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Analysis of water rights trading mechanism based on evolutionary game

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ABSTRACT

Agricultural irrigators and industrial water users are two kinds of subjects in the market of water rights trading. In this paper, evolutionary game method and multi-agent simulation were used to analyze the non-collaborating and coopetitive behavior of these two kinds of agents. The main conclusions of this study are increased benefits are brought by collaboration and the reward and punishment will promote the development of co-operation. The greater these values are, the more the collaboration can be promoted. When one party chooses to collaborate and other chooses to non-collaborate, non-collaborative benefit and collaborative loss will promote the non-collaboration. The bigger these values are, the harder they are to collaborate. The more the impartial new profit is distributed, the more the collaboration can be promoted. Collaborative tactics have a strong advantage when the benefits of collaboration far outweigh non-collaborative benefits. Finally, based on the conclusions, suggestions for promoting the collaboration between agricultural irrigators and industrial water users were put forward in a targeted manner.

Keywords: Agricultural irrigators; Industrial water users; Coopetitive behavior; Evolutionary game; Multi-agent simulation

1. Introduction

Through the market mechanism, water rights trading will promote water efficiency by transferring water rights from water users with low marginal efficiencies to high marginal efficiencies users. We sorted out the relevant research literature as follows:

The government has established a sound water rights trading system. Abstractionists who play a key role in the reform of short-term abstract licensing transactions must have full confidence that the basic approach is fair enough, reliable, and accurate [1]. The water rights trading system has a significant impact on water rights trading. If the government cannot properly implement a reasonable system, it will inevitably fail to reach the market development expectation [2–5].

Environmental Protection Agency needs to refine its reliance on incremental control cost as the sole measure upon which to assess the financial feasibility of water quality trading [6]. Water trading volume, water allocation, pollution reduction plans, system benefits, and other factors will affect the establishment of water rights trading mechanism. A proper water rights trading mechanism helps to develop the market system [7–11]. Decisions involving water use are important yet not always considered in a consistent framework [12].

Although the implementation of water markets may be positive for overall economic output and can hence assist

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adaptation, the effect on vulnerable or socially sensitive economic sectors, such as public water, should be taken into account when implementing such a market [13].Although, the value of water in municipal water supply is high, the value of water to profitable farmers is also high [14]. Cap and trade systems are becoming increasingly common in water resources management as a mechanism to allow water to move to its highest value use [15–17].

Water rights trading involves more than just a few fringe factors, such as protein, water quality degradation, food, irrigation intensity, etc. [18–22]. Due to the uneven distribution of water resources in China, water resources allocation efficiency is not high [23,24].The rotation of water resources is related to local production and living [25,26].

2. Evolutionary game model of agricultural water operators and industrial water users non-collaborating for water rights trading market

In this paper, evolutionary game method is used to study the complex coopetitive behaviors of the two main kinds of agricultural irrigation and industrial water users in the buyer market, which can provide reference for improving the water rights trading mechanism in the future. In order to predict the behavior of the water rights buyers, first, we need to solve the stability point by the dynamic equation, then simulate the real environment according to the initial tactics changes to obtain the dynamic stability proportion. Incremental benefits brought by the collaborative behavior and government awards play a very important role in this process.

2.1. Basic premises and assumptions

- We mainly focus on three kinds of subject in this paper. In the buyer market of water rights trading, agricultural irrigators and industrial water users are direct participants, the government, as a regulator, mainly supervise the behaviors of agricultural irrigators and industrial water users.
- We assume agricultural irrigators and industrial water users are in an environment in which they are under asymmetric information.
- Agricultural irrigators and industrial water users can correct their behaviors in the environment of asymmetric information. They will take actions with the principle of farthest benefit.
- Agricultural irrigators and industrial water users only have two decisions to make in the coopetition: non-collaboration and collaboration.
- The incomes of these two kinds of players vary as their coopetitive behaviors change, there are four tactics combinations: (a) {non-collaboration, non-collaboration}, we set the income of industrial water as IG and agricultural irrigation as IN; (b) {collaboration, non-collaboration}, we set the income of agricultural irrigators as IN – MN + F,(MN is collaborative loss, F is government reward and punishment) and industrial water users as IG + AG – F (AG is non-collaborative benefits); (c) {non-collaboration, collaboration}, we set the profit of the agricultural irrigators as IN + AN – F, (AN is non-collaborative profit) industrial water users as IG – MG + F (MG is collaborative loss); (d) {collaboration, collaboration}, we set the profit of agricultural irrigators as IN + (1 – C) * Z and industrial water users as IG + C * Z (Z is overall incremental benefits when they both choose to collaborate, and C is distribution coefficient, $0 < C < 1$).

Based on the assumptions above, the game gain matrix of agricultural irrigators and industrial water users can be expressed as Table 1.

2.2. Constructing the evolution game model of water right trading

Based on Table 1, the following evolutionary study can be performed:

Now, the authors suppose the probability of an agricultural irrigator to choose collaborative tactics is $p(0 \le p \le 1)$ and that of an industrial water user is $q(0 \le q \le 1)$. We consider the income of agricultural irrigators choosing collaboration, which can be expressed as NH, to be $(1 - q) * (\mathrm{IN} - \mathrm{MN} + F) + q * (\mathrm{IN} + (1 - C) * Z)$; We consider the income of agricultural irrigators choosing non-collaboration, which can be as ND, to be $\mathrm{ND} = (1 - q) * \mathrm{IN} + q * (\mathrm{IN} + \mathrm{AN} - F)$; we consider the average income, which can be expressed as NP, to be $\mathrm{NP} = q * \mathrm{NH} + (1 - q) * \mathrm{ND} = p * q * ((1 - C) * Z + \mathrm{MN} - \mathrm{AN}) + (F - \mathrm{MN}) * p + (\mathrm{AN} - F) * q + \mathrm{IN}$.

We set the income of industrial water users choosing collaborate, which can be expressed as GH, to be $\mathrm{GH} = (1 - p) * (\mathrm{IG} - \mathrm{MG} + F) + p * (\mathrm{IG} + C * Z)$; we set the income of industrial water users choosing non-collaborate, which can be expressed as GD, to be $\mathrm{GD} = (1 - p) * \mathrm{IG} + p * (\mathrm{IG} + \mathrm{AG} - F)$; we set the average income, which can be expressed as GP, to be $\mathrm{GP} = p * \mathrm{SH} + (1 - p) * \mathrm{SD} = p * q * (C * Z + \mathrm{MG} - \mathrm{AG}) + (F - \mathrm{MG}) * q + (\mathrm{AG} - F) * p + \mathrm{IG}$.

From the equations above, we can get the dynamic equations of replication (dynamic differential equations) for agricultural irrigators and industrial water users, respectively.

The dynamic equation for agricultural irrigators is as follows:

$$\mathrm{d}p/\mathrm{d}t = p(\mathrm{NH} - \mathrm{NP}) = p * (1 - p) * (q * (Z * (1 - C) - \mathrm{AN} + \mathrm{MN}) + F - \mathrm{MN}) \quad (1)$$

The dynamic equation for industrial water users is as follows:

Table 1
Game gain matrix for industrial water users and agricultural irrigators

Agricultural irrigators	Industrial water users	
	Non-collaboration	Collaboration
Non-collaboration	(IN, IG)	(IN + AN – F, IG – MG + F)
Collaboration	(IN – MN + F, IG + AG – F)	(IN + (1 – C) * Z, IG + C * Z)

$$\mathrm{d}q/\mathrm{d}t = q(\mathrm{GH} - \mathrm{GP}) = q * (1 - q) * (p * (Z * C - \mathrm{AG} + \mathrm{MG}) + F - \mathrm{MG}) \tag{2}$$

2.3. The equilibrium points and stability analysis of water right trade based on evolutionary game model

Because the reward and punishment value F will not exceed its collaborative loss, we can know that $F < \min(\mathrm{MN}, \mathrm{MG})$,increased benefits of collaboration is greater than increased benefits of non-collaboration $\min(Z * C, Z * (1 - C)) - \max(\mathrm{AN}, \mathrm{AG}) > 0$,together with the limitation of $p(0 \le p \le 1)$ and $q(0 \le q \le 1)$, then bring $\mathrm{d}p/\mathrm{d}t = 0$ and $\mathrm{d}q/\mathrm{d}t = 0$ into the Eqs. (1) and (2) above, we will obtain five equilibrium point: (Inline 2). Whether these equilibrium points are stable were analyzed by Jacobian matrix, which can be carried out using MATLAB software as follows:

$$J = \begin{bmatrix} (1-2p)*(q*(Z*(1-C)+ \mathrm{MN}-\mathrm{AN})+F-\mathrm{MN}) & p*(1-p)*(Z*(1-C)+ \mathrm{MN}-\mathrm{AN}) \\ q*(1-q)*(Z*C+ \mathrm{MG}-\mathrm{AG}) & (1-2q)*(p*(Z*C+\mathrm{MG}- \mathrm{AG})+F-\mathrm{MG}) \end{bmatrix} \tag{3}$$

The equilibrium points solved above were brought into the determinant and its trace of the Jacobian matrix, and Table 2 was obtained by the judgment rule of the stability of the differential equations.

As can be seen from Table 2, point S and point T are evolutionarily stable point, point O is a saddle point, point Y and point X are not stable, near the evolutionarily stable, random interference term in the system does not affect its convergency. Upon this, we can roughly make a dynamic evolutionary phase diagram of the non-collaboration and collaborative behaviors between agricultural irrigators and industrial water users.

Which of the evolutionarily stable points their coopetitive behaviors will converge to depends on two factors: the initial proportion of different tactics adopted by the two sides and the relative position of the saddle point O.

As we can see from the diagram above, area IOJT, area HOKS, area XIOH, and area JOKY are the areas that their initial tactics will fall into. In area IOJT, their coopetitive behaviors will eventually converge to point T (collaborative state) as the evolution progresses; in area HOKS, their coopetitive behaviors will eventually converge to point S (non-collaborative state); In area XIOH and JOKY, their behaviors may either converge to point T or S as the evolution progresses, which may be finally solved out upon additional factors. Generally, if the collaboration area is larger than the non-collaboration area, it may converge to point T, otherwise to point S instead.

The value of point O depends on value of Z (collaboration added benefit amount) and F (the regulatory department's rewards and punishments for the non-collaboration and collaborative behavior), if the values of Z and F become larger, point O will be located in the area nearer point S. At this time, the area of YTXO expands, and their coopetitive behaviors will eventually converge to point T (collaborative state). When AN (the amount of increase in the profit of agricultural irrigators when the game is in the third case), MN (the game is in the second In this case, the benefits of agricultural irrigators are reduced by the amount), AG (the increase in the profitability of industrial water users when the game is in the second case), and MG (when the game is in the third case, the industrial water users have benefit reduction) become larger, the area of regional YOXS will expand, their coopetitive behaviors will converge to point S (non-collaboration state), and the distribution coefficient C of increased benefits Z brought by collaboration will finally move point O towards Y or X. When point O becomes too close to point Y, agricultural irrigators will get more benefits than industrial water users in the collaboration, thus more industrial water users may choose non-collaboration tactics. When point O becomes too close to point X, industrial water users will get more benefits than agricultural irrigators in the collaboration, thus more agricultural irrigators may choose non-collaboration tactics. So a suitable distribution coefficient C will promote the collaboration of both sides, otherwise it will aggravate non-collaboration.

2.4. Simulation of evolutionary stability under different non-collaborating tactics

So far, we have theoretically analyzed the results of coopetiting behaviors of agricultural water users and industrial water users in the water rights trading market. However the

Table 2
Stability analysis

Trim point	Determinant	Plus/minus	Trace	Plus/minus	Stability
T	$(Z*C-\mathrm{AG}+F)*(Z*(1-C)-\mathrm{AN}+F)$	+	$\mathrm{AN}+\mathrm{AG}-Z-2F$	–	Evolutionarily stable
S	$(F-\mathrm{MG})*(F-\mathrm{MN})$	+	$2F-\mathrm{MG}-\mathrm{MN}$	–	Evolutionarily stable
X	$(Z*(1-C)-\mathrm{AN}+F)*(\mathrm{MG}-F)$	+	$Z*(1-C)-\mathrm{AN}+\mathrm{MG}$	+	Not stable
O	$-\dfrac{(\mathrm{MN}-F)*(Z*(1-C)-\mathrm{AN}+F)}{((1-C)*Z-\mathrm{AN}+\mathrm{MN})^2} * \dfrac{(\mathrm{MG}-F)*(Z*(1-C)-\mathrm{AN}+\mathrm{MN})}{(C*Z-\mathrm{AG}+\mathrm{MG})^2} *(Z*C-\mathrm{AG}+\mathrm{MG})*(Z*C-\mathrm{AG}+F)$	–	0	Zero	Not stable
Y	$(Z*C-\mathrm{AG}+F)*(\mathrm{MN}-F)$	+	$(Z*C-\mathrm{AG}+\mathrm{MN})$	+	Not stable

reality is very complicated, we will use NetLogo software to simulate the coopetiting behavior. At the beginning of the article, we have assumed that these two kinds of agents are homogeneous game agents, so we set IN = IG, AN = AG, MN = MG and $C = 0.5$. On this basis, we further assume that F = AN = AG, and combined with the mentioned additional assumptions F < min(MN, MG) above, we can obtain F = AN = AG < MN = MG.

Point O (competitive state) and point B (cooperative state) correspond to two evolutionarily stable points: (IN, IN) and (IN + 0.5 * Z, IN + 0.5 * Z) of the game above, respectively. We can also obtain the order of the values in the matrix, that is, IN – MN + F < IN < IN + 0.5 * Z. For the specific coopetiting tactics of agricultural water users and industrial water users, see Table 4.

For simplicity, the authors examined 11 combinations of tactics to test the evolution and equilibrium under different tactics. These kinds of tactics combinations are (collaborative tactics, non-collaborative tactics), (non-collaborative tactics, tit for tat tactics), (non-collaborative tactics, suspicious tactics), (collaborative tactics, tit for tat tactics), (collaborative tactics, suspicious tactics), (non-collaborative tactics, non-collaborative tactics, non-collaborative tactics), (non-collaborative tactics, non-collaborative tactics, non-collaborative tactics), (suspicious tactics, non-collaborative tactics, non-collaborative tactics), (non-collaborative tactics, non-collaborative tactics, collaborative tactics), (collaborative tactics, tit for tat tactics, suspicious tactics), (non-collaborative tactics, collaborative tactics, tit for tat tactics, suspicious tactics). Combinations containing collaboration tactics can be sorted into collaboration group, otherwise into non-collaboration group.

In this paper, NetLogo software (5.02 version) is used to simulate 729(27 × 27) agents in its grid space. Each agent randomly plays with four neighboring agents. Because the benefits of collaboration between agricultural irrigators and industrial water users are greater than non-collaboration, the specific assignment of non-collaboration is IN = 10, Z = 20, F – MN = –2. Based on the previous conclusions, we can calculate the position of the saddle point: (1/6, 1/6). For collaborative tactics combinations, the authors focused on testing the stability of two combinations: tactics combinations at the critical area of the saddle point and tactics combinations when the agents are equally distributed into each tactic; for non-collaborative tactics combinations, we only test one situation: tactics combinations when the agents are equally distributed. For each of the 11 tactics combinations above, simulation was performed 10 times. The detailed analysis results are shown in Table 5.

Table 3
Game gain matrix for industrial water users and agricultural irrigators

	Non-collaboration	Collaboration
Non-collaboration	(IN, IN)	(IN, IN – MN + F)
Collaboration	(IN – MN + F, IN)	(IN + 0.5 * Z, IN + 0.5 * Z)

3. Simulation results and stability discussion

3.1. Simulation analysis results based on NetLogo software (5.02 version)

After hundreds of thousands of simulations, we finally got the results as in Table 5.

As shown in Table 5, at the given conditions of Z = 20 and IN = 10 all of the situations are stable. In other strategic combinations under extreme conditions, the number of collaboration tactics has risen rapidly. From a quantitative perspective, collaboration tactics have significant advantages over suspicious and non-collaboration tactics.

In the case of dividing the number of agents equally, collaborative tactics has absolute advantages in almost every combination of tactics. In non-collaborative tactics combinations, non-collaborative tactics performs the worst in terms of evolutionary quantity, followed by suspicious tactics. The combination of these two tactics converges to the sub-optimal Nash equilibrium. Tit for tat tactics performed best, which has an evolutionary number exceeding the number of non-collaboration tactics and suspicious tactics.

If the benefits of collaboration between agricultural irrigators and industrial water users are less higher than the benefits of IN, less agents will choose collaboration tactics, and the advantages of the tit for tat tactics will not be so significant, the advantages of non-collaborative and suspicious tactics will be enhanced, therefore, the results will be more likely to converge to the sub-optimal Nash equilibrium.

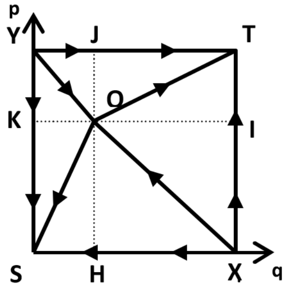

Fig. 1. Dynamic evolution of the coopetition between agricultural irrigators and industrial water users.

Table 4
Behavioral tactics matrix for industrial water users and agricultural irrigators

Behavioral tactic	Initial tactic	Next tactic when the rival chooses	
		Collaboration	Non-collaboration
Non-collaborative	Non-collaboration	Non-collaboration	Non-collaboration
Collaborative	Collaboration	Collaboration	Collaboration
Tit for tat	Collaboration	Collaboration	Non-collaboration
Suspicious	Non-collaboration	Collaboration	Collaboration

Table 5
Analysis of evolutionary stability of various combinations

Group	Tactics combination	Number of agents	Stability	Number of agents	Stability
Collaboration tactics	Collaborative non-collaborative	23 706	Stable, all converge to Point B	364 365	Stable, 10 times converge to Point B
	Collaborative tit for tat	23 706	Dynamically stable at 23:706	364 365	Dynamically stable at 364:365
	Collaborative suspicious	23 706	Dynamically stable at (559–573):(143–159)	364 365	Dynamically stable at (543–556):(129–139)
	Collaborative non-collaborative tit for tat	23 353 353	Dynamically stable at (387–396):0:(342–357)	243 243 243	Dynamically stable at (389–410):0:(241–269)
	Collaborative non-collaborative suspicious	23 353 353	Dynamically stable at (559–606):0:(118–139)	243 243 243	Dynamically stable at (498–529):0:(211–243)
	Collaborative tit for tat suspicious	23 353 353	Dynamically stable at (243–329):(350–382):(40–63)	243 243 243	Dynamically stable at (380–412):(229–352):(77–101)
	Collaborative non-collaborative tit for tat suspicious	23 235 235 236	Dynamically stable at (399–432):0:(206–235):(73–96)	182 182 182 183	Dynamically stable at (370–408):0:(199–230):(98–144)
Non-collaboration tactics	Non-collaborative tit for tat			364 365	Dynamically stable at 54:675
	Non-collaborative suspicious			364 365	Dynamically stable at 364:365
	Tit for tat suspicious			364 365	Dynamically stable at (616–650):(87–117)
	Non-collaborative tit for tat suspicious			243	Dynamically stable at 33:(508–538):(163–185)

3.2. Influence of distribution coefficient of incremental benefits

Although our simulation results showed the stability of collaborative tactics, but it was based on $\min(\mathrm{IN} + (1 - C) * Z, \mathrm{IG} + C * Z) \gg \max(\mathrm{IN}, \mathrm{IG})$, if Z is not large enough, then the advantages of collaborative tactics will be significantly reduced, in our simulation experiment, 23 agents with a very small critical number adopt collaborative tactics. But if the formulae above do not hold, there must be a large critical number of agents adopting non-collaboration tactics in order to ensure their profits, on the other hand, if one of the players in the game dominates the new gains (i.e., to make the distribution coefficient of one party larger) then the other sides of the game will be more motivated to choose non-collaboration. The authors believe that the distribution of the new gains should be based on the contribution of the players.

3.3. Influence of rewards and punishments from the government

F is the amount of reward and punishment that the government gives to both sides of non-collaboration, the greater the F is, the more the amount of punishment will be given to the side who chooses non-collaboration tactics, in order to avoid loss from the punishment, the two kinds of non-collaborators mentioned in this paper will try to get rid of any unnecessary non-collaboration. So increasing F can effectively reduce non-collaboration and encourage both sides to choose collaborative tactics.

4. Conclusion

By analyzing the coopetitive between agricultural irrigators and industrial water users, we found that rewards and punishments given by the government (or other management institutions) to water rights buyers according to their behavior will bring benefits to both sides. Countermeasures can hardly be effective in the case of information asymmetry, the government (or other management institutions) must reasonably control the countermeasures to collaborate or non-collaborate of both sides in order to promote the development of water right market. We thought the following suggestions should be useful.

In order to protect the collaborative relationship between the two parties, authorities should focus more on industrial water consumption, restrict the excessive development of agricultural irrigation, and share resources between the two parties.

As a relatively independent third party, government (or other management institutions) can play a unique role in helping the two sides to reduce information asymmetry and promote the collaboration relationships between them. Participants must understand the present situation correctly and get rid of the prisoner's dilemma to maximize the interests of both sides.

In the distribution of incremental benefits, departments concerned can make use of rewards and punishments to make agricultural irrigates and industrial water users reduce unnecessary non-collaborative behaviors which could be harmful to both of them, and help to build a long-term collaboration agreement.

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