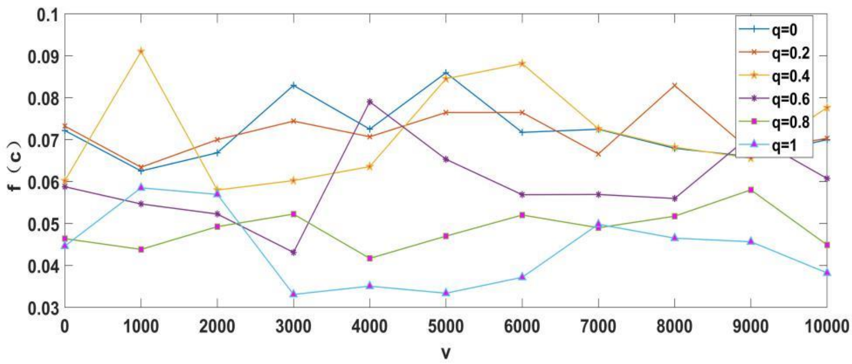


**Figure. 5.** The simulation diagram of the impact of collaboration workload on density of partners under the change of relationship strength.

In Figure. 5, no matter what the value of *q* is, the partner density of marine plastic waste management cooperation does not change greatly with the change of the workload of the management cooperation. As *v* increases, *f(c)* fluctuates around the initial partner density.

Regardless of the value of *v*, the strength of the relationship has an inhibitory effect on the group's cooperative behavior, and the form of expression of the effect is consistent with Figure. 3.

From the above analysis, we can infer that the workload of a single country in governance cooperation has no significant impact on the group's strategic choice and does not affect the equilibrium density of cooperators. Also, the strength of the relationship in governance cooperation still inhibits group's cooperation behavior. The intuitive cost *d* of governance cooperation is determined by the expected unit-cost and the workload of governance cooperation. Combined with the simulation results in Figure. 4, we can reasonably speculate that the higher cost of expected governance cooperation will limit the group's cooperative behavior.

4) The relationship between the benefits of individual governance and the density of partners under different relationship strengths.

We suppose that the direct benefit of the cooperation is 50, the unit-cost is 10, the workload is 10000, the spillover benefit is 20, the information and supervision cost is 5, and the cost of a single country to overcome the obstacles of cooperation is 10. The results are shown in Figure.6.

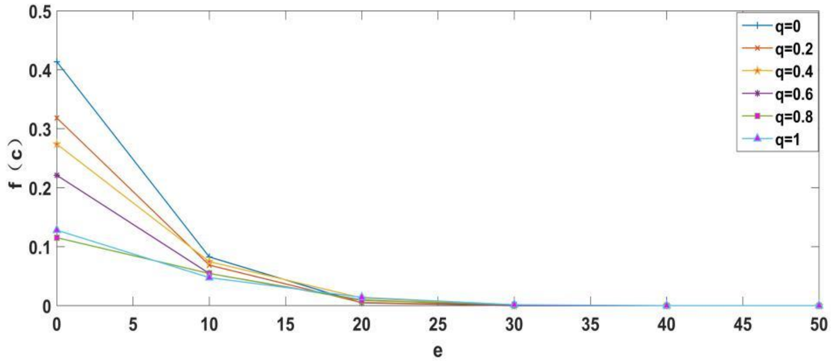


**Figure. 6.** The simulation diagram of the impact of the benefits of separate governance on the density of partners under the change of relationship strength.

In Figure. 6, regardless of the value of *q*, the density of partners of marine plastic waste treatment shows a decreasing trend as the income *e* of individual treatment increases, and the rate of decreasing gradually decreases. Specifically, *f(c)* decreases with the increase of *e* and then decreases to 0 after *e* increases to 30. In the range of (0,10), (10,20), and (20,30), the rate of declining of *f(c)* decreases in turn.

Regardless of the value of *e*, strong relationships show an inhibitory effect on group cooperation behavior, and the form of inhibition is consistent with Figure. 3.

It can be inferred from the above analysis that the benefits of individual governance are negatively related to the equilibrium density of partners. The greater the benefits of individual governance, the more countries in the network tend to govern alone, and the fewer countries choose cooperative strategies in the group. Besides, strong relationships still show an inhibitory effect on group cooperation behavior.

5) The relationship between the spillover benefit of cooperation and the density of collaborators under different relationship strengths.

It is assumed that the intuitive benefit of marine plastic waste governance cooperation is 50, the unit-cost is 10, the workload is 10000, the benefit of a single country in individual governance is 20, the information and supervision cost of governance cooperation is 5, and the cost to be paid by a single country to overcome cooperation barriers is 10. The result is shown in Figure. 7.

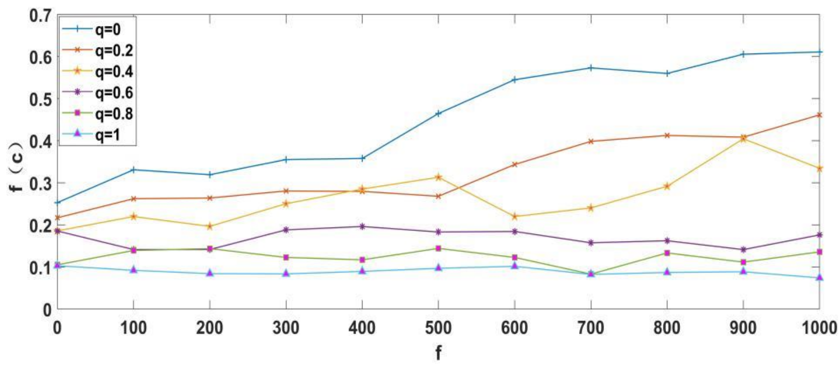

**Figure. 7.** The simulation diagram of the impact of spillover benefits of governance cooperation on the density of partners under the change of relationship strength.

In Figure. 7, when $q$ is small, the partner density increases as the overflow benefit $f$ increases. The partner density does not change with the overflow benefit when the value of $q$ is large. Specifically, in the curve corresponding to $q$=0.6, $q$=0.8, and $q$=1, *f(c)* fluctuates slightly around the initial level, while in the curve corresponding to $q$=0, $q$=0.2, $q$=0.4, it increases with the increase of $f$ and gradually reaches dynamic stability. Besides, the smaller the $q$, the higher the steady-state level.

On the whole, strong relationships inhibit the group's cooperative behavior of marine plastic waste management and the form of this inhibition in Figure 7 is consistent with previous Figures, such as Figures. 6, 7, 8, and 9. The curve with higher relationship strength is more stable than that with lower relationship strength. Specifically, the initial state of the curve corresponding to $q$=0.6, $q$=0.8 and $q$=1 is in equilibrium, while the curve corresponding to $q$=0, $q$=0.2 and $q$=0.4 shows an increasing trend in the whole process. Besides, the smaller the $q$, the greater the degree of fluctuation.

From the above analysis, it can be inferred that the spillover benefits brought by the cooperation of marine plastic waste treatment under the weak relationship strength promote the cooperative behavior of the group. On the one hand, the strong relationship inhibits the cooperative behavior of the group, on the other hand, it is conducive to the stability of the network.

6) The relationship between the information and supervision cost of cooperation and the density of collaborators under different relationship strengths

It is assumed that the direct benefit of the cooperation is 50, the unit-cost is 10, the workload is 10000, the benefit of the single governance is 20, the spillover benefit is 20, and the cost of a single country to overcome the obstacles of cooperation is 10. The results are shown in Figure. 8.

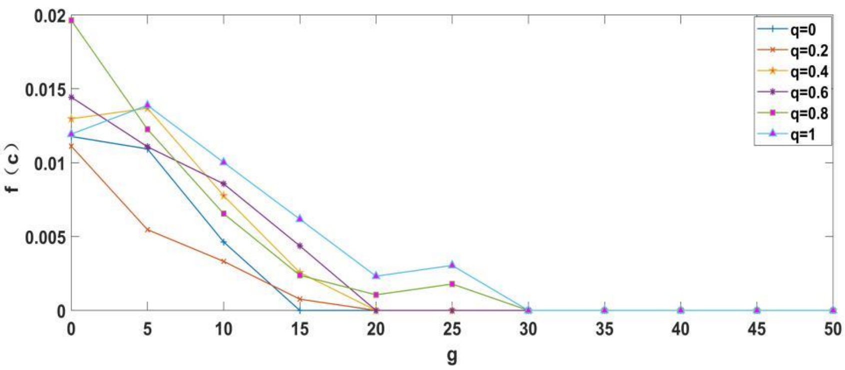


**Figure. 8.** The simulation diagram of the impact of the information and supervision cost on the density of cooperators under the change of relationship strength.

In Figure. 8, regardless of the value of $q$, the equilibrium density of partners *f(c)* is negatively related to the information of cooperation and the supervision cost $g$. The density *f(c)* gradually decreases with the increase of g and drops to 0 after $g$=30. Although *f(c)* rebounded during the downward process, it did not affect the decline overall.

The larger $q$ hinders the stability of the network and promotes the cooperative behavior of the group. The curve corresponding to different $q$ fluctuates differently in the process of reaching stability. Specifically, the curves corresponding to $q$=0, $q$=0.2, $q$=0.4, and $q$=0.6 decrease steadily in the range of (0,20), and then these four curves reach stability when $g$=20. In addition, the curves corresponding to $q$=0.8 and $q$=1 decrease in the range of (0,20), and *f(c)* drop to 0.002 and 0.003 respectively at $g$=20, but then it rebounds and finally stabilizes at g = 30. Besides, as a whole, the larger the $q$ is, the higher the curve position it represents, and the larger the *f(c)*. It is noting that the form of expression is opposite to that of Figure. 3, 4, 5, 6, and 7.

From the above analysis, we can infer that there is a negative correlation between the information and supervision cost of governance cooperation and the equilibrium density of group cooperation. In addition, the relationship strength does not inhibit the group cooperation behavior but promotes it. Also, the greater the relationship strength, the less conducive to the stability of the network. In the marine plastic waste management cooperation network, this phenomenon is specifically manifested in the sudden change of strategies in the influential countries in the network, which will drive neighbors to change their strategies, resulting in major changes of the partners density in the entire network.

7) The relationship between the cost of overcoming obstacles to governance cooperation and the density of partners under different relationship strengths.

It is assumed that the direct benefit of the cooperation is 50, the unit-cost is 10, the workload is 10000, the benefit of the country in separate governance strategy is 20, the spillover benefit is 20, and the information and supervision cost of the individual governance cooperation is 5. The results are shown in Figure. 9.

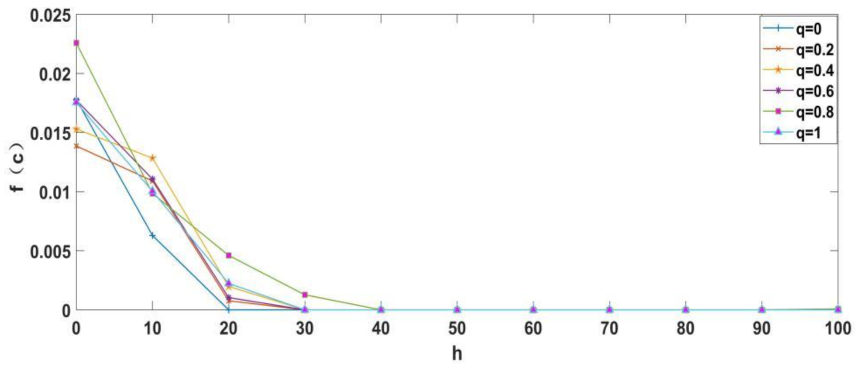


**Figure. 9.** The simulation diagram of the impact of the cost of overcoming barriers to cooperation on partner density under the change of relationship strength.

In Figure. 9, no matter what the value of $q$ is, the cooperator density is negatively correlated with the cost $h$ of overcoming the barriers. Different q corresponds to different initial *f(c)*. The *f(c)* decreases from the initial value and decreases to 0 at $h$ = 40.

The value of $q$ is different, the position of the curve is different. Specifically, in the range of (0, 40), the value of $q$ is positively correlated with the position of the corresponding curve overall.

From the above analysis, it can be inferred that the cost of countries overcoming obstacles to cooperation has an inverse relationship with the balanced partner density and the strong relationship promotes the cooperation behavior of the group as a whole.

*3.2.2. The situation where the relationship strength is fixed and the cumulative income weight gradually increases*

The gradual increase in the weight parameter of the cumulative income means that the social relationship cost is gradually weakened. The relationship between the remaining variables and *f(c)* is basically the same for different values of $q$. To avoid redundancy, $q = 0.4$ is used as an example here. The specific situation is as follows ($q$=0.4).

1) The relationship between the income of governance cooperation and partner density under different cumulative income weights.

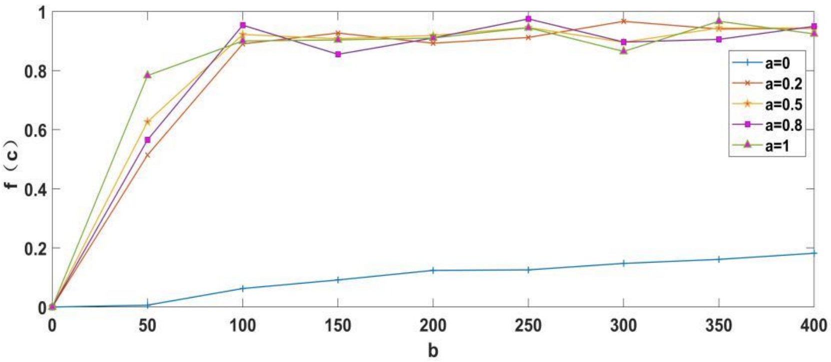


**Figure. 10.** The simulation diagram of the impact of intuitive benefits of cooperation on the density of collaborators when the relationship strength is 0.4.

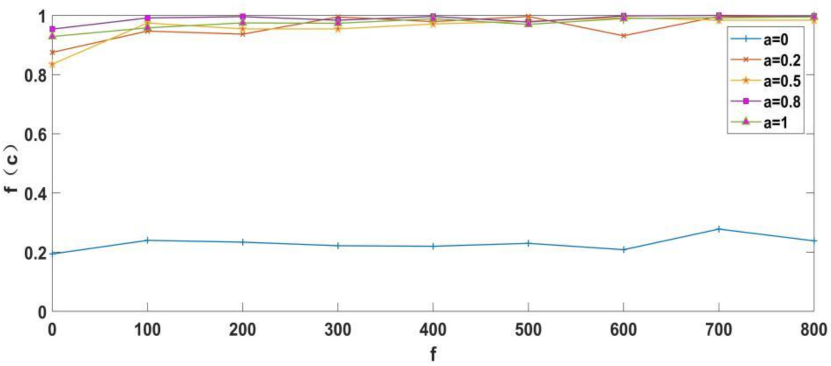


**Figure. 11.** The simulation diagram of the impact of the spillover benefits of cooperation on the density of partners when the relationship strength is 0.4.

We can obtain some results from the Figures above (Figure. 10 and 11). In the case of $q$=0.4, no matter what value the cumulative income weight takes, the trend between the income of government cooperation and the density of partners will not change.

The *f(c)* increases in a leap when the cumulative return weight increases from 0 to 0.2. The equilibrium states of the curves corresponding to the increasing cumulative return weight is basically the same gradually, and they all stay at a higher steady-state level.

2) The relationship between cooperation cost and partner density under different cumulative income weights.

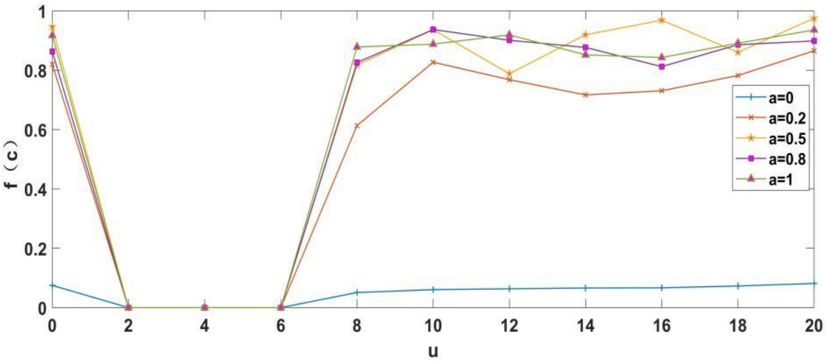


**Figure. 12.** The simulation diagram of the impact of cooperating unit cost on cooperator density when the relationship strength is 0.4.

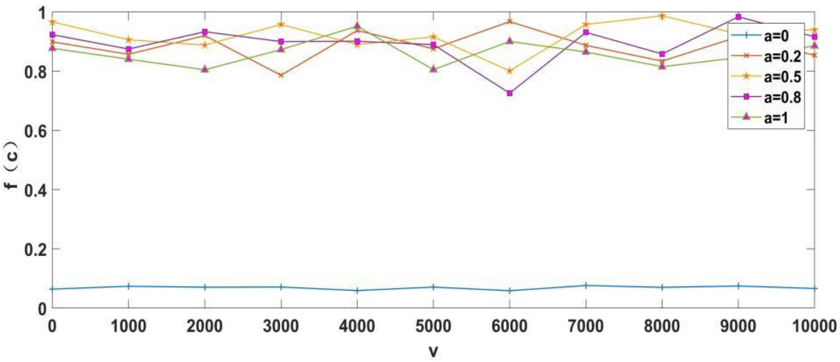


**Figure. 13.** The simulation diagram of the impact of the workload of cooperation on the density of collaborators when the relationship strength is 0.4.

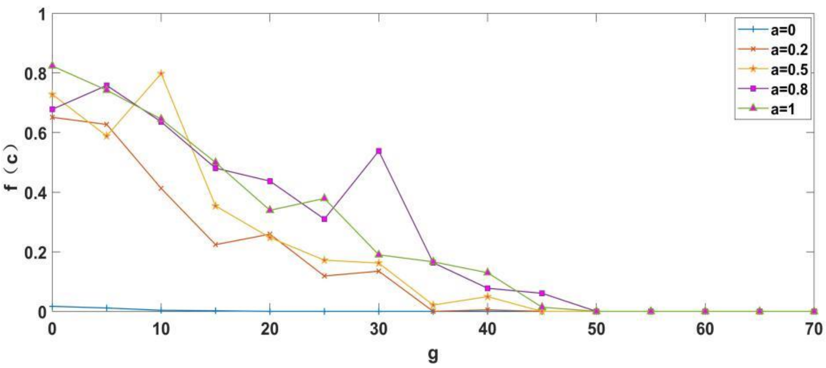


**Figure. 14.** The simulation diagram of the impact of cooperation information and monitoring costs on the density of partners when the relationship strength is 0.4.

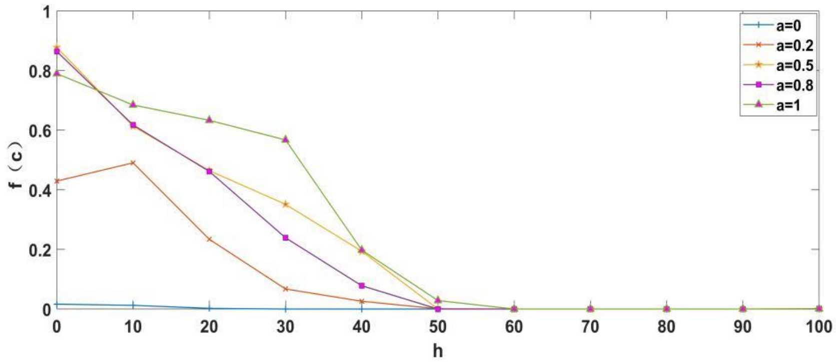


**Figure. 15.** The simulation diagram of the impact of the cost of removing barriers to cooperation on the density of partners when the relationship strength is 0.4.

In the above Figures (Figures 12, 13, 14 and 15), the value of *a* does not change the trend of the relationship between the cost and the density of cooperators, but the existence of *a* affects the cooperator density by affecting the country's strategic choice in the case of *q*=0.4. Specifically, the equilibrium level of the curve corresponding to *a*=0 is low, the equilibrium level of the curve corresponding to *a*=0.2 increases rapidly, and the equilibrium level of the curve corresponding to different *a* is basically the same when *a* exists.

In summary, the existence of the parameter of cumulative income weight greatly promotes the cooperative behavior of the group. In other words, in the calculation of the benefits of governance cooperation, the cost of social relations has a strong inhibitory effect on the group's cooperative behavior. In reality, countries especially countries with high influence have to pay a certain cost in the process of maintaining social relations. In the model, if the influential countries prefer their neighbors to follow them, they should consider maintaining social relations and leadership through a reasonable distribution structure of income. The weight of average income in the weighted benefit function reflects the change of a country's income structure and the size of social relationship cost.

## 4. Discussion

Through simulation analysis of governance cooperation of marine plastic waste, this article explores the specific impact of economic factors (the intuitive benefits of cooperation, the intuitive costs, the benefits of separate treatment, the unit-costs of cooperation, the workload, the spillover benefits, the information and supervision costs, and the costs of overcoming the obstacles of cooperation), relational structural (the relationship strength) and game structure (cumulative income weights) on the governance cooperation of marine plastic waste, and summarizes some patterns and experiences. The findings can strengthen the understanding on how to balance the participation of countries on a global scale and establish a stable and long-term cooperation mechanism on marine plastics waste.

### *4.1 Influencing factors*

1) Economic factors

The cost of overcoming obstacles to cooperation cannot be eliminated. Regulations, technologies, and social habits are different among various countries and these differences will hinder the progress of unified actions in the treatment of marine plastic waste. The more countries choose cooperation strategies, the more obstacles they encounter in cooperation. These differences between countries are one of the important obstacles affecting the establishment of cooperation mechanisms in the process of establishing dynamic relationships of marine plastic waste management cooperation.

The spillover benefits of governance cooperation have a positive role in promoting the construction of cooperation relationship of marine plastic waste governance. Comparing the steady-state level of Figure. 6 and Figure. 10, it can be found that the spillover effect on group cooperation behavior under weak relationship is greater than the intuitive benefit. In other words, spillovers are more attractive to countries. In fact, the spillover benefit is much larger than the predictable intuitive benefit and it is difficult to measure by specific value. Therefore, taking spillover benefits into account will promote the cooperative behavior of groups in the network, and the equilibrium density of group collaborators will be higher. In the future, we should strengthen the research on the calculation of spillover benefits, and attract more countries to participate in the cooperation of marine plastic waste management with the spillover benefits.

2) Relational structural

The simulation results show that the influence of the strong relationship on group cooperative behavior and network stability is bidirectional. That is, the influence of the strong relationship on the behavior of group cooperation may be either positive promotion or negative hindrance, and strong relationship sometimes promote network stability and sometimes inhibit it. This is the result of the influence and leadership of big countries in the international environmental cooperation network. The strength of the relationship determines the agglomeration of the network and then affects the cooperative behavior of the group. The network with high clustering often has one or even several central nodes with a large degree and the strategy of these nodes will affect the strategy choice of their neighbors and even the entire network. If these nodes tend to choose the strategy of governance cooperation, their neighbors are likely to choose the same strategy and the group's partner density will be higher. On the contrary, the group's partner density will be lower, which is not conducive to the establishment of group cooperation relationship. When a country with big influence is attracted by the interests and adjusts its strategy midway, its neighbors affected by its influence also choose adjustment strategy, leading to fluctuations in the entire network. On the contrary, the leading role of big countries is conducive to network stability when a big country chooses a certain strategy and its neighbors follow the strategy of it. Therefore, we need to fully consider the role and strategic choices of major powers in the cooperation network, so that the leading power of the big countries can play an active role in maintaining the stability of the governance cooperation network.

3) Game structure

In the marine plastic waste game model, this paper adopts the weighted income method to calculate the income. See Equation. 5 for details, where the value of $a$ is negatively related to the cost of social relations. Specifically, $a = 0$ means that the model considers the cost of social relations and the income is calculated by the average income method. As $a$ increases, the costs of social relations decreases; When $a$ = 1, the model does not consider the cost of social relations at all, and the income is calculated by the cumulative income method. In reality, countries especially large countries need to pay a certain cost when maintaining their social relations. Specifically, in the model, this part of the cost at the economic level is partly reflected in the distribution of governance cooperation benefits in the neighborhood subgroup. It is in line with the reality that countries make strategic choices base on the comprehensive effect of the strength and the cost of social relations.

*4.2 Simulation results*

From the whole simulation results, the density of partners in marine plastic waste management cooperation has been stable during the entire process, and its stable status is not fixed at a specific level but fluctuates. This shows that the strategy selection process of various countries is relatively complicated and the establishment mechanism of the cooperative relationship is dynamically changing in the governance cooperation of marine plastic waste, which is consistent with the complexity and change of the country's strategy selection in reality.

Further analysis of the simulation results, we find three interesting points. First, the participating subjects in marine pollution governance behave in the same way as those in other fields, and are driven by economic interests. The simulation results show that spillover benefits and direct predictable income positively contribute to cooperation in marine plastic waste management, which is consistent with the results of Fan(2018)'s view that long-term benefits benefit Arctic environmental governance [51]. Second, regarding the cooperation on marine plastic waste management, large countries maintain their network status through reasonable benefit sharing and cost sharing to promote the cooperation, while in the field of climate governance, the cooperation among countries is mainly reflected in the assistance of finance and technology, especially the developed countries provide financial support to developing countries. Third, the role and strategy choice of big powers should be fully considered in the cooperation network to maintain the network stability, which supports Zhang (2016)'s [36]view that the leading role of the concept of major powers will become the key factor for the success or failure of the legal mechanism of International environmental cooperation to certain extent. The withdrawal of the United States from the Paris Agreement made the Paris Agreement face a greater funding gap, which affects the ability and confidence of the developing countries, especially the least developed countries, to cope with climate change, caused confusion among allies, and ultimately reduced the effectiveness of the Paris Agreement. The promulgation of China's plastic ban has caused subversive changes in the international waste plastics trade network and promoted the positive development of the global waste plastic recycling system. Both China and the United States are global powers that have great influence in the world. These two events above prove the leading role of big powers in the international environment from both positive and negative aspects. Great powers have the ability to undertake international problems, but also have the ability to manipulate international affairs. Great powers can not only actively promote the settlement of world affairs, but also hinder the progress of international affairs in a positive direction. Therefore, we should give full consideration to the concept and strategic choice of big countries, so that the leading power of them can play a positive role.

There are various forms of environmental governance cooperation. With the gradual advancement of inter-regional cooperation, we must pay attention to the impact of inter-regional alliances on the marine plastic waste governance cooperation. Take the EU-ASEAN alliance as an example. To some extent, the cooperation between the two regional organizations is an example that social relations acting on national strategic choices. The two organizations are likely to choose the same strategic choices after the alliance between them, if one side adjusts its strategy, then the other will follow to adjust its strategy, which will cause network turmoil. In addition, with the development of economic and technology and the improvement of people's environmental awareness and social responsibility, the role of NGOs as active advocates of cooperation in marine plastic waste pollution management has become more and more prominent in the field of eco-environmental cooperation and governance [55].

*4.3 Comparison of cooperation in different areas*

Cooperative eco-environmental governance is a process and system of equal participation in environmental decision-making by government, NGOs and other actors who form equal interactions or partnerships to solve complex environmental problems, and use dialogue, consultation, cooperation and collective action as common governance mechanisms [30]. Cooperation on marine plastic pollution management has both similarities and differences with other areas of ecological or climate cooperation issues. Taking climate governance for reducing greenhouse gas emissions as an example, the results of the comparison are shown below.

There are three points of similarity. First, there are many different types of participants, including countries, international organizations, NGOs, enterprises, and the public; second, both marine plastic pollution management and emission reduction are public goods, and the trade-off between cooperation and non-cooperation can be seen as an evolutionary game process of public goods; third, both marine plastic waste management and greenhouse gas emission reduction may give rise to sovereignty disputes, the former involves sovereignty over territorial waters and the latter involves sovereignty over airspace. So political factors maybe one of the important factors affecting the outcome of the game.

Of course, there are also differences between the two fields. First, the cooperation mechanism of marine plastic waste management is loose, and there is no obvious trend of multi-polarity among subjects, especially among countries, while the trend of multi-polarity among subjects of emission reduction cooperation is obvious, which increases the transaction cost, reduces the efficiency of action, and fails to achieve the "ant colony effect". Second, climate issues, especially the reduction of greenhouse gas emissions, are more susceptible to market regulation than marine plastic waste pollution management. Under market regulation, the trading of carbon emission rights indirectly affects the effect of climate governance.

It is worth noting that both marine pollution management and climate management are public goods, and both have a "dilemma of collective action". However, without the strong guidance of core institutions or international organizations, the former may lead to the "prisoner's dilemma", while the latter will easily return to the "deer hunting game" when the trend of multi-polarization is gradually becoming apparent [56].

## 5. Conclusion

According to the simulation results and discussion, the conclusions are as follows.

The benefits and costs of economic have the most direct impact on the governance of marine plastic waste, and they are the most important factors for governance cooperation. The relational structural regulates the strategic choices of various countries based on the economic factors, and it has a significant impact on the governance cooperation of marine plastic waste. In addition, the game structure is an intermediary variable that refers to the distribution structure of the cooperative income between the game players, and the players have different strategic choices under different income structures. The simulation results show that the key to the cooperation mechanism of marine plastic waste treatment is to build a reasonable market mechanism, through which the cooperation enthusiasm and initiative of each subject can be mobilized to the greatest extent. At the same time, we should build an effective governance cooperation mechanism between the government and the society, adjust and control the governance relationship of marine plastic waste by changing and optimizing the relationship structure of cooperative governance to promote the governance cooperation of marine plastic waste.

Large countries have greater influence and leadership in the network of cooperation in marine plastic waste governance and have an important influence on the choice of governance cooperation strategies for other countries in the network. It is important for the reform of the national governance cooperation mechanism for marine plastic waste governance cooperation to encourage major powers to play an active leading role and restrain the impact of their destructive effects.

The profitability factors in the economic factors have a positive effect on the cooperation in the treatment of marine plastic waste, while the cost factors have a contrary effect on it. Economic factors are both objective and subjective, and the division of benefits and costs is different under different economic development thinking. Under the concept of sustainable development, the ecological environment itself is a resource and benefit, while environmental governance under the traditional economy is a cost item. Therefore, changing the economic thinking paradigm of marine governance and building a market transaction mechanism for marine ecological products under the concept of inclusive wealth is the core of promoting cooperation in marine plastic waste governance.

The contribution of this paper is mainly in two aspects. One is to use the network game model to analyze the equilibrium results of the cooperation in the management of marine plastic waste, which provides a theoretical basis for the international cooperation in the management of marine plastic waste. On the other hand, the three types of factors that affect the cooperation in the treatment of marine plastic waste are identified, and their respective mechanisms of action are compared through simulation methods, which provides a clear direction for the practice of international cooperation in the management of marine plastic waste.

This research also has certain limitations. On the one hand, the game between great powers is an extremely complicated process involving politics, economy, and other factors.

However, the design of the model is relatively simple and the assumptions are more idealized, which has a certain gap with reality. On the other hand, the global governance of marine plastic waste covers different subjects such as international organizations, non-governmental organizations, governments, the public, and enterprises, but this article only considers the more important subject level of the country, which cannot fully replicate the interaction in reality. Therefore, in future research, political and economic factors can be considered to join the model to build a multi-level network model, enhance the reality and feasibility of the model, and provide the basis for the cooperation of marine plastic waste treatment.

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