Literature Review of Repeated Game Analyses on International Environmental Agreements

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Literature Review of Repeated Game Analyses on International Environmental Agreements

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Abstract

This study reviews existing research using repeated games to analyze long-term international environmental agreements (IEAs), focusing on the issue of deviations. Several studies have examined the effectiveness of IEAs and the conditions of a stable agreement. Models of cooperation for climate control can be divided roughly into two groups: reduced-stage game models, and repeated game models. A considerable number of studies address the formation of stable IEAs in reduced-stage game models. Few studies examine the formation of agreements in repeated game models, which should be paid more attention. Therefore, this study reviews the literature on IEAs, focusing on repeated games, and describes the equilibrium concept and strategies of repeated game models.

Keywords: international environmental agreements; subgame perfect; renegotiation-proof; repeated game

1 International environmental agreement

Countries' local environmental problems, such as air pollution due to automobiles and power generation, can be addressed by their respective governments. However, no supranational authority exists to resolve trans-boundary environmental problems. In addition, an abatement action by a country can affect other countries, because, in general, a reduction in pollution has the characteristics of a public good. For these reasons, each country must enter into negotiations on emission reductions and conclude IEAs.

In order to address this challenge analytically, a considerable body of literature studies the provision of global international pollution control. Models of IEAs can be divided roughly into two groups: reduced-stage game models, and repeated game models.[1)] The difference between reduced-stage and repeated game models is the stability concept they employ and their assumptions on compliance of cooperation.

1) Asheim et al. (2006) divide the models of cooperation for climate control into reduced-stage game models and repeated game models.

Reduced-stage game models (in the sense of Asheim et al., 2006) depict the formation of agreements as a two-stage game. In the first stage, countries decide whether to sign an IEA. In the second stage, the signatories choose the abatement levels jointly, while each non-signatory decides on its abatement levels independently (e.g., Barrett, 1994, 2001; Carraro and Siniscalco, 1993; Finus and Rübbelke, 2013; van der Pol et al., 2012).[2] Barrett (1994) and Carraro and Siniscalco (1993) show that an agreement that can significantly improve global welfare is sustained if entered into by a few countries. In summary, these studies indicate how difficult it is to forge a grand coalition with effective abatement levels and full participation within a reduced-stage game framework.

However, if the game is repeated, an equilibrium wherein every country cooperates with effective abatement levels can be achieved through the threat of punishment.[3] In repeated game models, the agreement should be sustained as an outcome of a weakly renegotiation-proof (WRP) equilibrium.[4] However, there is limited literature examining the cooperative relationship between countries in a repeated game framework (e.g, Asheim et al., 2006; Asheim and Holtsmark, 2009; Barrett, 1999, 2002, 2003; Finus and Rundshagen, 1998; Froyn and Hovi, 2008; Heitzig et al., 2011; Kratzsch et al., 2012).[5]

In repeated game models, the agreement is enforced by the strategy that specifies the countries' behavior. It must be in the best interest of each country to act in accordance with the strategy individually (i.e., the subgame perfection requirement). Additionally, in such an agreement, a renegotiation must be prevented (i.e., the renegotiation-proofness requirement). In particular, it must be in the best interest of punishing countries to punish a non-compliant country collectively before a cooperative relationship is restarted. If these requirements are satisfied, the IEA is sustained as an outcome of a WRP equilibrium. That is, the types of IEAs that can be achieved depend on the contents of the strategy.

Barrett (2002) demonstrates that a full participation agreement can be sustained, by limiting the per-country abatement level (a consensus treaty). Asheim et al. (2006) present the *Regional Penance* strategy, which permits the same types of countries as the deviator to punish non-compliance, to sustain the two regional agreements. The results of Asheim et al. (2006) show that participation can be doubled in a two-region world. Froyn and Hovi (2008) achieve all countries' participation, while observing effective abatement levels by proposing a strategy called *Penance-m,* which limits the number of countries allowed to punish a deviation.

In reality, several IEAs have been implemented. The Montreal Protocol, which took effect in 1989,

2) Some studies consider a three (or more)-stage game (e.g., Barrett, 1997; Fujita, 2013; Kosfeld et al., 2009; Osmani and Tol, 2010; Rubio and Ulph, 2006).

3) Punishment in repeated games means that the signatories stop their abatement action. For more details, see Asheim and Holtsmark (2009) and Barrett (2003, Chapter 10).

4) WRP is defined as a condition where there exists no other equilibrium in which each player can increase his benefits simultaneously (Farrell and Maskin, 1989, pp.330–331).

5) Hovi et al. (2015) categorize the studies of Asheim et al. (2006), Asheim and Holtsmark (2009), Barrett (1999, 2002, 2003), and Froyn and Hovi (2008) as those that demonstrate IEA formation in a repeated game framework.

regulates the use of chemicals such as chlorofluorocarbons (CFCs) that deplete the stratospheric ozone layer. The agreement achieved universal ratification, and participants must reduce the production and consumption of ozone-depleting substances. The Montreal Protocol succeeded because promised cuts in emission were implemented, keeping more countries ratified in the agreement. The Helsinki Protocol was adopted in 1985. Like the Montreal Protocol, it established targets for cutting atmospheric emissions of pollutants. Each signatory was required to reduce emissions of sulfur oxides by at least 30 percent from the 1980 level by 1993. However, the agreement failed to achieve full participation.

The Kyoto Protocol, established at the third conference of the parties (COP3) in 1997, compels approximately 40 developed countries (Annex I countries in the UNFCCC) to reduce GHG emissions. An example of an IEA that has achieved regional cooperation is the European Climate Change Programme, launched by the European Union (EU) in 2000 to coordinate the reduction of GHG emissions, including an emission trading scheme within the EU. Additionally, there is speculation that the United States is interested in a regional agreement for climate change that would include NAFTA members (Canada, Mexico, and the United States), which could be facilitated by the North American Commission on Environmental Cooperation. For IEAs achieving full participation, a new basic framework aimed at the prevention of global warming was compiled during COP21, held in Paris, France, in 2015. The framework's scope is to uphold and promote regional and international cooperation in order to mobilize stronger and more ambitious climate action by all parties and non-party stakeholders.[6)]

In general, an agreement is implemented for a long-term period and, thus, needs to address the issue of deviations.[7)] Therefore, this study introduces researches that use a repeated game framework for long-term agreements with a severe punishment clause and enforcement rules. Recently, much attention has been given to coalition formation in IEAs, although few studies investigate stable IEA formation in a repeated game framework. Hovi et al. (2015) review formal models of IEAs for international cooperation from economics and political science. We focus on the introduction of the strategy, which is a significant concept for cooperative relationships in repeated games.

The remainder of the paper is structured as follows. Section 2 presents the analytical frameworks of IEAs and describes the equilibrium concept in a repeated game. Section 3 introduces the basic strategies with two players in repeated game frameworks, and Section 4 describes the strategies with n players presented by previous studies in such frameworks. The final section provides our concluding remarks and describes possible areas of future research.

6) For more details, see UNFCCC (2016).

7) As examples of "a long-term period," the Kyoto Protocol and Montreal Protocol are implemented for multi-year periods. As an example of a "deviation," the United States has deviated from the Kyoto Protocol.

2 Theoretical analyses of IEAs in game theory

2.1 The reduced-stage game models

This subsection introduces the analyses of IEAs based on the reduced-stage game. In this game, the stable agreement is referred to as self-enforcing. Self-enforcing IEAs must have two characteristics. First, no signatory should have an incentive to defect from the agreement (internal stability). Second, no non-signatory should have an incentive to join the agreement (external stability).

We consider the following game. In the first stage, each country decides whether to sign an IEA. In the second stage, the signatories decide the abatement levels jointly, and each non-signatory decides their abatement levels independently. The net benefit is expressed as a function of the abatement levels.

As stated in Section 1, several studies have been conducted on the formation of stable IEAs that use reduced-stage game models.[8)] Barrett (1994) and Carraro and Siniscalco (1993) show that only a small coalition of countries can significantly improve global welfare. That is, if there are many countries in an agreement, this would never lead to a significant improvement in global welfare. Thus, there is no point in forming such agreements. Barrett (1997) analyzes the links between policies for climate control and international trade in segmental markets. Barrett (1997) shows that the credible threat of trade sanctions can sustain full cooperation in terms of emission reductions on the condition of a minimum participation clause, which restricts the lower bound number of participants. Barrett (2001) reveals that strong asymmetry among countries warrants a change in the rules of the game of global public goods provision. Furthermore, side payments increase participation in a cooperative agreement when some countries are effectively committed to being non-signatories to an agreement, eschewing money transfers.

Finus and Rübbelke (2013) categorize the benefits of abatement into large-scale and regional benefits. The latter are ancillary benefits that can be received privately, and their effect on IEA participation can be examined. Finus and Rübbelke (2013) hold the pessimistic view that an agreement can be sustained if entered into by a few countries, and that these benefits have a neutral or negative impact on the number of signatories. Osmani and Tol (2010) assume two types of asymmetric countries, and demonstrate similarities between one and two self-enforcing IEAs. If a coalition is formed by a few countries, and these countries have smaller benefits and higher costs from pollution abatement, two IEAs show greater improvements in abatement and welfare than in the case of one IEA. van der Pol et al. (2012) consider two types of altruism, namely impartial and community altruism, in the decision to participate. Their results show that a certain degree of altruism is sufficient to stabilize the agreement. Fujita (2013) incorporates "matching schemes," in which all signatories commit to additional abatement, depending on other countires' abatement decisions, and shows the existence of a self-enforcing agreement leading to an efficient and equitable outcome.

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8) With regard to climate change, the reduced-stage game is used in international policies, such as IEAs, and in domestic environmental policies; for instance, see Ouchida and Goto (2014, 2016).

Calcott and Petkov (2012) and Biancardi and Villani (2010) consider monetary transfers in IEA formation in a reduced-stage game. Biancardi and Villani (2010) consider IEA formation in a static model, while Calcott and Petkov (2012) consider IEA formation in an infinite-horizon game model, which is an infinite-horizon version of the static IEA model. Rubio and Ulph (2007) study IEAs involving stock pollutants using the infinite-horizon model, where each country freely chooses to join or leave the agreement, and signatories commit themselves to an infinite-horizon path of emissions.

2.2 Repeated game models

Reduced-stage game models assume that the signatories to an IEA are bound by the agreement. However, if the possibility of a deviation is considered, the cooperative relationship among countries cannot be sustained. There can be situations in which some signatories can increase their benefits by free riding on the abatement levels of others after the conclusion of the IEA, and not be punished by the other signatories. Thus, non-cooperative behavior is a dominant strategy in the one-shot prisoner's dilemma game. However, if the game is repeated, an equilibrium in which every country cooperates can be reached through the threat of punishment.[9] This type of game is described as a repeated game. Punishment in a repeated game means that the signatories stop their abatement. Repeated game models assume that the game is repeated infinitely, and countries participating in the IEA have to be enforced in subsequent stages using credible threats (e.g., Asheim et al., 2006; Asheim and Holtsmark, 2009; Froyn and Hovi, 2008).

Here, we seek a condition in which all signatories exhibit cooperative behavior in a WRP equilibrium. To be WRP, the strategy must satisfy two requirements for IEAs. The first is that the strategy profile must be subgame perfect. This requires that no player can gain from a one-period deviation after any history. We know from the theory of repeated games with discounting that if a player cannot gain from a one-period deviation, then he/she cannot gain from a multi-period deviation (Abreu, 1998, p. 390). Hence, we need only check that no player can gain from a one-period deviation after any history.

The second requirement is that the strategy profile must be renegotiation-proof. This requirement is fulfilled if not all players strictly gain by collectively restarting cooperation at once, instead of carrying out the threatened punishment when a deviation has occurred in the previous period. That is, the punishing countries select the punishment if the collective payoff is higher when punishing the deviator than it is when returning to cooperation through renegotiation.

Barrett (1999, 2002) shows that only a less ambitious agreement can attain full participation by presenting a *consensus treaty*. The *Regional Penance* strategy proposed by Asheim et al. (2006) permits the same types of countries as the deviator to punish non-compliance in order to sustain the agreement. The result of Asheim et al. (2006) shows that two regional agreements can sustain more than twice the number of

9) The punishment in repeated games means that the signatories stop their abatement action. For more details, see Asheim and Holtsmark (2009) and Barrett (2003, Chapter 10).

participants that one agreement can. However, the condition to attain such agreements is severe. That is, two asymmetric agreements cannot be implemented as a WRP equilibrium.[10] Froyn and Hovi (2008) present the *Penance-m* strategy, which limits the number of countries that can punish a deviator, in order to show the feasibility of a stable agreement with full participation and efficient abatement levels. Asheim and Holtsmark (2009) also adopt the *Penance-m* strategy, and show an efficient time lag between the deviation and punishment in the case of a full participation agreement. Heitzig et al. (2011) propose an enforcement system based on a simple dynamic strategy of linear compensation. This strategy redistributes abatement obligations according to past compliance levels, while keeping the total abatement level constant across periods.

As Hovi et al. (2015, p.675) point out, all models considered thus far treat emissions as a flow variable. Thus, these models assume that emissions in a particular period have no lasting effect over time, and that the set of possible per-period payoffs remains constant over the entire repeated game. These assumptions are arguably implausible for applications to climate change cooperation. Kratzsch et al. (2012) assume that GHG emissions accumulate in the atmosphere over time, and that the current stock causes climate change. They show that broad, or even full participation can be achieved even when the model considers the amount of emitted gases to be a stock variable, depreciated slowly over time, and by adopting the *Penance-m* strategy. Such an agreement is easier to reach for long-lasting GHGs than it is for short-lived gases.

3 The basic strategy

This section introduces the basic strategies in the repeated game model of IEAs.[11] Suppose that two countries negotiate an agreement. Each country chooses to *cooperate* (i.e., accept abatement levels that maximize the coalition payoff) or to *defect* (i.e., accept abatement levels that maximize each country's individual payoff). Player i's payoff function is given by

$$\pi_i = b(q_1 + q_2) - cq_i,$$

where $q_i \in [0,1]$ is the abatement level of country $i\,(=1,2)$, b is the marginal benefit, c is the marginal cost, and cq_i represents the total abatement costs of country i. We assume that $2b > c > b > 0$, which means that each country cannot obtain their payoffs by unilateral abatement. If not, each country abates individually, irrespective of the agreement. We weight the future payoffs by a discount factor $\delta\,(0 < \delta < 1)$. The present value of the payoff gained in period t is the current value multiplied by δ^t.

3.1 Tit-For-Tat

The Tit-For-Tat strategy specifies that each player begins by choosing to *cooperate*, and continues to

10) See Asheim et al. (2006, p.99).

11) For the Grim and Tit-For-Tat, see Barrett (2003). For the characteristics of public goods in emission reduction, see Hanley et al. (2007).

play *cooperate* so long as the other player played *cooperate* in previous period. That is, each player takes the same action as the other player did in the previous period. If a player plays *defect*, the other player plays *defect* in the next period. Only after the deviator has played *cooperate* will the other player return once again to playing *cooperate*. Moreover, if any player does not return to playing *cooperate*, he is punished by the other player.

Let there be two countries, X and Y, and suppose country Y deviates in period t and returns to Tit-For-Tat in period $t+1$. In returning to the Tit-For-Tat, Y plays the same action as X did in the previous period. Thus, in period $t+1$, Y will play *cooperate*. However, if X is playing Tit-For-Tat, it must choose to *defect* in period $t+1$ as punishment. Starting in period $t+1$, if X plays Tit-For-Tat, it will get

$$b\delta^{t+1} + (b-c)\,\delta^{t+2} + b\delta^{t+3} + (b-c)\,\delta^{t+4} + \cdots,$$

and if X deviates and returns to play *cooperate*, it obtains

$$(2b-c)\,(\delta^{t+1} + \delta^{t+2} + \delta^{t+3} + \delta^{t+4} + \cdots).$$

If the discount factor is close to 1, the average per-period payoff of playing Tit-For-Tat is $(2b-c)/2$, while the average par-payoff of deviation is $2b-c$. For sufficiently large discount factors, each country does not play the Tit-For-Tat strategy. In other words, the Tit-For-Tat strategy does not satisfy the subgame perfection requirement.

3.2 Grim strategy

According to Barrett (2003), the Grim strategy specifies that the two players pledge to play *cooperate*, and further agree that should either player play *defect* in any period, then both countries will revert to playing *defect* forever. We investigate whether this strategy can sustain full cooperation as an equilibrium outcome.

If both players comply fully with the strategy, each player plays *cooperate* in every period, and receives a payoff of $2b-c$ in each period. If one country deviates in period t, the deviator obtains a payoff of b in period t, but gets 0 at every period after period $t+1$.

Therefore, a full cooperation outcome is achieved as a subgame perfect equilibrium if

$$(2b-c)\,(\delta^{t} + \delta^{t+1} + \cdots) \geq b\delta^{t} + 0 + \cdots.$$

Solving for δ, we have

$$\delta \geq (c-b)\,/\,b.$$

Therefore, if δ is close to 1, the Grim strategy satisfies the subgame perfection.

However, if a country deviates unilaterally, this strategy does not satisfy the renegotiation-proofness requirement. If a player deviates in period t, then the average per-period payoff that the players receive after period t by choosing the Grim strategy is 0. If the players restart cooperation and re-institute the Grim strategy, each country receives a payoff of $2b-c$ in each period. Therefore, each country renegotiates and restarts the cooperative relationship.

4 The strategy with n players

This section introduces the strategies with n players and considers the condition that agreement is sustained as a WRP equilibrium. Consider a world with $n>2$ countries, and let $N=\{1, \cdots, n\}$ denote the set of all countries. Furthermore, suppose that $nb > c > b > 0$.

4.1 Getting-Even strategy with n players

The Getting-Even strategy demands that each country plays *cooperate* unless he/she has played *defect* less often than the other players have in the past. Suppose that all n countries agree to play Getting-Even, and one country (player j) deviates in period t, and then reverts to Getting-Even in period $t+1$.

First, we consider the incentive constraint for each country to play *cooperate* when there is no deviation in any period. Player j receives payoff $b(n-1)$ in period t, and payoff $b-c$ in the punishment period. From period $t+2$, the player receives $bn-c$. If player j plays *cooperate* in period t, he/she receives $bn-c+\delta(bn-c)$ in periods t and $t+1$. For player j, to play *cooperate* in accordance with the Getting-Even strategy is individually rational if

$$bn-c+\delta(bn-c) \geq b(n-1)+\delta(b-c).$$

Solving the above inequality for n, we have

$$n \geq (c-b+\delta b)/\delta b.$$

Assuming that δ is close (but not equal) to 1, we have

$$n \geq c/b. \tag{1}$$

Since $bn > c$, (1) always holds. It is rational for each player to play *cooperate*, in accordance with the Getting-Even strategy.

Second, we consider the incentive constraint for a deviator to follow Getting-Even and to play *cooperate* after a unilateral deviation in period t. Player j receives payoff $b-c$ in period $t+1$ and payoff $bn-c$ at subsequent periods if each player plays Getting-Even from $t+2$ onwards. If j does not return to Getting-Even in period $t+1$, and then reverts to Getting-Even in the next period, he/she receives a payoff of 0 in period $t+1$ and a payoff of $b-c$ in period $t+2$. For a deviator j, it is individually rational to play *cooperate* in period $t+1$, provided that

$$b-c+\delta(bn-c) \geq \delta(b-c). \tag{2}$$

Since $bn > c$, (2) is always satisfied.

Third, we consider the incentive constraint for country $i\,(\neq j)$ to punish deviator j. Player i receives payoff b in period $t+1$ and payoff $bn-c$ at subsequent periods if each player plays Getting-Even from $t+2$ onwards. If i fails to punish the deviator in period $t+1$, and then reverts to Getting-Even in next period, he/she receives payoff $2b-c$ in period $t+1$ and payoff $b(n-1)$ in period $t+2$.

For a punishing country i, it is individually rational to play *cooperate* in period $t+1$, provided that

$$b + \delta(bn - c) \geq 2b - c + \delta b(n-1). \tag{3}$$

Since $c > b$, (3) is always satisfied. From (1), (2), and (3), the Getting-Even strategy always satisfies the subgame perfection requirement.

If the countries other than j play Getting-Even in the punishment phase, they receive a payoff of b. If these countries return to a cooperative relationship, they receive $bn - c$. Thus, the renegotiation-proof requirement is satisfied if

$$b \geq bn - c.$$

Getting-Even satisfies the renegotiation-proof requirement, provided that

$$n \leq (c + b) / b. \tag{4}$$

If (4) is satisfied, all countries play *cooperate* in accordance with the Getting-Even strategy.

4.2 Consensus treaty

Barrett (1994) and Carraro and Siniscalco (1993) show that an agreement that can significantly improve global welfare is sustained if entered into by a few countries. This pessimistic result is largely caused by an assumption that the signatories take the abatement level that maximizes the coalition benefit collectively. Barrett (1999, 2002) has argued that there is a trade-off between “narrow, but deep” and “broad, but shallow” treaties: either only a few countries participate, each with an efficient and large abatement, or many countries participate, each with an inefficient and small abatement. In the Barrett (1999) model, each country has a binary choice between *cooperate* (i.e., abate emissions) or *defect* (no abatement). Barrett (1999) considers that there is a subset of signatories in a treaty, and a defecting signatory is punished by having all other signatories defect in the next period. Then, if there are too many signatories, these will gain by renegotiating a cooperative relationship without imposing the punishment, thereby undermining the credibility of the equilibrium. In Barrett’s (2002) model, each country has a continuum choice, and full participation (a “consensus treaty”) is achieved by allowing for variation in abatement levels, provided that the abatement levels are watered down. The consensus treaty specifies that (i) each country takes $q_i < 1$, unless another country has been the sole deviator from the consensus treaty in the previous period, and (ii) if a deviation occurs, the deviator takes the abatement level q_j, and the $n-1$ countries, other than the deviator, take q_m as punishment for the deviator.

The total benefit for country i consists of public benefits and private costs. The payoff for participation by country i is:

$$\pi_i = bQ - cq_i,$$

where b is the slope of the marginal benefit, and c is the slope of the marginal cost. The public good part of the benefits, bQ, depends on the total abatement, and the abatement cost, cq_i, depends on the individual abatement, q_i.[12) Here, $\bar{\pi}_S$ is the maximum payoff that can be sustained by the consensus treaty. The deviator j plays *cooperate* after a deviation if

$$b(n-1)q_m \leq \bar{\pi}_S. \tag{5}$$

The left-hand side of (5) is the payoff a deviator j can get by continued non-compliance. The right-hand side of (5) is the average payoff j will receive if he/she plays the strategy allowing a new cooperative relationship to be established. We can easily show that there is no incentive for one country to deviate when (5) holds and, thus, the consensus treaty is subgame perfect.

Next, we check for renegotiation-proofness. The $n-1$ punishing countries punish the deviator by choosing q_m, in accordance with the consensus treaty, if

$$b(q_j + (n-1)q_m) - cq_m \geq \bar{\pi}_S. \tag{6}$$

If $q_j = 1$, from inequalities (5) and (6), the abatement levels of punishing countries is

$$(\bar{\pi}_S - b)/(b(n-1)-c) \leq q_m \leq \bar{\pi}_S/(b(n-1)). \tag{7}$$

From (7), we have

$$\bar{\pi}_S \leq b^2(n-1)/c. \tag{8}$$

The right-hand side of (8) denotes that the maximum payoff when the consensus treaty is sustained as a WRP equilibrium.

4.3 The *Regional Penance* strategy

The *Regional Penance* strategy, proposed by Asheim et al. (2006), permits the same types of countries as the deviators to punish non-compliance in order to enforce the agreement. Let there be two regions, A and B. Their study reveals that two regional agreements can sustain more than twice the number of participants that one agreement can. However, full participation is not achieved. The content of the strategy is as follows.

(i) A participating country plays *cooperate*, except if another participating country in the same region has previously been the sole deviator from *Regional Penance*.
(ii) If deviation by a participating country in region A occurs, the punishment by participating countries in region A is meted out in the next stage, but is not meted out by those parties in region B, and vice versa.
(iii) If a deviator plays *cooperate* after a deviation, the cooperative relationship of each agreement will be restarted.

Asheim et al. (2006) obtain a WRP equilibrium to sustain two agreements as follows:

$$\begin{cases} (c-(d-b))k_B/d < k_A \leq b/d + (c-(d-b))k_B/d, \\ (c-(d-b))k_A/d < k_B \leq b/d + (c-(d-b))k_A/d, \end{cases}$$

where k_A and k_B denote the number of participating countries in regions A and B, d is the slope of the benefit

12) The expression of “public good part” is used in Finus and Rübbelke (2013).

function of a country playing *cooperate*, b is the slope of the benefit function of a country playing *defect*, and c denotes the cost of cooperation. For the proof, see Appendix A.

4.4 The *Penance-m* strategy

4.4.1 Froyn and Hovi's (2008) study

Froyn and Hovi (2008) show that a full participation agreement is formed as a WRP equilibrium using the strategy called *Penance-m* within the linear abatement benefit and cost functions. The main feature of *Penance-m* is to select $m\,(1 \leq m \leq n-1)$ punishing countries. *Penance-m* is specified as follows:[13)]

(i) Any signatory plays *cooperate*, unless another signatory has been the sole deviator from *Penance-m* in the previous period.
(ii) If a unilateral deviation occurs, m countries are selected from among the signatories, other than the deviator, and these m countries play *defect*. On the other hand, n-m countries play *cooperate*. Punishment in this case means that m punishing countries abandon their abatement actions.
(iii) If a deviator plays *cooperate* after a deviation, the cooperative relationship will be resumed afterwards.

Froyn and Hovi (2008) obtain a WRP equilibrium to sustain an agreement with full participation as follows (given that δ is close to 1):

$$(c - b - (d - b)n) / b < m \leq (c - (d - b)n) / b,$$

where $b, c,$ and d are the same as those defined in Section 4.3. For the proof, see Appendix B.

4.4.2 Asheim and Holtsmark's (2009) study

Asheim and Holtsmark (2009) show that full participation is possible using *Penance-m* within linear benefit and quadratic cost functions and an efficient time lag between the deviation and punishment considering that countries have a continuum of emission choices. In their study, they consider that low time discounting and a short detection lag contribute to a low discount rate, and that high time discounting and a long detection lag contribute to a high discount rate.

With considerable time lags between deviations and punishments, the relevant discount rate will be high. Under such circumstances, a shallow agreement might result. In other words, all countries participate with a small abatement, meaning that a "broad, but shallow" agreement is achieved. A "broad, but deep" agreement can always be implemented as a WRP equilibrium, for a sufficiently high discount factor. That is, it is necessary that noncompliance is detected early and that punishments are carried out promptly. As an example, the first commitment period of the Kyoto Protocol is five years, and the protocol's rule for

13) More details of *Penance-m* can be found in Froyn and Hovi (2008, p.318).

emission accounting and reporting mean that deviations will be detected no earlier than two to three years after the end of the commitment period.

5 Summary and discussion

We have introduced several studies of IEAs in the following frameworks of game theory: reduced-stage game models, and repeated game models. In the reduced-stage game models, a deviation by a signatory is not considered, and self-enforcement, the equilibrium concept, needs to satisfy internal and external stabilities. In repeated game models, a deviation by a signatory can occur, and a WRP equilibrium is obtained in terms of the subgame perfection and renegotiation-proof requirements. In reality, an agreement is implemented for several periods and needs to address the issue of deviations. Therefore, studies of IEAs that use repeated games are highlighted in this study.

During the last three decades, several environmental agreements have been implemented (e.g., the European Climate Change Programme, Kyoto Protocol, Helsinki Protocol, and Montreal Protocol).[14] With regard to climate change, a new framework of international cooperation by all countries, including developing countries, needs to be implemented as a Post-Kyoto Protocol. Such a framework, aimed at the prevention of global warming, was compiled during COP21, the scope of which was upholding and promoting regional and international cooperation in order to mobilize stronger and more ambitious climate action by all parties and non-party stakeholders (See UNFCCC, 2016). However, few theoretical studies have examined achieving an agreement in which developed and developing countries participate. Therefore, such agreement should be analyzed in future research.

Some studies consider a full participation agreement in a repeated game framework. Barrett (2002) reveals that full participation is achieved by a consensus treaty only if every country abates in inefficient emission levels. Froyn and Hovi (2008) show that full participation with efficient levels of emission reductions is achieved by the *Penance-m* strategy. *Penance-m* achieves full participation without decreasing the abatement levels, whereas a consensus treaty achieves this with inefficient abatement. Intuitively, the theory of repeated games suggests that the problem of international cooperation is choosing an equilibrium over the avoidance of free riders or compliance enforcement. Therefore, each country selects full participation outcomes through pre-play communication, irrespective of the effect of ancillary benefits.[15] Moreover, Asheim and Holtsmark (2009) show that full participation is achieved using *Penance-m* in the case of linear benefits and quadratic cost functions.

Several analyses of full participation IEAs using repeated games should be examined in future. The following directions for future research seem promising. First, we should explore the impact of international

14) The United Nations Conference on Environment and Development was held in Rio de Janeiro, 1992.
15) The rules of the repeated game permit pre-play communication implicitly. For more details, see Barrett (2003, Chapter 10).

trade on full participation IEAs. For instance, Cai et al. (2013) reveal that international trade enhances the incentive of participation in agreements. Therefore, it is important to consider cooperative coalition formation in the event that one country's provision of public goods encourages abatement in another country. Second, the case of IEAs with a domestic environmental policy and the concept of environmental R&D should be studied. Finally, we should also analyze the full participation agreement for heterogeneous countries.[16)]

Appendix A

Assume that $b(n-1) > dn - c$, meaning that full participation is not a Nash equilibrium of the stage game, and full participation Pareto-dominates no participation. From the assumptions $d \geq b$ and $b(n-1) > dn - c$, it follows that

$$\text{for all } k \in \{1, \cdots, n\}, b(k-1) > dk - c,$$

which means that playing *defect* is dominant in the stage game.[17)]

A.1 Subgame perfection requirement

We examine the following three incentive constraints for each country following the *Regional Penance* strategy.

(i) The incentive constraints of each country to play *cooperate* when there is no deviation at any given period. A country j in region A receives $d(k_A + k_B) - c$ in each period if no deviation has occurred in the previous period. If country j deviates in period t and returns to *Regional Penance* in period $t+1$, it receives $b(k_A - 1 + k_B)$ in period t and $d(1 + k_B) - c$ in period $t+1$. Thereafter, each country receives $d(k_A + k_B) - c$ from period $t+2$ onwards. Therefore, each country plays *Regional Penance* in all periods if

$$(1+\delta)(d(k_A + k_B) - c) > b(k_A - 1 + k_B) + \delta(d(1 + k_B) - c).$$

Now, if δ is close (but not equal) to 1 in the above inequality,

$$k_B > (c - (d - b))k_B / d. \tag{A.1}$$

(ii) Assuming that a unilateral deviation by a country in region A occurs in period $t-1$, consider the incentive constraints of the deviator and k_B countries in following *Regional Penance*, and in playing *cooperate* after the deviation.

First, we consider the incentive constraints of the deviator. If the deviator plays *cooperate* in period t, it

16) The heterogeneity of countries is considered in several fields. For example, McGinty (2007) considers the asymmetric case of a country's benefit function in reduced-stage game models for pollution abatement IEAs. Zhuang et al. (2007) and Zhuang (2010) considers the heterogeneity of countries for investment in homeland security.

17) For more details, see Asheim et al. (2006).

first receives $d(k_B+1)-c$, and then $d(k_A+k_B)-c$ from period $t+1$ onward. If it deviates again in period t and returns to *Regional Penance* in period $t+1$, it first receives bk_B, and then $d(k_B+1)-c$ in period $t+1$ because of the punishment by k_A-1 countries. Thereafter, it receives $d(k_A+k_B)-c$ from period $t+2$ onward. Therefore, it needs to compare the payoffs in periods t and $t+1$. The deviator plays *Regional Penance* after a unilateral deviation if

$$d(k_B+1)-c+\delta(d(k_A+k_B)-c) \geq bk_B+\delta(d(k_B+1)-c).$$

Now, if δ is close (but not equal) to 1 in the above inequality,

$$k_A > (c-(d-b))k_B/d. \tag{A.2}$$

Second, we consider the incentive constraints of k_B countries. If the countries play *cooperate* in period t, they first receive $d(k_B+1)-c$ and then $d(k_A+k_B)-c$ from period $t+1$ onward. If one of them deviates in period t and returns to *Regional Penance* in period $t+1$, that country first receives dk_B, and then $d(k_A+1)-c$ in period $t+1$ because of the punishment by k_B countries. Thereafter, each country receives $d(k_A+k_B)-c$ from period $t+2$ onward, and the countries need to compare the payoffs in periods t and $t+1$. The deviating countries play *Regional Penance* after a unilateral deviation if

$$d(k_B+1)-c+\delta(d(k_A+k_B)-c) \geq bk_B+\delta(d(k_A+1)-c).$$

Now, if δ is close (but not equal) to 1 in the above inequality,

$$k_B > (c-(d-b))k_A/d. \tag{A.3}$$

(iii) The incentive constraint of punishing countries k_B to punish a deviation. We consider the payoff of a punishing country when it fails to punish, that is, when it plays *cooperate* in period t after a deviation in period $t-1$. In this case, the payoff is dk_A. Since the country defecting in period t will be punished in period $t+1$, this defection leads to a loss in period $t+1$. The punishment is implemented if

$$b(k_B+1) > d(k_B+2)-c.$$

From the assumption $b(k-1) > dk-c\forall k$, an above inequality holds, so the punishing countries never fail to punish a deviator.

From (A.1), (A.2), and (A.3), we obtain the condition for individual rationality, as follows:

$$\begin{cases} k_A > \left(c-(d-b)\right)k_B/d, \\ k_B > \left(c-(d-b)\right)k_A/d. \end{cases} \tag{A.4}$$

Second, we consider the incentive constraints when a deviation occurs in region B, as is the case with a deviation in region A. We obtain the same condition above. Therefore, the condition for the subgame perfection requirement is

$$\begin{cases} k_A > \left(c-(d-b)\right)k_B/d, \\ k_B > \left(c-(d-b)\right)k_A/d. \end{cases} \tag{A.5}$$

From (A.4) and (A.5), we obtain the subgame perfection requirement.

A.2 Renegotiation-proofness requirement

We examine the binding conditions for an agreement to be renegotiation-proof after a deviation occurs in region A. Assume that one country in region A deviates in period $t-1$.

$$b(1+k_B) \geq d(k_A+k_B)-c,$$

or

$$k_A \leq b/d+(c-(d-b))k_B/d. \tag{A.6}$$

The renegotiation-proof requirement when a deviation in region B occurs is as follows:

$$k_B \leq b/d+(c-(d-b))k_A/d. \tag{A.7}$$

From (A.6) and (A.7), we obtain the renegotiation-proofness requirement.

Appendix B

Consider the conditions under which *Penance-m* satisfies the subgame perfection and renegotiation-proof requirements. One country's periodic payoff when n countries play *cooperate* is $dn-c$. If one country deviates, the deviator receives $b(n-1)$. Here, the slope of the benefit function is set as $d \geq b$, and it is assumed that $b(n-1) > dn-c > 0$. This means that full participation Pareto-dominates no participation, but that full participation is not a Nash equilibrium. From the assumption that $d \geq b$ and the assumption that $b(n-1) > dn-c > 0$, it follows that, for all $k \in \{1, 2, \cdots, n\}$, $b(k-1) > dk-c$. Thus, deviating behavior Pareto-dominates cooperative behavior in the stage game, particularly when $c > d$.

B.1 Subgame perfection requirement

In this section, we consider three conditions to examine the incentive constraints of each country following the *Penance-m* strategy.

(i) The incentive constraint of $n-m$ countries to follow *Penance-m* and to play *cooperate* after a unilateral deviation in period $t-1$. If the countries play *cooperate* in period t, they first receive $d(n-m)-c$ and then receive $dn-c$ from period $t+1$ onwards. If one of them deviates in period t and returns to *Penance-m* in period $t+1$, that country first receives $b(n-m-1)$, and then receives $d(n-m)-c$ in period $t+1$ because of punishment by m countries. Thereafter, each country receives $dn-c$ from period $t+2$ onwards. Therefore, the countries need to compare the payoffs in periods t and $t+1$. They assume that $dn > c > d > b > 0$ and set the discount factor to δ. Then, $n-m$ countries play *Penance-m* after a unilateral deviation if

$$d(n-m)-c+\delta(dn-c) \geq b(n-m-1)+\delta(d(n-m)-c). \tag{B.1}$$

By rearranging (B.1), we obtain

$$m \geq (c-b-(d-b)n)/(\delta d-(d-b)). \tag{B.2}$$

Now, if δ is close (but not equal) to 1, (B.2) becomes

$$m > (c - b - (d - b)n) / b. \tag{B.3}$$

(ii) The incentive constraint of each country to play *cooperate* when there is no deviation in any period. A participating country j receives $dn - c$ in each period if no deviation occurs in the previous period. If country j deviates in period t and returns to *Penance-m* in period $t + 1$, it receives $b(n - 1)$ in period t and $d(n - m) - c$ in period $t + 1$. Thereafter, each country receives $dn - c$ from period $t + 2$ onwards. Therefore, each country plays *Penance-m* in all periods if

$$(1 + \delta)(dn - c) \geq b(n - 1) + \delta(d(n - m) - c). \tag{B.4}$$

By rearranging (B.4), we obtain

$$m \geq (c - b - (d - b)n) / \delta d.$$

Now, if δ is close (but not equal) to 1 in the above inequality, then

$$m > (c - b - (d - b)n) / d. \tag{B.5}$$

(iii) The incentive constraint of m punishing countries to punish a deviation. First, we consider the payoff of a punishing country when it fails to punish (i.e., when it plays *cooperate* in period t after a deviation in period $t - 1$). In this case, the payoff is $d(n - m + 1) - c$. Since the country defecting in period t will be punished in period $t + 1$, this defection leads to a loss in period $t - 1$. The punishment is implemented if

$$b(n - m) > d(n - m + 1) - c. \tag{B.6}$$

By assumption, we have $d \geq b$ and $b(n - 1) > dn - c$, and it follows that (B.6) always holds. Therefore, the incentive constraint to be considered is (i) or (ii). From $d \geq b$, (B.5) is satisfied whenever (B.3) is satisfied. Thus, (B.3) is the binding incentive constraint of the subgame. Inequality (B.3) provides the lower bound of the number of punishing countries. If the number of punishing countries is lower than this bound, the number of cooperating countries and the benefit of deviation increases. In this case, a deviation by a country has occurred.

B.2 Renegotiation-proofness requirement

In this section, we examine the binding conditions for an agreement to be renegotiation-proof. Assume that one country deviates in period $t - 1$. An agreement is renegotiation-proof if not all countries' payoffs decrease as a result of the punishment. The deviator and the $n - m$ cooperative countries lower their payoffs because m countries (other than the deviator) play *defect* as a punishment. Therefore, the condition for an agreement to be renegotiation-proof is that the payoff of the m countries is at least as good with punishment as it is with renegotiation.

Consider the behavior of m countries in period t. They receive $b(n - m)$ if they adopt the *Penance-m* strategy, and $dn - c$ if they do not punish by renegotiation. Since they receive $dn - c$ in each period, irrespective of their action from period $t + 1$ onwards, we need to compare the payoffs in period t. Renegotiation will be deterred if

$$dn - c \leq b(n - m),$$

or

$$m \leq (c - (d - b)n) / b. \tag{B.7}$$

The right-hand side of inequality (B.7) indicates an upper bound on the number of punishing countries. If the number of punishing countries surpasses this bound, renegotiation takes place.

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