Research Article

A new emission trading with bounded rational countries: a network game approach

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Abstract

This paper designs a new carbon trading mechanism, that is, developed countries will give developing countries a certain amount of subsidies and require them to undertake a certain amount of additional emission reduction tasks in order to promote emission reduction of developing countries. This is equivalent to developed countries "buying emission permits" from developing countries. We study the dynamic property of this kind of emission trading and treat the trading process as a social network that exhibits network effects in which there exist only one developed country and many developing countries. Furthermore, we model the developing countries as bounded rational, i.e., they are unable to pay immediate attention to price changes. Finally, we find that the developed country's optimal prices trajectory has the following structure: the price is low when the number of bounded countries is less than a certain level and is high when the number is greater than the target. We also show that a certain number of bounded rational developing countries are conducive to the success of emission trading.

Keywords Emission trading · Network effect · Dynamic games · Bounded rational

1 Introduction

At present, the problem of global warming is receiving an increasing amount of attention [6]. At the recent Paris Climate Summit, an international agreement on climate issues was adopted, which kept the increase in the global average temperature below 2^oC. In order to achieve this goal, more than 150 participants submitted emissions reduction plans, and the issue of financing and technology transfer has also been resolved: it is hoped that an annual financing of US$100 billion will be achieved by 2020 to support developing countries to achieve emissions reduction targets.

Research on green subsidies transfers generally involves two issues, namely green fund transfer [9, 11], and green technology transfer [16, 36]. For the green fund, studies are mainly focused on two issues. The first is the source of green fund. Authors in Markandya et al. [37] suggest a combination of historical responsibility and economic capacity (measured by GDP or per capita GDP) as indicators to allocate financing tasks. In addition, scholars have also considered raising green capital by other means, such as a carbon tax [2, 3], climate-related derivatives markets [32], and transactions of carbon emission permissions [54].

The second issue is capital allocation; the main consideration is fairness and effectiveness [14]. Capital allocation standards should consider not only the disaster fragility of a country but also more scientific criteria [23]. Furthermore, Dellink et al. and Füssel [17, 22] believe that non-economic factors should be considered to ensure that every developing country can face "adaptation and mitigation measures" equally (see [14]). The adaption measure relates to the fragility of developing countries when facing a climate disaster, whereas the mitigation measure relates more to eliminating the negative effects of short- and long-term mitigation on developing countries.

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For the green technology, studies are mainly focuses on the following three topics:

(1) Analyzing obstacles to technology transfers. Research shows that when the economic gap between two countries is too large, successful technology transfers are very difficult [1, 41]. Studies such as Ockwell [39] and Rai et al. [45], however, believe that differences in intellectual property rights between developed and developing countries are also an obstacle to successful technology transfers. In addition, fewer policies and incentives [25], transfers of outdated technologies by developed countries [39], and a poor understanding of low-carbon technologies, from *R&D* to commercial diffusion, in developing countries [25, 40] make technology transfers difficult.
(2) Understanding the conditions for successful technology transfers. In fact, studies such as find three necessary conditions for transferring technology successfully. The recipient country should (a) be open enough to ensure low transfer costs [21], (b) have sufficient capacity and knowledge to apply and maintain a high level of foreign technology [24], and (c) have a demand for the transferred technology [36] and [43].
(3) Enhancing the *R&D* capabilities of developing countries that accept technology transfers. To improve these capabilities, the physical transfer of technology, the enablement of financial mechanisms, capacity development in the receiving country, and the development of a monitoring system should all be performed well [33, 48].

On the other hand, the carbon trading market is also an effective way to mitigate climate change [57], so it is attracting more and more scholars' attention. Many inspiring results have emerged: references such as Seifert et al. [13]; Daskalakis et al. [15]; Chang et al. [50] studied the property of price of carbon trading market theoretically and empirically; scholars in Bernard et al. [7] and Li [31] introduced differential game into the carbon trading market.

However, few scholars take network effects into the account and carbon trading market, similar to some other markets, has network effect characteristics.

A good or service is said to exhibit network effects or is called a network good if the value to each consumer of the good or service is influenced by the consumption choices made by some or all other consumers [44]. In fact, a country, indexed as i here, that receives the subsidies (funds or technologies) must bear the pressure of reducing emissions. When the countries around country i do not reduce emissions, it will produce a strong sense of discomfort, which will lower its earnings. As the number of countries around country i that choose to reduce emissions increases, this discomfort will gradually decline. That is, country i's revenue is connected to its neighbors' choices. Therefore, financing and technology transfer can be observed as a network good.

Network effects find their origin in the seminal paper [46] and papers of Katz and Shapiro [29] and Farrell and Saloner [20]. These works build the theory of network effects. Since then, a large number of related articles have been published and enriched this field. As a supplement to the previous work, the network structure of network effects has been taken into account by Jullien [27], Sundararajan [51], Sääskilahti [52] and Banerjiand Dutta [4]. Then, research about network effects has spread into many related subjects, such as optimal pricing and marketing strategy [19] and [30]. Banerji and Dutta [4], Sääskilahti [51] and Sundararajan [52] consider uniform monopoly prices, whereas Jullien [27] and Bloch and Qurou [10] study discriminatory pricing at different nodes. Furthermore, reference prices have been studied in Xia et al. [56]; Mazumdar et al. [27], Jullien [38] and Banerji andDutta [4] introduce competition between two price-setting firms into the study of network effects.

However, all the above-mentioned papers typically assume that the consumers in the social network are complete rationality: consumers can observe the entire price strategy of the seller and immediately react to changes in the price strategy by changing their expectation demand, which is then impacted in equilibrium. However, on the larger scale of network goods, all members being completely rational is difficult to achieve. Moreover, it becomes more difficult as the network size increases [44].

On the other hand, this study is closely related to the literature that study games theory [12, 34, 49, 53, 55]. Generally speaking, a differential game model has two different optimal solution types: an open-loop Nash equilibrium solution and a feedback Nash equilibrium solution [5, 35]. Therefore, studies in this field can be roughly divided into two categories: (a) those with only an open-loop Nash equilibrium ([8] and [28]) and (*b*) those with a closed-loop Nash equilibrium. Ploeg and Zeeuw [42] provides a feedback equilibrium for the transnational pollution problem in the non-cooperative case, [26] studies a cooperative differential game of transboundary industrial pollution between two asymmetric regions, and a more general nonlinear Nash equilibrium solution is given in Dockner and Long [18]. Furthermore, Rubio and Casino [47] compares the feedback solutions in the cooperative and non-cooperative cases.

Motivated by the above analysis, we build a network effects model to study the emission trading between developed and developing countries in this paper. In this model, we assume that consumers are bounded rational.

To be specific, we present a model of a monopoly market (that is, only one developed country in the market) for a special goods (emission permits) with network effects, in which (i) developing countries, namely "consumers" in the network, cannot (all) immediately react to every change in the developed country's price and, furthermore, (ii) make their mitigation strategies based on their "bounded rational" assessment of expected mitigation. We use this model to study the dynamic evolution problem of the emission trading established by the developed country. The adoption strategies of the developing countries continuously influence the total mitigation adjustment over time, and the developed country therefore chooses an optimal trajectory of "price" (financing or technology transfer) provided to it that maximizes its discounted profits, which is defined as acquiring maximum mitigation with the minimum financing or technology transfer.

To this end, the contributions of this paper are the following:

1. A network effects model with bounded rational "consumers" is built to study the dynamic evolution problem of emission trading.
2. The differences between the optimal solutions of models in the rational and bounded rational cases are discussed.
3. We examine how the developed country's optimal price trajectory varies when the rate of bounded rational "consumers" evolves.

The rest of the paper is organized as follows: Sect. 2 formulates the problem. The main results are proved in Sect. 3, and further discussion is presented in Sect. 4. Section 5 concludes the paper.

2 The game model

We model the subsidies transfer (technology transfer or capital transfer) in global climate negotiations as a emission trading problem with social network good since the utility of subsidies transfer of each country not only depends on the magnitude of the subsidize but also increases as more of her neighbors received the subsidize. The value of subsidies is denoted as the price of the emission permits in this paper. Furthermore, the model in this paper is a continuous-time formulation with only one developed country, as the limiting case of a discrete-time model.

First, time can be divided into a series of disjoint intervals

$$[0, h),\ [h, 2h),\ \dots, [nh, (n+1)h), \dots .$$

Obviously, the length of each interval is h, and interval i begins at $t = ih$ and ends at $t = (i+1)h$, with $i = 1, 2, 3, \dots, +\infty$. The price is provided by the developed country, which "sells" it in units within one period. At the beginning of period i, the developed country provides a price $T_m(t)$ (per unit time) for the time interval $[ih, (i+1)h)$. It is assumed that T_m is nonnegative and has an upper bound. A continuum of consumer countries are indexed by a "type" parameter θ. If a country of type θ receives the subsidy from the developed country in one period, it should shoulder a certain mitigation task R to exchange the subsidy. Then, the instantaneous utility of the country that receives the subsidize during period i can be expressed as

$$u_\theta(T_m, R) = \theta T_m - R(t), \tag{1}$$

Denote by F the cumulative distribution function of θ, and for the convenience of discussion, in this paper, we assume that $F(\theta)$ is absolutely continuous and strictly increasing, $F(0) = 0$, and $F(1) = 1$, with $0 \le \theta \le 1$on the unit interval. More details can be found in Radner et al. [44]. Therefore, a country of type θ will accept the subsidies if and only if $\theta T_m(t, h) \ge R(t)$.

The bounded rationality of our model is the rate at which countries react to subsidies changes. At the beginning of each period, a "random" fraction kh of countries of each type "pay attention to" the current price $T_m(t)$. Correspondingly, the remaining fraction $(1 - kh)$ of countries of each type do not pay attention to the developed country's price announcement, and their choice remains unchanged in period n from that in period $(n + 1)$. Note that an equal fraction kh of consumers of each type pay attention in each period and that the magnitude of this fraction depends on the length of the interval h. One might therefore interpret k as measuring the "rate of attention" of consumers to subsidies changes.

To highlight how the dynamics of the system depend on the parameter h, we change the notation slightly and let $R_h(t)$ denote the actual total mitigation task that a country receiving the subsidies should perform at time $t = nh$. Let $w_h(\theta, t)$ denote the magnitude of the mitigation task (per consumer) for consumers of type θ in period t. Thus,

$$R_h(t) = \int_0^1 w_h(\theta, t) dF(\theta).$$

Recall that only a "fraction" kh of consumers of type θ pay attention to $T_m(t)$ and decide whether to adopt the subsidies for period n. Therefore, if $\theta \ge \frac{T_m(t)}{R(t,h)}$, each country in this fraction kh adopts the price, and if $\theta < \frac{T_m(t)}{R(t,h)}$, then none of these consumers adopt the price. Because the remaining fraction $(1-kh)$ continue to do in period n what they were doing in period $n-1$, it follows that

$$w_h(\theta,t)=\begin{cases} kh+(1-kh)w_h(\theta,t-h), & \theta \geq \frac{T_m(t)}{R(t,h)} \\ (1-kh)w_h(\theta,t-h), & \theta < \frac{T_m(t)}{R(t,h)} \end{cases} \quad (2)$$

The last two expressions imply

$$\begin{aligned} R_h(t) &= \int_0^1 (1-kh)R_h(t-h)w_h(\theta,t-h)dF(\theta) \\ &\quad + \int_{T_m/R(t,h)}^1 khdF(\theta) \\ &= (1-kh)R_h(t-h)+kh\left(1-F[\frac{T_m}{R(t,h)}]\right). \end{aligned} \quad (3)$$

Our continuous-time model is obtained by letting the length h of the interval in the discrete-time model tend to zero, i.e.,

$$\begin{aligned} &\lim_{h\to 0}\frac{R_h(t)-R_h(t-h)}{-h} \\ &= \lim_{h\to 0}\frac{-khR_h(t-h)+kh\left(1-F\left[\frac{T_m}{R(t,h)}\right]\right)}{-h} \end{aligned}$$

A straightforward calculation yields the differential equation for the demand trajectory:

$$\dot{R}(t)=k\left\{1-R(t)-F\left[\frac{T_m(t)}{R(t)}\right]\right\}. \quad (4)$$

The developed country wants to choose a price trajectory $T_m(t)$ to maximize her profit, i.e.,

$$\int_0^\infty e^{-rt}T_m(t)R(t)dt. \quad (5)$$

subject to Eq. (4).

Proposition 1 *The optimal problem (5) subject to condition (4) has a unique solution.*

The proof and more details can be found in Ref. [44] and are omitted here.

3 Optimal solution

Note that countries in the network play a Stackelberg differential game. The sequence of game is as follows: the developed country provides price $T_m(t)$ at the beginning of each period. Then, country i decides its control variables $R(t)$.

The developed country's Hamiltonian–Jacobi–Bellman function $V(R)$ is

$$rV(R)=\max\left\{T_mR+\frac{\partial V}{\partial R}k\left[1-R-F\left(\frac{T_m}{R}\right)\right]\right\}, \quad (6)$$

Denote by $\lambda=\frac{\partial V}{\partial R}$ the shadow price, i.e., the future value obtained with an additional unit of technology transfer, and let $p=\frac{T_m}{R}$. $\lambda>0$ indicates that the developed country has an incentive to increase T_m to stimulate immediate subsidies.

The first-order condition of (6) is

$$\frac{\partial V(R)}{\partial T_m}=0 \Leftrightarrow F'(p)=\frac{R^2}{\lambda k}. \quad (7)$$

That is,

$$\lambda=\frac{R^2}{kF'(p)}. \quad (8)$$

By using Pontryagin's maximum principle, for the costate λ, we have

$$\begin{aligned} \dot{\lambda} &= r\lambda-\frac{\partial V(R)}{\partial R(t)} \\ &= (r+k)\lambda-k\lambda F'(p)\frac{T_m}{R^2} \\ &= (r+k)\lambda-pR. \end{aligned}$$

Then, we obtain the following HJB system:

$$\begin{cases} \dot{\lambda}=(r+k)\lambda-pR, \\ \dot{R}(t)=k\{1-R(t)-F(p)\}. \end{cases} \quad (9)$$

The following proposition provides the interior equilibria of the system (9):

Proposition 2 *The optimal problem has a unique interior equilibrium*

$$(\lambda^*,R^*)=\left(\frac{[1-F(p^*)]^2}{kF'(p^*)},1-F(p^*)\right)$$

with $p^*=\frac{r+k}{k}\frac{1-F(p^*)}{F'(p^*)}$.

The optimal problem (5)–(4) has a unique optimal subsidy policy T_m*, which is*

$$T_m^*=\frac{r+k}{k}\frac{[1-F(p^*)]^2}{F'(p^*)}. \quad (10)$$

The interior equilibrium (λ^*,R^*) *is a saddle point.*

Proof See "Appendix A". □

It can be observed from (10) that the control variable T_m of the developed country depends on the rate of attention k and discount rate r. The relationship between T_m, r and k, however, is not linear. In fact, T_m is linearly correlated with $\frac{r}{k}$. That is, when r is constant, T_m is inversely proportional to k, i.e., T_m become smaller when k increases, which has the following practical significance: larger k means more irrational countries in the network; thus, the developed country is unwilling to provide larger price T_m. Otherwise, it will obtain a lower profit. However, if the discount rate r in a period is large, properly increasing k is beneficial to lower the price burden of the developed country.

On the other hand, from Proposition 2, one can observe that the shadow price λ^*, the optimal emissions reduction R^* and the optimal price policy T_m are all strictly dependent on the cumulative distribution function $F(\cdot)$ and the density function $F'(\cdot)$, whereas both $F(\cdot)$ and $F'(\cdot)$ are inherent properties of the mitigation network. That is, the optimal solution of system (9) will be very different when the network structure is different. As a result, in order to achieve the optimal emissions reduction, it is also very important to find an optimal network structure.

Denote $\lambda_1 > 0$ and $\lambda_2 < 0$ as eigenvalues of matrix J^* and v_1 and v_2 as eigenvectors with respect to λ_1 and λ_2, respectively. Then, we have the following proposition:

Proposition 3 *The interior equilibrium of system (9) is conditionally stable. That is, the interior equilibrium is stable when the initial value of system (9) $(\lambda(0), R(0))$ is on the line on which v_2 is located.*

Proof See "Appendix A". □

In this system, $\lambda(0)$ is the shadow price of emissions reduction, which generally depends on the technical level at the time and cannot be changed. However, $R(0)$ is the emissions reduction required by developed countries for developing countries, and it is a decisionable variable that can be adjusted. Therefore, developed countries and developing countries can initially negotiate the size of $R(0)$ to satisfy $(\lambda(0), R(0)) = c_2v_2$, thus making the system stable.

4 Rational expectations equilibrium

In this subsection, we establish a performance benchmark by considering the problem of a rational network, that is, all consumers in a network of each type could discover subsidies changes in a timely manner, i.e., $k = 0$. Therefore, for the subsidies T_m, the total mitigation R must satisfy

$$R = 1 - F(\hat{p}), \tag{11}$$

which implies

$$\hat{p} = F^{-1}(1 - R). \tag{12}$$

The corresponding profit is

$$\pi = T_mR = F^{-1}(1 - R)R^2. \tag{13}$$

Define $R^{**} = arg\max_R \pi(R)$. Then,

$$\frac{\partial \pi}{\partial R} = 0 \Rightarrow 2\hat{p}F'(\hat{p}) - (1 - F(\hat{p})) = 0, \tag{14}$$

which implies

$$\hat{p} = \frac{1 - F(\hat{p})}{2F'(\hat{p})}.$$

That is,

$$R^{**} = 1 - F(\hat{p}^*)$$

with $\hat{p}^* = \frac{1-F(\hat{p}^*)}{2F'(\hat{p}^*)}$.

Then, the optimal subsidy T_m satisfies

$$T_m^{**} = \hat{p}^*R^{**} = \frac{(1 - F(\hat{p}^*))^2}{2F'(\hat{p}^*)}.$$

It is observed that in the rational case, $k = 0$, and T_m^{**} is independent of both k and r; it only depends on the network structure ($F(\cdot)$ and $F'(\cdot)$).

5 Bounded case versus rational case

In this section, we will perform a comparison between the optimal strategies in the bounded rational case and in the rational case by providing the following proposition:

Proposition 4 *From the perspective of emissions reduction, the bounded rationality of developing countries will significantly reduce the emissions reduction effect, i.e., $R^* < R^{**}$.*

Denote $G(p) = \frac{1}{2}\left[\frac{1 - F(\hat{p})}{1 - F(p)}\right]^2 \frac{F'(p)}{F'(\hat{p})} - 1$; for the developed country,

$$\begin{aligned} &T_m^* > T_m^{**}, \quad 0 < \frac{r}{k} < G(p), \\ &T_m^* = T_m^{**}, \quad \frac{r}{k} = G(p), \\ &T_m^* < T_m^{**}, \quad G(p) < \frac{r}{k} < 1. \end{aligned} \tag{15}$$

However, from the perspective of developed countries, tempered bounded rationality, i.e., $r/k \in (0, G(p)^*)$ with $G(p) = \frac{1}{2}[\frac{1 - F(\hat{p})}{1 - F(p)}]^2 \frac{F'(p)}{F'(\hat{p})} - 1$ of developing countries will increase the profits of developed countries, that is, $\pi^* > \pi^{**}$.

Proof See "Appendix B". □

6 Discussion

According to the Kyoto Protocol, it is difficult for developed countries to further improve their emission reduction efficiency in a short time. Therefore, they are willing to invest in clean projects, namely CDM, in developing countries to complete their emission reduction tasks. However, developing countries can not only get the green technologies or funds required for emission reductions in CDM but also make profits through emission reductions. Therefore, they are also willing to accept such project cooperation.

It can be seen that in the CDM project, everyone defaults that: (1) such investment in developed countries is free, and developed countries have no additional requirements for developing countries; (2) developing countries have no emission reduction tasks. Obviously, these two assumptions can no longer satisfy the current situation. On the one hand, developed countries are unwilling to provide green funds or technologies to developing countries for free; on the other hand, the Kyoto Protocol stipulates that after 2012, developing countries will also need to undertake emission reduction tasks. Therefore, the traditional CDM mechanism can no longer meet the current demand for emission reduction.

Therefore, this paper proposes a new trading mechanism: developed countries sell the funding (green technology or funds) used to promote emission reductions as a commodity. Its "price" is the amount of emissions reductions in a developing country over a period of time. It can be seen that as long as the ratio of funding and emission reductions is adjusted reasonably, developing countries' emission reductions can meet their own emission reduction needs and those of developed countries. It can be seen that in our mechanism, funding from developed countries is no longer free. The receiving developing countries must not only complete their own emission reductions within a specified period, but also undertake some emission reduction tasks of developed countries.

7 Example

In this section, we will provide numerical examples to demonstrate the effectiveness of the proposed results (Fig. 1).

Example 1 Assume that the distribution of developing countries of type θ satisfies $F(\theta) = \theta^2, r = 0.3$ and $k = 0.2$.

Then, it follows from Proposition 2 that the interior equilibrium (λ^*, R^*) is $(\frac{1.6}{1.3}\sqrt{\frac{1}{0{,}65}}, \frac{0.8}{1.3})$, and

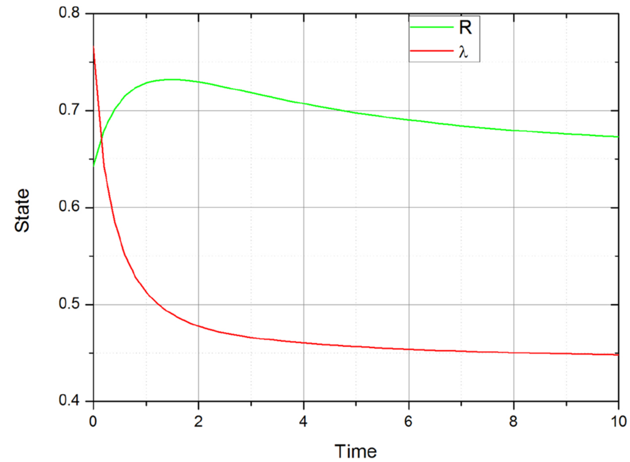

Fig. 1 Trajectories for the system (9)

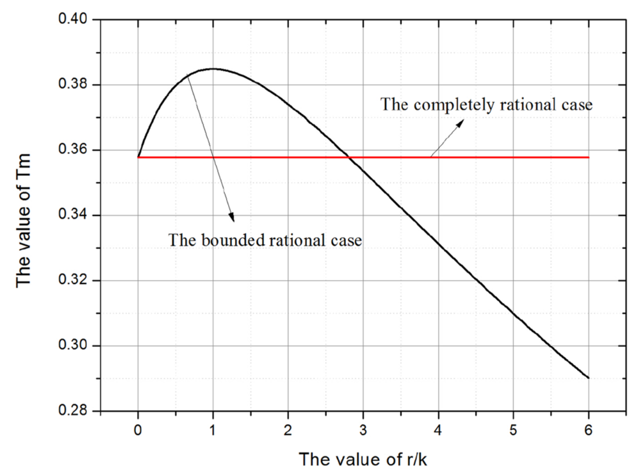

Fig. 2 Trajectories for the optimal subsidies policy

$v_2 = (0.6422, 0.7666)^T$. Denote $x(0) = v_2 = v_2 = (0.6422, 0.7666)^T$; then, we have

Obviously, the interior equilibrium (λ^*, R^*) is stable.

Next, we illustrate the relationship between T_m and R with $\frac{r}{k}$ by using Proposition 4.

In Figs. 2 and 3, $\frac{r}{k} = 0$ means $r = 0$. Denote $\frac{r}{k} = \frac{1}{m}$, $m \neq 0$; then, we have $k = mr$. As a result, $k = 0$ when $r = 0$.

It follows from Figs. 2 and 3 that when $k = 0$, which means that all developing countries in the network are able to pay immediate attention to price changes, the values of optimal price and optimal mitigation in the bounded rational case are the same as those in the completely rational case. When $\frac{r}{k} \neq 0$, the optimal mitigation in the bounded rational case decreases with increasing $\frac{r}{k}$; see Fig. 2. For the optimal price, the situation is somewhat

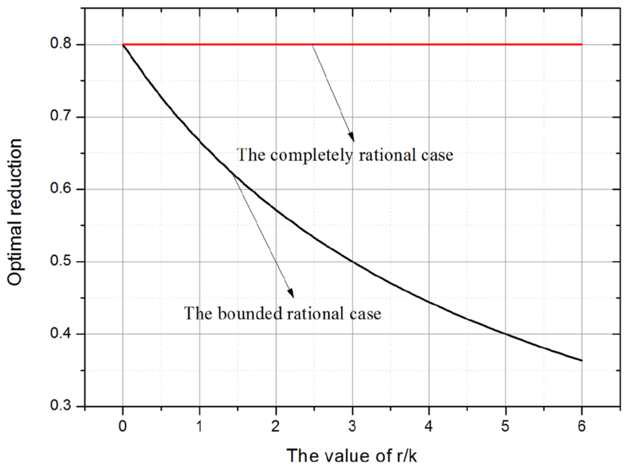

Fig. 3 Trajectories for the optimal mitigation policy

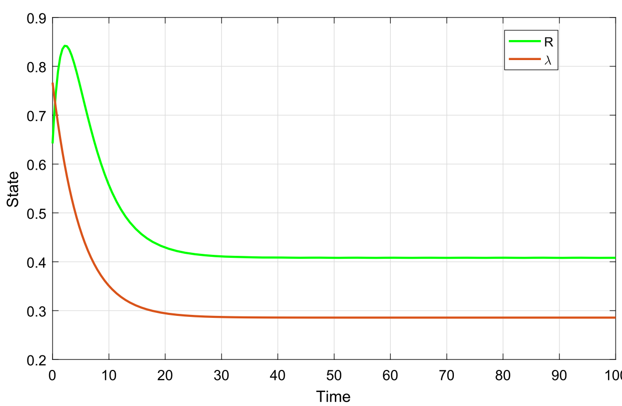

Fig. 4 Trajectories for the system (9)

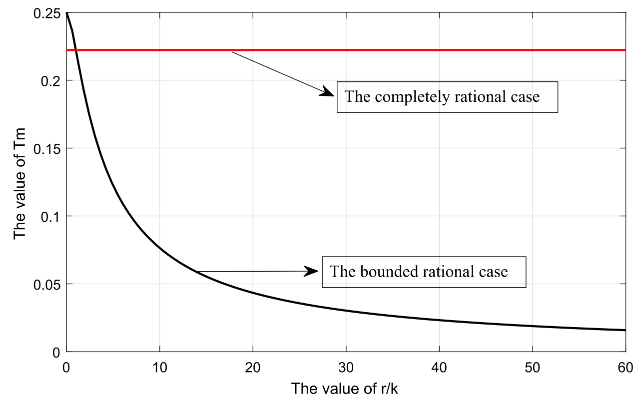

Fig. 5 Trajectories for the optimal subsidies policy

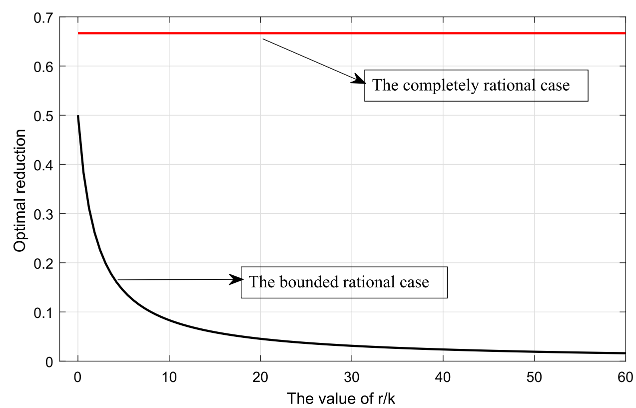

Fig. 6 Trajectories for the optimal mitigation policy

complicated: as $\frac{r}{k}$ increases, the optimal amount of subsidies increases first and then decreases. As a result, the optimal amount of subsidies in the bounded rational case will be less than that in completely rational case when $\frac{r}{k}$ achieve a certain value ($\frac{r}{k} \approx 2.5$ according to Eq. (15)).

Example 2 In this case, we assume that the distribution of developing countries of type θ satisfies $F(\theta) = \theta$. The value of r and k is the same with Example 1.

Similar to Example 1, when the initial value $x(0)$ of HJB system (9) satisfies $x(0) = v_2 = v_2 = (0.5412, 0.7863)^T$, the HJB system is stable (Fig. 4).

Then, we have the relationship between T_m and R with $\frac{r}{k}$ by using Proposition 4.

It follows from Figs. 5 and 6 when $\frac{r}{k} \neq 0$, the optimal mitigation in the bounded rational case decreases with increasing $\frac{r}{k}$ and the value of the optimal mitigation in the bounded rational case is always lower than that in the rational case; see Fig. 6. For the optimal price, the optimal amount of subsidies is also decreasing with increasing $\frac{r}{k}$ and the optimal amount of subsidies in the bounded rational case will be less than that in the completely rational case when $\frac{r}{k}$ achieve a certain value ($\frac{r}{k} \approx 1.212$ according to Eq. (15)).

Example 3 In this case, we assume that the distribution of developing countries of type θ satisfies $F(\theta) = \ln \theta$. The value of r and k is the same with Examples 1 and 2.

Similar to Example 1, when the initial value $x(0)$ of HJB system (9) satisfies $x(0) = v_2 = v_2 = (5.2413, 2.1833)^T$, the HJB system is stable (Fig. 7).

Then, we have the relationship between T_m and R with $\frac{r}{k}$ by using Proposition 4.

It follows from Figs. 8 and 9 when $\frac{r}{k} \neq 0$, the optimal mitigation in the bounded rational case decreases with

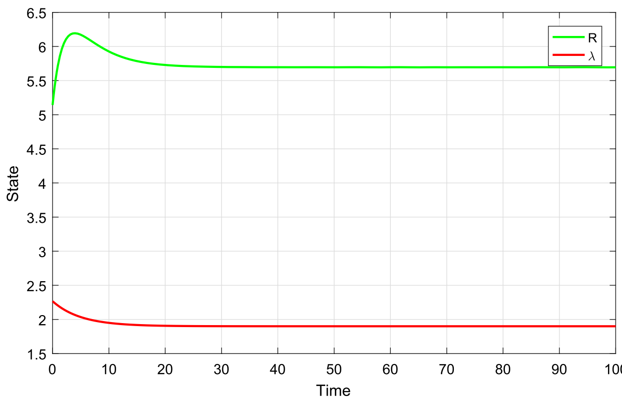

Fig. 7 Trajectories for the system (9)

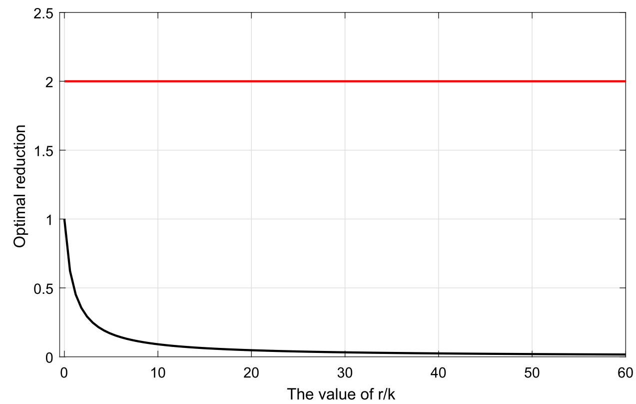

Fig. 9 Trajectories for the optimal mitigation policy

increasing $\frac{r}{k}$ and the value of the optimal mitigation in the bounded rational case is always lower than that in the rational case; see Fig. 6. For the optimal price, the optimal amount of subsidies is also decreasing with increasing $\frac{r}{k}$ and the optimal amount of subsidies in the bounded rational case will be less than that in the completely rational case when $\frac{r}{k}$ achieve a certain value ($\frac{r}{k} \approx 1.522$ according to Eq. (15)).

As a conclusion, we have:

(1) For different network structures, the dynamic characteristics of subsidy and emission reduction are different. Therefore, in order to achieve better emission reduction effect, it is meaningful to choose a suitable network structure.

(2) In the initial stage of international climate cooperation, to attract developed countries to join the network of emissions reduction, a certain ratio (i.e., $k \in (0, 0.4r]$ in Example 1) of bounded rational developing countries is advantageous and even necessary because in this case, the return of developed country is greater than in the case in which all developing countries are completely rational. However, when bounded rational developing countries are greater than a certain level (corresponding to $k \in (0.4r, 1]$ in Example 1), the developed country's return is less than the case in which all developing countries are completely rational. Therefore, the developed country is skeptical about the reduction network, and as a result, it is not conducive to the development of the emissions reduction network.

(3) At the beginning of the emission trading, developing countries cannot choose their reduction $R(0)$ arbitrarily. Otherwise, the trading system (9) would be unstable, which means the price T_m and reduction R would be out of control and could be arbitrary. As a result, the mitigation network will collapse soon, and then, global warming will continue getting worse, such that people will face catastrophic consequences. Thus, developing countries should choose a reduction $R(0)$, which depends on the shadow price $\lambda(0)$, such that the trading system (9) has a stable equilibrium point.

(4) As increasingly many countries join the emissions reduction network, in order to achieve the emissions reduction targets as soon as possible, the number of rational developing countries should be as high as possible because under the bounded rationality, the optimal emissions reductions for each country are less than the maximum emissions reductions under full rationality, which is not conducive to the realization of emissions reduction targets.

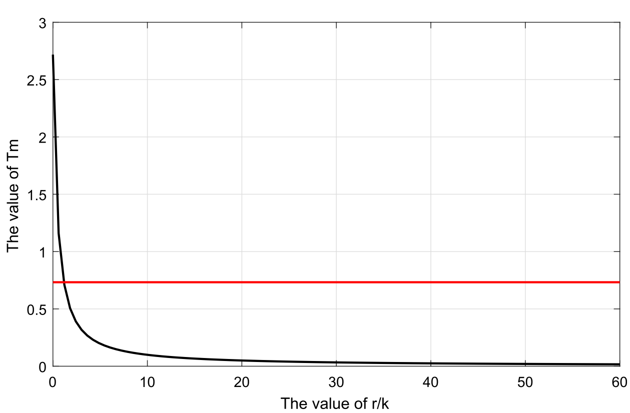

Fig. 8 Trajectories for the optimal subsidies policy

8 Conclusion

In order to inspire developed countries and heighten the confidence of developing countries, a network effects model with bounded rational agents is set up with the purpose of achieving emissions reduction targets, and we obtain the following conclusions:

The traditional CDM mechanism requires that developed countries should provide free green funds or technologies to developing countries and the developing countries have no reduction task. Obviously, these two requirements cannot be met in the real world. Therefore, a new subsidy mechanism should be proposed to meet the current emission reduction requirements.

In this paper, we study the problem that a developed country provides subsidies (green funds or technologies) to developing countries and the subsidies are not free. We treat these green subsidies as goods with network effects. Moreover, we assume that part of the developing countries in the model could be bounded rational. The results show that the bounded rational is not always harmful to the international climate cooperation. In fact, a certain ratio of bounded rational developing countries is helpful at the beginning period. Moreover, we prove that both the value of subsidies from a developed country and the optimal reduction policy are depended on the structure of network ($F(\theta)$). Therefore, choosing a suitable network structure is not only conducive to the development of emission reductions but also can reduce the expenditure of developed countries. The conclusion of this paper offers a valuable reference for climate policy makers.

Our study still has some limitations. For example, we considered only one developed country in the model. More than two developed countries will cause competition, which would render the analysis more complex. This complexity will be the focus of future work.

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Compliance with ethical standards

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

Appendix A

Letting the right-hand side of system (9) equal 0, we have

$$\dot{R} = 0 \Rightarrow R^* = 1 - F(P),$$
$$\dot{\lambda} = 0 \Rightarrow \lambda^* = \frac{pR}{r+k}.$$

Combining the above with Eq. (8), one has

$$\frac{pR}{r+k} = \frac{R^2}{kF'(p)},$$

which means

$$p = \frac{r+k}{k}\frac{1-F(p)}{F'(p)}.$$

Then, we have

$$\lambda^* = \frac{[1-F(p)]^2}{kF'(p)},$$
$$T_m^* = \frac{r+k}{k}\frac{[1-F(p)]^2}{F'(p)}.$$

To discuss the stability of the interior equilibrium, we should linearize system (9) at the equilibrium (λ^*, R^*); the Jacobian matrix is

$$J = \begin{bmatrix} r+k-R\frac{\partial p}{\partial \lambda} & -p-R\frac{\partial p}{\partial R} \\ -k\frac{\partial F(p)}{\partial \lambda} & -k-k\frac{\partial F(p)}{\partial R} \end{bmatrix}.$$

It follows from Eq. (8) that

$$F'(p) = \frac{R^2}{k\lambda},$$

which implies

$$\frac{\partial p}{\partial \lambda} = \frac{kF'^2(p)}{1-F(p)}g'\left(\frac{R^2}{k\lambda}\right),$$
$$\frac{\partial p}{\partial R} = 2g'\left(\frac{R^2}{k\lambda}\right)F'(p),$$
$$\frac{\partial F(p)}{\partial \lambda} = -\frac{kF'^3(p)}{(1-F(p))^2}g'\left(\frac{R^2}{k\lambda}\right)$$
$$\frac{\partial F(p)}{\partial R} = 2\frac{F'^2(p)}{1-F(p)}g'\left(\frac{R^2}{k\lambda}\right)$$

with $g(\cdot) = F'^{-1}(\cdot)$.

Then, the linearized Jacobian matrix at (λ^*, R^*) is

$$J^* = \begin{bmatrix} (r+k) + \frac{kF'^2(p)}{1-F(p)}g'\left(\frac{R^2}{k\lambda}\right) & -g\left(\frac{R^2}{k\lambda}\right) - 2g'\left(\frac{R^2}{k\lambda}\right)F'(p) \\ -\frac{k^2F'^3(p)}{(1-F(p))^2}g'\left(\frac{R^2}{k\lambda}\right) & -k-2\frac{kF'^2(p)}{1-F(p)}g'\left(\frac{R^2}{k\lambda}\right) \end{bmatrix}.$$

As is well known, matrix J^* is negatively defined if and only if the following conditions are satisfied:

$$(r+k)+\frac{kF'^2(p)}{1-F(p)}g'\left(\frac{R^2}{k\lambda}\right)-k-2\frac{kF'^2(p)}{1-F(p)}g'\left(\frac{R^2}{k\lambda}\right)<0,$$

and

$$Det(J^*)>0.$$

However,

$$\begin{aligned}Det(J^*)\\ &=-\left\{\left((r+k)+\frac{kF'^2(p)}{1-F(p)}g'\left(\frac{R^2}{k\lambda}\right)\right)\right.\\ &\quad\left(k+2\frac{kF'^2(p)}{1-F(p)}g'\left(\frac{R^2}{k\lambda}\right)\right)\\ &\quad\left.+\left(g\left(\frac{R^2}{k\lambda}\right)+2g'\left(\frac{R^2}{k\lambda}\right)F'(p)\right)\frac{k^2F'^3(p)}{(1-F(p))^2}g'\left(\frac{R^2}{k\lambda}\right)\right\}\end{aligned} \tag{16}$$

Because $F(\cdot), F'(\cdot), g(\cdot)$ and $g'(\cdot)$ are all positive in this paper, all terms inside the brace are positive, and therefore, det(J) is negative.

As a result, the interior equilibrium of system (9) is a saddle point.

It can be seen from the definition of stability that when the equilibrium point of the system is a saddle point, this state is unstable because matrix J^* has a positive eigenvalue. However, we cannot simply make conclusions about system instability and must perform further analysis.

First, the general solution of system (9) can be written as

$$x(t)=c_1v_1e^{\lambda_1 t}+c_2v_2e^{\lambda_2 t},$$

with $x=(\lambda(0),R(0))=c_1v_1+c_2v_2$.

Then, when the initial value is on the line on which v_2 is located, $x=(\lambda(0),R(0))$ can be written as

$$x=c_2v_2.$$

Then, the trajectory of system (9) can be expressed as

$$x(t)=c_2v_2e^{\lambda_2 t}.$$

Since $\lambda_2<0$, we have $x(t)\to 0$ when $t\to\infty$. That is, the solution is stable.

Appendix B

To prove $R^*<R^{**}$, we first show that $p>\hat{p}$.

Recalling that $\hat{p}=\frac{1-F(\hat{p})}{2F'(\hat{p})}$ and $p=\frac{r+k}{k}\frac{1-F(p)}{F'(p)}$, we have

$$2F'(\hat{p})\hat{p}=1-F(\hat{p})$$

$$2F'(p)p=\left(\frac{2r}{k}+2\right)(1-F(p)).$$

Note that the function $F'(p)p$ is increasing in p since its derivative $F'(p)+pF''(p)>0$ with $p\in(0,1)$. Obviously,

$$1-F(p)<\left(\frac{2r}{k}+2)(1-F(p)\right)$$

for all $r,k>0$. We then have $p>\hat{p}\Rightarrow R^*<R^{**}$.

Then, the relationship between T_m^* and T_m^{**} is given as follows:

let $T_m^*=T_m^{**}$. We have

$$\frac{r}{k}=\frac{1}{2}\left[\frac{1-F(\hat{p})}{1-F(p)}\right]^2\frac{F'(p)}{F'(\hat{p})}-1.$$

Denote $G(p)=\frac{1}{2}\left[\frac{1-F(\hat{p})}{1-F(p)}\right]^2\frac{F'(p)}{F'(\hat{p})}-1$; then, we have

$$T_m^*>T_m^{**},\quad 0<\frac{r}{k}<G(p),$$

$$T_m^*=T_m^{**},\quad \frac{r}{k}=G(p),$$

$$T_m^*<T_m^{**},\quad G(p)<\frac{r}{k}<1.$$

As a result, we can obtain that π^*, the object function of developed country, in the boundedly rational case is greater than π^{**} in the rational case if and only if $\frac{r}{k}\in(0,G^*(p))$ with $G^*(p)\in(0,G(p))$.

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