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AN EVOLUTIONARY APPROACH TO INTERNATIONAL ENVIRONMENTAL AGREEMENTS WITH FULL PARTICIPATION

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Abstract

Under two often employed imitation mechanisms, we show that an international environmental agreement with full participation can be the unique stochastically stable equilibrium if countries' efficiency of emission reductions is high. By contrast, if the efficiency of emission reduction is low, no agreement among countries to reduce emissions will be the unique stochastically stable equilibrium. We provide the convergence rates to these two equilibria as well. In addition, it is demonstrated that the equilibria are affected by different imitation rules and model's parameters, such as marginal benefits and costs of emission reduction and the number of participating countries.

Keywords: evolutionary game, international environmental agreement, imitations, mutation, long run equilibrium, stochastically stable

JEL classification: C73, Q54

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1. Introduction

Achieving international environmental agreements with as many participating countries as possible is a very important issue in environmental economics. Three major branches of non-cooperative game-theoretical models have analyzed this topic. In the first branch, a two-stage game is constructed by Carraro and Siniscalco (1993), Barrett (1994, 1997), and Hoel (1992). All countries decide whether they will join the coalition in the first stage of the game. Then the coalition and the non-participating countries choose their emissions non-cooperatively in the second stage of the game. The concepts of internal and external stabilities are used to characterize whether the coalition is stable. Their results display that only a few countries will join the coalition at equilibrium. Accordingly, the succeeding research tries to enlarge sizes of the coalition by allowing transfers to allocate the efficiency gains from cooperation (e.g., Barrett, 1997, 2001; Botteon and Carraro, 1997, McGinty, 2007), by considering ancillary benefits of emission reduction (e.g., Finus and Rubbelke, 2013), by imposing trade sanctions on non-cooperative countries (e.g., Barrett, 1999a), or by including spillover effects of R&D or issue linkage (e.g., Botteon and Carraro, 1998; Kemfert, 2004). Nevertheless, the impacts of these factors on enlarging the coalition are limited. The second branch literature adopts an infinitely repeated game to investigate countries' participation in environmental agreements. Relevant studies include Barrett (1999b, 2003), Finus and Rundshagen (1998), Asheim et al. (2006), Froyn and Hori (2008), and Asheim and Holtsmark (2009). In their games, the credible punishments for non-compliant countries are necessary, and international environmental agreements with countries' full participation can be supported by (weakly) renegotiation-proof equilibrium under some conditions, such as large enough discount factors and limited numbers of punisher.

Although the second branch literature can fix the problem of small coalition sizes, it is hard to coordinate compliant countries to punish the non-compliant in the real world. Questions like how to execute the punishments and who will be the punisher are not addressed in the models above. Moreover, these models presume that countries are perfectly rational, which is not practical. Many countries are actually boundedly rational. Thus, the third branch literature investigates whether boundedly rational countries can achieve environmental agreements in various dynamic set-ups. Breton et al. (2010) construct a discrete-time replicator dynamic to represent the evolution of the proportion of countries participating in an agreement over time. Under this dynamic, the signatories will increase (decrease) if the current participants perform well (poorly). Their numerical results reveal that under some conditions the outcome of no participant will co-exist with the outcome with a partial-cooperation or a full-cooperation in the long run. The initial number of participating countries will determine the final result. Under a similar replicator dynamic, Breton and Carrab (2014) show that when countries are farsighted, the formation and stability of environmental agreements will be enhanced. On the other hand, McGinty (2010) formulates environmental agreements as three kinds of evolutionary games according to the types of returns to abatement. He assumes that countries choose actions of the best-reply to the current distribution of population, and the concept of evolutionary equilibria is adopted to describe countries' long run behaviors. He shows that at evolutionary equilibria no country prefers to be an outsider and the equilibria are robust to trembles.

Different from the two dynamics above, this paper proposes an alternative dynamic to characterize countries' boundedly rational behaviors-that is, imitations, which are often seen in the real world. For instance, after the establishment of the Kyoto Protocol in 1997, the United States, the world's largest emitter of GHG's, disengaged itself from the Protocol in 2001. Thus, Canada, Japan and Russia refused to accept the new Kyoto commitments in 2010 mainly because the Protocol did not applied to the United States and China. By contrast, in the 2015 United Nations Climate Change Conference, the emission-reduction commitments of the United States and China played a key role in reaching the Paris Agreement. Following the big two, other countries made commitments as well. Thus, this paper aims to analyze how countries' imitation behaviors would affect the formation of international environmental agreements through imitating successful actions. In particular, we focus on whether an agreement with full participation can be achieved.

Two imitation rules often adopted in evolutionary games (e.g., Apesteguia et al., 2007; Chen et al., 2012, 2013) are borrowed to characterize countries' behaviors. Precisely, all countries are assumed to imitate the actions with the largest average payoff or the biggest total payoff. For each imitation rule, we build an infinitely repeated evolutionary game to describe countries' long run behaviors. At the beginning of each time period, a country can observe the actions taken by all other countries and their realized payoffs in the last period. Then, each country will choose its action with the highest average or total payoff in the current period. However, at the end of each time period, countries are allowed to change their boundedly rational choices with a small probability. This is so-called the mutation rate, which is caused by countries' mistakes or experiments. The concept of stochastically stable equilibrium will be employed to delineate countries' long run behaviors. Our results show that an agreement with full participation can be the unique stochastically stable equilibrium if countries' efficiency of emission reductions is large enough. Otherwise, no agreement will be the unique stochastically stable equilibrium. These findings do not depend on the imitation rules. Therefore, this research provides an alternative theoretical support for international environmental agreements with full participation. The convergence rates to all equilibria are given too. Finally, we analyze how imitation rules and model's parameters affect the equilibria.

The rest of this paper is organized as follows. Section 2 presents our model. Section 3 demonstrates the results. Section 4 draws the conclusions. Moreover, the proofs of our findings are presented in the Appendix.

2. The Model

As in Asheim et al. (2006) and Froyn and Hovi (2008), we consider n, $n \geq 2$ identical countries. At time period t, $t = 1, 2, ...$, every country decides whether it should reduce its pollutant emissions. Denote $\{C, D\}$ a country's action set at each time period, where C represents *cooperate* (or emission reduction) and D represents *defect* (or no emission reduction). As assumed by Barrett (1999b), the periodic payoff for the country taking action C is $(dk-c)$ and the periodic payoff for the country taking action D is bk, if there are k countries participating in the environmental agreement and $(n-k)$ countries not participating in the agreement for $0 \leq k \leq n$. Here $c > 0$ represents the cost of emission reduction, and b and d are the marginal benefits of taking actions D and C, respectively. As in the previous studies, we assume $d \geq b > 0$.

The state space, S, of our dynamical system is accordingly a set containing the action profiles of all countries - that is, $S \equiv \{C, D\}^n$ with element $\vec{s} = (s_1, s_2, \ldots, s_n)$, where s_i is the action adopted by country i, $i = 1, 2, \ldots, n$. For simplicity, let labels $\vec{C} = (C, C, \ldots, C)$ and $\vec{D} = (D, D, \ldots, D)$ represent states where all countries choose C and D, respectively. At the beginning of each period, all countries' actions and payoffs (after mutation) in the last period are observable.

Our dynamical system consists of an imitation and a mutation parts in order. In the imitation process, we consider two rules often adopted in the literature of evolutionary games. First, as in Chen et al. (2013), each country is presumed to imitate the actions taken by other countries or itself yielding the highest average payoff (hereafter imitate-the-best-average). Given state $\vec{s} = (s_1, s_2, \ldots, s_n) \in S$ with k countries taking C at the beginning of time t, then $\bar{\pi}_i^C(\vec{s}) = (dk - c)$ and $\bar{\pi}_i^D(\vec{s}) = bk$ are the average payoffs for taking actions C and D among all countries after the game is played at time t for $i = 1, \ldots, n$. Thus, denote $\bar{r}_i(\vec{s})$ country i's boundedly rational choice (before mutation) if the previous state is $\vec{s}$ by

$$\bar{r}_i(\vec{s}) \in \bar{M}_i(\vec{s}) \stackrel{\text{def}}{=} \arg \max_{E \in \{C, D\}} \bar{\pi}_i^E(\vec{s}) \quad \text{for } i = 1, 2, \ldots, n. \tag{1}$$

No ambiguity occurs when $\bar{M}_i(\vec{s})$ is a singleton. If $\bar{M}_i(\vec{s}) = \{C, D\}$, then all countries are assumed to stick to their original actions due to inertia. Let $\bar{r}(\vec{s}) = (\bar{r}_1(\vec{s}), \ldots, \bar{r}_n(\vec{s}))$ represent the action profile of all countries' boundedly rational choices under the imitate-the-best-average rule. Second, as in Chen et al. (2012), each country is assumed to imitate the actions earning the highest total payoff (hereafter imitate-the-best-total). Given state $\vec{s} = (s_1,\ s_2, \ldots, s_n) \in S$ with k countries taking action C at the beginning of time t, then $\pi_i^C(\vec{s}) = k(dk - c)$ and $\pi_i^D(\vec{s}) = bk(n-k)$ are the total payoffs for taking actions C and D among all countries after the game is played at time t for $i = 1, \ldots, n$. Thus, denote country i's boundedly rational choice (before mutation) if the previous state is $\vec{s}$ by

$$r_i(\vec{s}) \in M_i(\vec{s}) \stackrel{\text{def}}{=} \arg \max_{E \in \{C,\ D\}} \pi_i^E(\vec{s}) \ \text{ for } i = 1,\ 2, \ldots, n. \tag{2}$$

Again, if $M_i(\vec{s}) = \{C, D\}$, then all countries are assumed to stick to their original actions. Let $r(\vec{s}) = (r_1(\vec{s}), \ldots, r_n(\vec{s}))$ represent the action profile of all countries' boundedly rational choices under the imitate-the-best-total rule.

After completing the imitation process, all countries will independently alter their rational choices with identical probability $\epsilon > 0$, which is called the mutation rate, at the end of each period. The mutation rate can be regarded as the probability of a country experimenting with new actions or making some errors. Accordingly, our dynamical system associated with the imitate-the-best-average rule defines a Markov chain $\{X_t : t = 0, 1, ...\}$ on S with probability transition matrix Q_ϵ, which is a perturbation of Q_0 and given by $Q_\epsilon(\vec{s}, \vec{u}) \approx \text{constant} \cdot \epsilon^{U(\vec{s},\vec{u})}$ for any $\vec{s}, \vec{u} \in S$, where $U(\vec{s}, \vec{u}) = \min_{\bar{r}(\vec{s})} d(\bar{r}(\vec{s}), \vec{u})$ and $d(\bar{r}(\vec{s}), \vec{u}) = |\{i \in \{1,\ 2, \ldots, n\} : \bar{r}_i(\vec{s}) \neq u_i\}|$ counts the total number of country i revising its rational choice $\bar{r}_i(\vec{s})$ at state $\vec{s}$. Alternatively, $U(\vec{s}, \vec{u})$ can be regarded as the cost of jumping from $\vec{s}$ to $\vec{u}$. Similarly, the dynamic system associated with the imitate-the-best-total rule is also a Markov chain with the same probability transition matrix as the above but $U(\vec{s}, \vec{u}) = \min_{r(\vec{s})} d(r(\vec{s}), \vec{u})$ and $d(r(\vec{s}), \vec{u}) = |\{i \in \{1,\ 2, \ldots, n\} : r_i(\vec{s}) \neq u_i\}|$.

Introducing mutation makes our dynamical system $\{X_t\}$ become ergodic. Let μ_ϵ

be the associated unique invariant distribution, which is independent of the initial distribution and characterized by

$$\mu_\epsilon = \mu_\epsilon \cdot Q_\epsilon. \tag{3}$$

We are interested in the limit invariant distribution $\mu_* \overset{\text{def}}{=} \lim_{\epsilon \to 0} \mu_\epsilon$ and its support

$$S_* \overset{\text{def}}{=} \{\vec{s} \in S \ : \ \mu_*(\vec{s}) > 0\}. \tag{4}$$

Elements in S_* are called stochastically stable states or long-run equilibria (hereafter LRE). Moreover, we are interested in the order estimate of $E(T_\epsilon)$, where

$$T_\epsilon = \inf\{t \geq 0 : X_t \in S_*\} \tag{5}$$

is the first time that $\{X_t\}$ hits S_* with, say, the initial X_0 uniformly distributed on S.

By letting $\epsilon \downarrow 0$ in (3), we obtain $\mu_* = \mu_* Q_0$. Thus,

$$S_* \subseteq S_0, \tag{6}$$

where $S_0 \equiv \{s \in S \mid [\lim_{t\to\infty} \mu(Q_0)^t](s) > 0$ for some probability distribution μ over $S\}$ is the set collecting limit states of $(S,\ Q_0)$. Equation (6) indicates that we need to characterize S_0 before finding S_*. Moreover, we will adopt Ellison's (2000) Radius and Modified Coradius Theorem to find S_* defined in (4) and $E(T_\epsilon)$ defined in (5).

3. The Results

Given the imitating-the-best-average rule and state $\vec{s} = (s_1,\ s_2, \ldots, s_n) \in S$ with k countries taking action C at the beginning of time period t, we have

$$\bar{\pi}_i^C(\vec{s}) = (dk - c) \geq \ (\leq)\ \bar{\pi}_i^D(\vec{s}) = bk \ \text{ iff } \ k \geq \ (\leq)\ \frac{c}{d-b} \tag{7}$$

for $d > b,\ k > 0$, and $i = 1, \ldots, n$. Conditions in (7) suggest that all countries will take action C if the number of countries participating in the agreement (k) is large, and will take action D if k is small. Denote $\bar{\delta} = \lceil \frac{c}{d-b} \rceil$ the smallest integer no less than $\frac{c}{d-b}$, which measures a country's efficiency in term of its emission reduction cost (c) relative to the net benefit of the reduction ($d - b$). The smaller is $\bar{\delta}$, the larger is the efficiency of emission reduction for a country. By contrast, if $d = b$ or $k = 0$, we have $\bar{\pi}_i^C(\vec{s}) < \bar{\pi}_i^D(\vec{s})$ for $i = 1, \ldots, n$. That is, all countries should take action D when the marginal benefits of emission reduction and no reduction are equal or when no country takes action C. Based on the above, country i's boundedly rational choice (before mutation) given the previous state $\vec{s}$ is

$$\bar{r}_i(\vec{s}) = \begin{cases} C & \text{if } k \geq \bar{\delta} \\ D & \text{if } k < \bar{\delta} \end{cases} \tag{8}$$

if $d > b$, and is $\bar{r}_i(\vec{s}) = D$ if $d = b$ for $i = 1,\ 2, \ldots, n$.

Given the imitating-the-best-total rule and state $\vec{s} = (s_1,\ s_2, \ldots, s_n) \in S$ with $k \geq 0$ countries taking action C at the beginning of time period t, we have

$$\pi_i^C(\vec{s}) = k(dk - c) \geq\ (\leq)\ \pi_i^D(\vec{s}) = bk(n-k) \ \text{ iff }\ k \geq\ (\leq)\ \frac{nb+c}{d+b}. \tag{9}$$

Conditions in (9) suggest that all countries will take action C if the number of countries participating in the agreement (k) is large, and will take action D if k is small. Denote $\delta = \lceil \frac{nb+c}{d+b} \rceil$ the smallest integer no less than $\frac{nb+c}{d+b}$. Then, country i's boundedly rational choice (before mutation) given the previous state $\vec{s}$ is

$$r_i(\vec{s}) = \begin{cases} C & \text{if } k \geq \delta, \\ D & \text{if } k < \delta. \end{cases} \tag{10}$$

By analyzing (8), we can obtain the following.

Proposition 1. *Suppose that S_* and T_ϵ are defined in (4) and (5) respectively, and the imitate-the-best-average rule in (1) holds.*

(i) *If $b = d$, then $S_* = \{\vec{D}\}$ and $E(T_\epsilon) \approx 0$.*

(ii) *If $b < d$ and $\bar{\delta} = \lceil \frac{c}{d-b} \rceil$, then we have the following.*

(iia) *If* $\bar{\delta} < \frac{n+1}{2}$, *then* $S_* = \{\vec{C}\}$ *and* $E(T_\epsilon) \approx \epsilon^{-\bar{\delta}}$.

(iib) *If* $\bar{\delta} = \frac{n+1}{2}$, *then* $S_* = \{\vec{C},\ \vec{D}\}$ *and* $E(T_\epsilon) \approx \epsilon^{-\bar{\delta}}$.

(iic) *If* $\bar{\delta} > \frac{n+1}{2}$, *then* $S_* = \{\vec{D}\}$ *and* $E(T_\epsilon) \approx \epsilon^{-(n-\bar{\delta}+1)}$.

Proof. See the Appendix.

Proposition 1 shows that whether an international environmental agreement with full participation can be a long run equilibrium depends on efficiency of the participating countries in reducing pollutant emissions ($\bar{\delta}$) and the number of participants (n). If the marginal benefits of emission reduction and no reduction are equal, i.e., $b = d$, then all countries will choose action D because $\bar{\pi}_i^C(\vec{s}) = (bk - c) < \bar{\pi}_i^D(\vec{s}) = dk$ for all $\vec{s} \in S$ and $i = 1, \ldots n$. Thus, even some countries may choose action C by mistakes or experiments, they will not stick to C due to its lower payoff. Obviously, all countries taking action D will be the LRE. That is what Proposition 1(i) displays. By contrast, if the marginal benefit of emission reduction is greater than that of no reduction, we could have $\vec{C}$ only, $\vec{D}$ only, or both $\vec{C}$ and $\vec{D}$ being the long run equilibrium. They are explained below.

Note that the stochastically stable equilibria are the states which are hard to jump out from their basin of attraction, but other limit states can enter their basin of attraction easily. The minimum number of mutations needed to enter the basin of attraction of $\vec{C}$ from $\vec{D}$ is $\bar{\delta}$, while the minimum number of mutations needed to enter the basin of attraction of $\vec{D}$ from $\vec{C}$ is $(n-\bar{\delta}+1)$. Thus, if a country's emission reduction is efficient or $\bar{\delta}$ is small with $\bar{\delta} < \frac{n+1}{2}$, then $\vec{C}$ will be the unique LRE because it is easy to enter but hard to leave. This is what Proposition 1(iia) exhibits. By contrast, if $\bar{\delta} > \frac{n+1}{2}$, then $\vec{D}$ will be the unique LRE because it is easy to enter but hard to leave. This is the content of Proposition 1(iic). However, if $\bar{\delta} = \frac{n+1}{2}$, both $\vec{C}$ and $\vec{D}$ will be the LRE because both states can communicate with each other at the same cost. This suggests that both states will be visited with positive probability in the long run. This is what Proposition 1(iib) proves.

Proposition 1 also provides convergence rates to all LRE. The convergence rates depend on a country's efficiency in reducing emissions and the number of participating countries. For instance, if the LRE is $\vec{C}$ as shown in Proposition 1(iia), the convergence rate is of order $\epsilon^{-\bar{\delta}}$. Thus, the larger $\bar{\delta}$ is or the less efficient in reducing emissions is, the more time is needed for countries to coordinate at $\vec{C}$. Similarly, if the LRE is $\vec{D}$ as shown in Proposition 1(iic), the convergence rate is of order $\epsilon^{-(n-\bar{\delta}+1)}$. Accordingly, the larger is n or the smaller is $\bar{\delta}$, the more time is needed for countries to coordinate at $\vec{D}$.

It is worthy to compare our results with those in previous studies. First, Proposition 1 demonstrates that the threshold of efficiency in reducing emissions is $\frac{n+1}{2}$. This implies that an agreement with full participation is more likely to survive in the long run as the number of involved countries increases, because more mutations are needed to deviate from participating to non-participating but the minimum number of mutations required to deviate from non-participating to participating is unchanged. Thus, an agreement with full participation ($\vec{C}$) may emerge in the long run. This is different from the finding of Barrett (1999), in which participating countries are stable only if they are a few. Second, unlike Breton et al. (2010), our LRE are independent of the initial number of participating countries. Even no country participates in the beginning, all countries may eventually coordinate in an agreement due to the existence of mutations in the long run if emission reduction of the countries is efficient. Third, unlike McGinty (2010), we provide an condition for environmental agreements with full participation to exist when all countries are symmetric.

On the other hand, the efficiency of emission reduction, $\bar{\delta}$, is affected by the marginal benefits of the reduction and no reduction as well as the cost of emission reduction. The relationship is summarized below.

Lemma 1. *Suppose that the imitate-the-best-average rule in (1) holds and* $\bar{\delta} = \lceil \frac{c}{d-b} \rceil$. *Then, we have* $\frac{\partial \bar{\delta}}{\partial b} = \frac{c}{(d-b)^2} > 0$, $\frac{\partial \bar{\delta}}{\partial c} = \frac{1}{(d-b)} > 0$, $\frac{\partial \bar{\delta}}{\partial d} = \frac{-1}{(d-b)^2} < 0$, *and* $\frac{\partial \bar{\delta}}{\partial n} = 0$.

Lemma 1 suggests that participating countries are more likely to be stable in the long run if the marginal benefit of emission reduction (d) increases, the marginal benefit of no emission reduction (b) decreases, or the emission cost decreases (c). Under these circumstance, the payoff for countries to reduce emissions will rise, and they are more willing to cooperate. However, the number of participating countries will not affect the efficiency of emission reduction.

By analyzing (10), we can obtain outcomes associated with the imitate-the-best-total rule below.

Proposition 2. *Suppose that S_* and T_ϵ are defined in (4) and (5) respectively, the imitate-the-best-total rule in (2) holds, and $\delta = \lceil \frac{nb+c}{d+b} \rceil$.*
(a) *If $\delta < \frac{n+1}{2}$, then $S_* = \{\vec{C}\}$ and $E(T_\epsilon) \approx \epsilon^{-\delta}$.*
(b) *If $\delta = \frac{n+1}{2}$, then $S_* = \{\vec{C},\ \vec{D}\}$ and $E(T_\epsilon) \approx \epsilon^{-\delta}$.*
(c) *If $\delta > \frac{n+1}{2}$, then $S_* = \{\vec{D}\}$ and $E(T_\epsilon) \approx \epsilon^{-(n-\delta+1)}$.*
Proof. The proofs are similar to Proposition 1's, and thus omitted.

As in Proposition 1, all countries' long run behaviors depend on δ and n. The smaller δ is, the more likely all countries' participation occurs in the long run. However, unlike Proposition 1, as the number of involved countries increases, whether their participation could be the LRE is uncertain. To explain this, we first summarize the impacts of b, d, c, and n on δ below.

Lemma 2. *Suppose that the imitate-the-best-total rule in (2) holds and $\delta = \lceil \frac{nb+c}{d+b} \rceil$. Then, we have $\frac{\partial \delta}{\partial b} = \frac{nd-c}{(d+b)^2} > 0$, $\frac{\partial \bar{\delta}}{\partial c} = \frac{1}{(d+b)} > 0$, $\frac{\partial \delta}{\partial d} = \frac{-(nb+c)}{(d+b)^2} < 0$, and $\frac{\partial \delta}{\partial n} = \frac{b}{d+b} > 0$.*

The impacts of b, d, and c on δ are the same as their qualitative influences on $\bar{\delta}$ displayed in Lemma 1. However, unlike Lemma 1, δ will increase as the number of participating countries increases. This suggests that more mutations are needed to jump out of the basin of attraction of $\vec{D}$ to $\vec{C}$ when n increases. The minimum number of mutations needed to leave the basin of attraction of $\vec{C}$ increases as well due to rising

δ. Thus, the net effect of increasing n on the LRE is uncertain.[1]

Finally, we like to explore how different imitation rules affect the LRE. By some calculations, we get

$$\frac{c}{(d-b)} - \frac{nb+c}{(d+b)} = \frac{b[2c-n(d-b)]}{(d^2-b^2)} \geq\ (\leq)\ 0 \text{ iff } \frac{c}{(d-b)} \geq\ (\leq)\ \frac{n}{2}. \tag{11}$$

Thus, if $\bar{\delta} = \lceil \frac{c}{d-b} \rceil < \frac{(n+1)}{2}$, we have $\bar{\delta} \leq \delta$ for large n by (11). Countries are more likely to participate if the imitate-the-best-total rule is adopted. By contrast, if $\bar{\delta} = \lceil \frac{c}{d-b} \rceil \geq \frac{(n+1)}{2}$, then $\bar{\delta} > \delta$ by (11). Thus, countries are more likely to participate if the imitate-the-best-average rule is employed. These results are summarized below.

Lemma 3. *Given the imitating-the-best-average rule in (1) and the imitating-the-best-total rule in (2), we have the following.*
(i) *If* $\bar{\delta} < \frac{n+1}{2}$, *then countries are more likely to participate under the imitate-the-best-total rule.*
(ii) *If* $\bar{\delta} \geq \frac{n+1}{2}$, *then countries are more likely to participate under the imitate-the-best-average rule.*

4. Conclusions

This paper investigates whether an environmental agreement with countries' full participation can survive in the long run when these participants are boundedly rational. Two imitation rules are assumed. Under the first rule, countries are assumed to imitate the actions yielding the highest average payoff. We find that all countries will coordinate to decrease pollutant emissions in the long run if the action to reduce emissions is efficient enough. By contrast, they will all agree not to decrease emissions in the long run if the reducing action is inefficient. Similar outcomes appear under

[1]Since $\frac{\partial \delta}{\partial n} = \frac{b}{d+b} > 0$ and $\frac{\partial (\frac{n+1}{2})}{\partial n} = \frac{1}{2} > 0$, relative sizes of $\frac{b}{d+b}$ and $\frac{1}{2}$ will determine the net effect of changing n on the LRE.

the second rule, which presumes that countries imitate the actions yielding the highest total payoff. In addition, this paper provides the convergence rates to all LRE, which are affected by the efficiency of countries in reducing emissions as well as the number of participating countries. We also investigate how countries' long run behaviors are affected by different imitation rules and model's parameters, such as marginal benefits and costs of emission reduction.

Different from previous works, our results give an alternative theoretical support for international environmental agreements with full participation from the viewpoint of boundedly rational countries, which are often observed in the real world. It will be interesting to extend our model to consider the ancillary benefits of emission reduction, asymmetric countries, the R&D spillover effect, or some regional environmental agreements in the future.

Appendix

Proof of Proposition 1: We will adopt Ellison's (2000) radius and co-radius method to find S_* and ET_ϵ. Before reciting Ellison's (2000) outcomes, two notations are introduced following Vega-Redondo (2003).

Definition 1: Let V be a union of limit sets of the unperturbed Markov process $(S,\ Q_0)$. The radius of V is

$$R(V) \equiv \min_{(\omega,\ \omega')\in V\times(S_0\setminus V)} \hat{c}(\omega,\ \omega'),$$

where $\hat{c}(\omega,\ \omega')$ is the cost of transferring from state ω to state ω'.

This indicates that the radius of any set V is the minimum cost involved in moving out of V.

Definition 2: Given V, the co-radius of V is

$$CR(V) \equiv \max_{\omega\in S_0\setminus V}\ \min_{\omega'\in V}\ \hat{c}(\omega,\ \omega').$$

This means that the co-radius of any set V is the maximum of all minimum costs moving from other limit states to V.

Then, Ellison (2000) shows the following.

Theorem A: If $R(V) > CR(V)$, then $S_* \subset V$. In addition, as $\epsilon \downarrow 0$, the maximum expected waiting time to visit set V, $E(T_\epsilon)$, grows with the same order as $\epsilon^{-CR(V)}$.

Based on Theorem A, we can derive S_* and $E(T_\epsilon)$ in our model. First, if $b = d$, we always have $\bar{r}_i(\vec{s}) = D$ for $i = 1,\ 2, \ldots, n$. Thus, $S_0 = \{\vec{D}\}$. As shown by (6), we have $S_* = \{\vec{D}\}$ and $E(T_\epsilon) = \epsilon^{-\infty} = 0$. These prove Proposition 1(i). Second, suppose $d > b$. Since all countries follow the same action updating rule given in (8) over time, we will have the limit set of unperturbed process $S_0 = \{\vec{C},\ \vec{D}\}$. Under the circumstance, deriving $R(\vec{C})$ and $CR(\vec{C})$ is equivalent to deriving how states $\vec{C}$ and $\vec{D}$ can transfer to each other at the minimum cost.

Conditions in (8) show that all countries will choose C (D) if the number of participating countries k is large (small) with $k \geq \bar{\delta}$ $(k < \bar{\delta})$. Thus, we have $CR(\vec{C}) = \bar{\delta}$, because all countries will shift from state $\vec{D}$ to $\vec{C}$ when there are at least $\bar{\delta}$ countries deviating from $\vec{D}$ by taking action C. In contrast, we have $R(\vec{C}) = n - \bar{\delta} + 1$ because all countries will shift from state $\vec{C}$ to $\vec{D}$ when there are at least $(n - \bar{\delta} + 1)$ countries deviating from $\vec{C}$ by taking action D. Thus, if $CR(\vec{C}) < R(\vec{C})$ or $\bar{\delta} < \frac{n+1}{2}$, we will get $S_* = \{\vec{C}\}$ and $E(T_\epsilon) \approx \epsilon^{-CR(\vec{C})} = \epsilon^{-\bar{\delta}}$ by Theorem A. These prove Proposition 1(iia). Similarly, we have $CR(\vec{D}) = (n - \bar{\delta} + 1)$ because all countries will shift from state $\vec{C}$ to $\vec{D}$ as there are at least $(n - \bar{\delta} + 1)$ countries deviating from $\vec{C}$ by taking action D. In contrast, we have $R(\vec{D}) = \bar{\delta}$ because all countries will shift from state $\vec{D}$ to $\vec{C}$ as there are at least $\bar{\delta}$ countries deviating from $\vec{D}$ by taking action C. Thus, if $CR(\vec{D}) < R(\vec{D})$ or $\bar{\delta} > \frac{n+1}{2}$, we will get $S_* = \{\vec{D}\}$ and $E(T_\epsilon) \approx \epsilon^{-CR(\vec{D})} = \epsilon^{-(n-\bar{\delta}+1)}$. These prove Proposition 1(iic). However, if $\bar{\delta} = \frac{n+1}{2}$, we will get $S_* = \{\vec{D},\ \vec{D}\}$ and $E(T_\epsilon) \approx \epsilon^{-\bar{\delta}}$. These prove Proposition 1(iib).

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