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International environmental agreements between asymmetric countries: A repeated game analysis☆

Nobuyuki Takashima

Kyushu University Platform of Inter/Transdisciplinary Energy Research (Q-PIT), 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

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ABSTRACT

This paper introduces a new approach to performing a relaxed analysis using a repeated game to achieve an international environmental agreement (IEA) with the full participation of countries when an asymmetric relationship exists with respect to emissions-related benefits and environmental damage. Our model reveals that a stable IEA depends on the magnitude of the relationship between the benefit-cost ratios of the two types of countries, not on their compositions. That is, the number of punishing countries for a weakly renegotiation-proof equilibrium depends on the benefit-cost ratios of the two types of countries. Our results show that a global cooperation on abatement among the two types of countries can be achieved by addressing deviation through flexibly selecting punishing countries based on benefit-cost ratios.

1. Introduction

One typical feature of global environmental problems is that no supranational authority exists to control trans-boundary pollutants. Thus, international environmental agreements (IEAs) must be implemented to coordinate actions among countries. For example, the Kyoto Protocol, which was established at the Third Conference of the Parties (COP3) in 1997, required Annex I countries of the United Nations Framework Convention on Climate Change (UNFCCC) to limit or abate greenhouse gas (GHG) emissions in the first commitment period from 2008 to 2012. Additionally, the Paris Agreement, which was compiled in 2015 during the twenty-first session of the Conference of the Parties (COP-21) of the United Nations held in Paris, France, provides a new basic framework for the prevention of global warming.

Because every country benefits from other countries' abatement of trans-boundary pollutants in a non-exclusive and non-competitive manner, each country has an incentive to free ride on the others' abatement efforts. Furthermore, because of the public nature of trans-boundary pollutant abatement, the effectiveness of IEAs depends on the number of participating countries and the level of public good provided. Therefore, the design of any IEA should prevent any free riding and sustain a larger number of participating countries.

Generally, two theoretical models are employed to analyze an IEA's formation: one is a stage game model, and the other is a repeated game model (see Asheim et al., 2006; Hovi et al., 2015). In these models, a game represents any situation where countries negotiate and decide on their pollution abatement levels. The stage game model depicts an IEA's formation in a one-shot game and typically focuses on participation. Two basic models relating to IEAs in the stage game framework, Barrett (1994) and Carraro and Siniscalco (1993), show that an agreement that significantly improves global welfare can be sustained only if several countries enter into it. That is, these models provide a very pessimistic view of cooperation on global environmental problems. In the stage game model, a coalition is said to be stable if it satisfies internal and external stability conditions. Internal stability means that no signatory should have an incentive to defect from the agreement; external stability means that no non-signatory should have an incentive to join the agreement. An agreement is said to be *self-enforcing* if the internal and external stability conditions are satisfied. This stability concept has been expanded upon through the consideration of different policies such as monetary transfers (e.g., Barrett, 2001; Biancardi and Villani, 2010; Chou and Sylla, 2008), trade sanctions (Barrett, 1997), and

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E-mail address: ntakashima@econ.kyushu-u.ac.jp.

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matching schemes (Fujita, 2013) and through the introduction of effects such as ancillary benefits (Finus and Rübbelke, 2013) and altruism (van der Pol et al., 2012).

A repeated game model typically assumes that each participating country in the agreement has an incentive to free ride on the abatement of others and focuses on compliance. That is, the repeated game model is used to analyze the conditions under which participants cooperate in accordance with their commitments. Compliance is ensured by the threat of future decreased total abatement, called 'punishments', associated with deviation. If the game is infinitely repeated, an equilibrium in which every country cooperates can be reached when a single case of non-compliance is punished by the other signatories. An agreement is renegotiation-proof if the punishment threats prevent the punishing countries from renegotiating and resuming cooperative behavior after a unilateral deviation.[1] The equilibrium concept in the repeated game is called a weakly renegotiation-proof (WRP) equilibrium (as described in Farrell and Maskin, 1989, pp.330-331). A WRP equilibrium requires that not all players be strictly worse off by carrying out the punishment than by renegotiating. That is, repeated game models aim to analyze the conditions under which participants meet their commitments under a punishment clause, and enforcement rules are sustained in a WRP equilibrium.

In the repeated game model, before the game begins, countries are assumed to enter into an agreement that the participants must enforce throughout the game using the punishment (credible threats) prescribed in the strategy (see Barrett (2003) and Hovi et al. (2015)). That is, an agreement is enforced by the strategy that specifies the countries' behavior. For example, the *Getting Even* strategy (Barrett, 1999, 2003) specifies that each country cooperates unless it has defected less often than the other countries playing have in the past. As a result, a limited number of participants can be sustained if the agreement significantly improves social welfare. Barrett (2002) also demonstrates that full participation (a "consensus treaty") can be sustained by allowing for variations in abatement levels and by limiting per-country abatement. Asheim et al. (2006) present the *Penance* (*Regional Penance*) strategy, which permits signatories in the same region as a deviator to punish non-compliance in order to sustain regional agreements. They show that two regional agreements can achieve more participants and improve social welfare more than a single agreement. Froyn and Hovi (2008) extend Asheim et al.'s (2006) analysis by proposing a strategy called *Penance-m*, which limits the number of punishing countries that are able to respond to a deviation. Their research revealed that a stable agreement with full participation and efficient abatement levels is feasible when a certain number of punishing countries are selected.

Asheim and Holtsmark (2009) further utilize *Penance-m* to show that full participation is possible within quadratic cost and linear benefit functions, illustrating that in IEAs where all participants cooperate, a WRP equilibrium can be developed if countries do not discount future payoffs too heavily. Takashima (2017a) assumes that ancillary benefits are generated by environmental protection and utilizes *Penance-m* to examine the effect of those ancillary benefits on full IEA participation within two types of abatement cost functions: linear and quadratic. Takashima (2017b) considers the possibility of an accidental deviation from an agreement and provides a new framework using a *Regional Cooperative* strategy for regional IEAs that includes punishment exceptions for accidental deviations. However, these strategies assume that countries are identical in all relevant characteristics.

From the theoretical perspective of the stage game and repeated game models, one important question is how developed and developing countries participate in existing effective IEAs. During the first commitment period under the Kyoto Protocol, developing countries, including major GHG-emitting countries such as China and India, were not required to reduce their emissions, and the United States refused to ratify the protocol. Following the expiration of that period in 2012, the parties to the UNFCCC Paris Agreement agreed to uphold and promote international cooperation; that is, they aimed to mobilize stronger and more ambitious climate actions by all party and non-party stakeholders.[2]

Barrett (2001) insists that *asymmetry* among countries is a key factor in the stability of agreements. Using the stage game model, Barrett (2001), Chou and Sylla (2008), and Biancardi and Villani (2010) consider two asymmetric groups of symmetric countries, namely, developed and developing countries. They show that it is simpler for developed countries to initially form a stable agreement that is small in size and then engage in a monetary transfer scheme to increase the agreement size. Chou and Sylla (2008) and Biancardi and Villani (2010) define developed countries as industrially advanced with a high gross domestic product (GDP) per capita and developing countries as those with a low GDP per capita. As described in Chou and Sylla (2008), the former generally have high pollution emissions, stronger preferences for environmental quality, and high abatement costs, while the latter have low emissions, weaker preferences for environmental quality, and low abatement costs. Developed countries prioritize environmental preservation and conservation above economic development, whereas developing countries prioritize economic development.

Some developed countries, such as Japan, the United States, and Canada, have not participated in the second Kyoto Protocol commitment period from 2013 to 2020.[3] Additionally, the United States announced its withdrawal from the Paris Agreement. These withdrawals and non-participations reveal that in the realm of international environmental cooperation, all international parties should consider not only how to reach a grand agreement in which all developed and developing countries participate but also how to achieve long-term cooperation.

This study provides a new analytical framework by which to assess the formation of an agreement that includes asymmetric countries, such as developed and developing countries, using a repeated game model. The WRP equilibrium concept within the repeated game model allows us to analyze a long-term stable agreement that contains a deviation prevention scheme. That is, this study examines the question of how international environmental cooperation between developed and developing countries is achieved over a long-term period.

This study expands upon Froyn and Hovi's (2008) work using a new strategy called *Flexible Penance* to investigate the coalition formation of an IEA in which developed and developing countries participate. This study assumes the existence of asymmetric countries, namely, type 1 and type 2, in a world where the cost and benefit structure between countries leads to an asymmetric distribution of gains. *Flexible Penance* allows punishing countries to be selected from participating countries as follows: (a) both country types are selected, (b) only type 1 countries are selected, and (c) only type 2 countries are selected. The primary feature of this strategy is that the selection ratio of punishing countries is flexible and can be changed.

The main contributions of this paper are as follows. With the *Flexible Penance* strategy, which permits only a subset of participating countries to punish, full participation can be sustained as a WRP equilibrium even in a global agreement with asymmetric countries. The results show that in *Flexible Penance*, the number of punishing countries for full participation depends on the magnitude of the relationship between the benefit-cost ratios of the two types of countries, not on their compositions. Additionally, even if the benefit-cost ratios are different for the two types of countries, the condition of full cooperation will be the same. As a result, this study reveals that the benefit-cost ratios of the

[1] In a repeated game model, a "deviation" means "non-compliance" with the agreement rules.

[2] For details on the Paris Agreement, see UNFCCC (2016).

[3] Canada withdrew from Kyoto Protocol in 2012. For more details, see UNFCCC (2012).

two types of countries are a key factor in the formation of stable agreements.

The remainder of the paper is structured as follows: Section 2 introduces the models and *Flexible Penance*, Section 3 presents the WRP equilibrium outcomes, Section 4 discusses the contributions of this study, and Section 5 provides our conclusions.

2. Model and strategy

2.1. Model

There are two types of countries: types 1 and 2. The number of type i countries is n_i (i = 1,2). In every period, a type i country can choose to *cooperate* (i.e., reduce emissions) or to *defect* (not reduce emissions). We assume that the marginal benefit from a unit of the public good (b_i) is smaller than the marginal cost of cooperating (c_i) ($b_i < c_i$; i = 1,2). If this assumption is not satisfied, every country individually engages in abatement irrespective of the agreement. Given that $\tilde{n}_i$ type i countries contribute to the public good (i = 1, 2), the payoff of a contributing type i country is

$$b_i(\tilde{n}_1 + \tilde{n}_2) - c_i.$$

As in Pavlova and de Zeeuw (2008), this study assumes a two-sided asymmetry for all countries; the benefit and cost parameters are high and low, respectively. Given $\tilde{n}_1$ and $\tilde{n}_2$, if contributing type i country changes its action to *defect*, its payoff becomes

$$b_i(\tilde{n}_1 + \tilde{n}_2 - 1).$$

Hence, the payoff obtained by each country if it chooses to *cooperate* (*defect*) is a linear function of the total number of countries that cooperate. For notational simplicity, this paper defines $\gamma_i \equiv c_i/b_i$. Furthermore, as in Barrett (2002, 2003), Asheim et al. (2006), and Takashima (2017a, 2017b), each country discounts its future payoffs using a common discount factor, $\delta \in (0,1)$, which is close to 1.[4]

2.2. The strategy

A repeated game model assumes that countries agree, before the game begins (or in the first period), on a contract that has to be enforced in subsequent periods through credible threats (future punishments).[5] The *Flexible Penance* strategy is derived from the *Penance-m* strategy considered in Froyn and Hovi (2008) to achieve full participation for asymmetric countries (i.e., type 1 and type 2 countries) in an IEA. It specifies that (*i*) a signatory plays *cooperate* unless another signatory has been the sole deviator from *Flexible Penance* in the previous period; (*ii*) if a unilateral deviation occurs, m countries excluding the deviator are selected from the type 1 and type 2 countries, and those m $(1 \leq m < \tilde{n}_1 + \tilde{n}_2)$ countries play *defect*. Conversely, $\tilde{n}_1 + \tilde{n}_2 - m$ countries play *cooperate*. The *Flexible Penance* strategy also assumes that a potential renegotiation can occur when the entire group consists of type 1 and type 2 punishing countries and when sub-groups consist solely of type 1 or type 2 punishing countries.[6]

As in Asheim et al. (2006, 2009), Froyn and Hovi (2008), and Takashima (2017a, 2017b), this paper assumes that all punishments last for only a single period. Hovi et al. (2015) describe that some of the more recent repeated game studies ensure renegotiation-proofness by replacing the Grim strategy with some other strategy. The *Getting Even*, *Penance (Regional Penance)*, *Penance-m*, and *Regional Cooperative* strategies all prescribe that a deviator must endure punishment (pay penance) in a single period of the repeated game before cooperation begins.

Additionally, from the assumption that countries agree on a strategy before the game begins, we assume that the condition of the number of punishing countries under which participants play *cooperate* in accordance with *Flexible Penance* is common knowledge among participants before the cooperation starts.[7]

The total number of punishing countries is determined as follows:

$$m = \theta m + (1 - \theta)m,$$

where θ $(0 \leq \theta \leq 1)$ is the ratio of type 1 countries selected as punishing countries. Similar to Asheim et al. (2006, 2009), Froyn and Hovi (2008), and Takashima (2017a, 2017b), the parameter for the number of punishing countries, m, is an integer because of the need to represent the number of countries selected. The ratio θ is the value such that θm and $(1-\theta)m$ are integers. In extreme examples, only type 1 (type 2) countries are selected as punishing countries if $\theta = 1$ $(\theta = 0)$.

3. WRP equilibrium

3.1. The concept of the WRP equilibrium

This study uses the WRP equilibrium concept, as Asheim et al. (2006); Froyn and Hovi (2008) and Takashima (2017a, 2017b) have previously. The strategy must satisfy two requirements for IEAs to be sustained as a WRP equilibrium: the strategy profile must be a subgame perfect equilibrium, and the strategy profile must be renegotiation-proof.[8]

(1) Subgame perfection requirement: Within the context of a repeated game in which discounting occurs, no player can gain by a one-period deviation after any history.[9] In other words, no player ever changes its actions, as specified by the strategy, if subgame perfection is satisfied.
(2) Renegotiation-proofness requirement: The strategy profile must be renegotiation-proof. This requirement is fulfilled if not all players strictly gain by collectively restarting a cooperative relationship at once rather than carrying out the threatened punishment when a unilateral deviation has occurred in the previous period, because we assume the punishments last only one period. An agreement is said to be renegotiation-proof if a deviation is deterred by threats.

The WRP equilibrium requires that it must be in each country's best interest to conform to the specified strategy, and it must be in at least some countries' best interest to punish a deviator without accepting an invitation to renegotiate if a deviation from the strategy occurs. Punishment here implies that all punishing countries play *defect* after the deviation. This makes not only the deviator but all non-punishing countries worse off in the punishment scenario.

We examine the condition under which an agreement where all participants agree to *Flexible Penance* is sustained as a WRP equilibrium.

[4] This setting indicates the implicit assumption of the folk theory in the repeated game framework. For details, see Farrell and Maskin (1989).

[5] Asheim et al. (2006) describe that countries agree in the first period on a contract that has to be enforced in subsequent periods through credible threats in repeated game models.

[6] This study assumes that all countries aim to achieve the same abatement levels. That is, the payoffs of countries depend on the number of cooperators. It is sufficient to consider a potential renegotiation by the whole group or subgroups of punishing countries because the incentives for renegotiation can be different between type 1 and type 2 punishing countries and depend on the number of punishing countries. For additional details, see Lemma 2.

[7] Several strategies in repeated game model implicitly make a similar assumption. For example, see Asheim et al. (2006, 2009), Barrett (1999, 2002, 2003), Froyn and Hovi (2008), and Takashima (2017a, 2017b).

[8] Asheim et al. (2006) use the expressions "subgame perfection" and "renegotiation-proofness".

[9] From the theory of repeated games with discounting, a player cannot gain by multiple period deviations if he/she cannot gain by a one-period deviation (Abreu, 1988, p. 390). Thus, we need only check that no player can gain by a one-period deviation after any history.

3.2. Subgame perfection and renegotiation-proofness requirements

Lemma 1 shows the conditions for subgame perfection.

Lemma 1. *The Flexible Penance strategy with m punishing countries satisfies subgame perfection if*

$$m \geq \frac{max\{\gamma_1, \gamma_2\}-1}{\delta}.$$

(Proof). See AppendixA. □

For the *Flexible Penance* strategy to satisfy subgame perfection, the number of punishing countries must be an integer larger than or equal to the values of $(\gamma_1-1)/\delta$ and $(\gamma_2-1)/\delta$. The rationale behind this result is that the incentive for deviation increases as the level of the benefit-cost ratio increases. Therefore, when $\gamma_1 > \gamma_2$ $(\gamma_2 > \gamma_1)$, the condition of $m \geq (\gamma_1-1)/\delta$ $(m \geq (\gamma_2-1)/\delta)$ is needed to deter both types of countries from deviating. Lemma 2 shows the conditions for the renegotiation-proofness requirement.

Lemma 2. *The Flexible Penance strategy to achieve full participation with m punishing countries is renegotiation-proof if*

$$m \leq min\{\gamma_1, \gamma_2\}.$$

(Proof). See AppendixB. □

For the *Flexible Penance* strategy to satisfy renegotiation-proofness, the number of punishing countries must be an integer that is smaller than or equal to the values of γ_1 and γ_2. The intuition behind this result is as follows. The incentive for renegotiation (choosing to abate) increases as the level of the benefit-cost ratio decreases. To weaken the punishing countries' incentive to renegotiate, their payoffs must be increased by decreasing the number of punishing countries because their payoffs increase as more countries choose to abate during the punishment phase. In our two-type country model, it is necessary to deter a country with a weaker benefit-cost ratio from renegotiating by decreasing the number of punishing countries. Therefore, when $\gamma_1 > \gamma_2$ $(\gamma_2 > \gamma_1)$, the condition of $m \leq \gamma_2$ $(m \leq \gamma_1)$ is needed to deter renegotiation by both types of countries.

Proposition 1 is directly obtained from Lemmas 1 and 2.

Proposition 1. *An agreement where all* $\tilde{n}_1$ *and* $\tilde{n}_2$ *countries provide a public good and play the Flexible Penance strategy is sustained as a weakly renegotiation-proof equilibrium if there exists* m *such that*

$$\frac{max\{\gamma_1, \gamma_2\}-1}{\delta} \leq m \leq min\{\gamma_1, \gamma_2\}.$$

The following implications can be derived from this proposition. First, the number of punishing countries depends on the magnitude relationship of the benefit-cost ratios between both types of countries, not on the selection ratio of the punishing countries, θ. The intuition is that each country's payoff depends on the number of cooperating countries, irrespective of their composition. This is because the deviation of one country reduces the same amount of the others' payoffs, irrespective of the type of deviating country. Even if the costs and benefits are different for the two types of countries, the condition of full cooperative IEA will be the same. Second, m is uniquely determined if it can exist because $min\{\gamma_1, \gamma_2\}-(max\{\gamma_1, \gamma_2\}-1)/\delta < 1$. If m is determined, all participating countries play *cooperate* for fear of credible punishment. Cooperation is not achieved if the exogenous parameters do not satisfy the condition in Proposition 1 because punishment for deviation is not credible. Additionally, the value of $min\{\gamma_1, \gamma_2\}-(max\{\gamma_1, \gamma_2\}-1)/\delta$ increases as the values of γ_1 and γ_2 become close.

Furthermore, we mention the benefit-cost ratio when $c_i < b_i$ $(i = 1,2)$. This study assumes that $c_i > b_i$, meaning that a solo abatement cannot be profitable. Even if $c_i < b_i$, the benefit-cost ratio between two types of countries can be equal. However, each country abates without concluding the agreement. Additionally, when $\gamma_i < 1$, the number of punishing countries cannot be determined as an integer because as shown in Proposition 1. In this case, participants play *cooperate* without punishment.

Finally, we clarify the difference between the main results and those of Takashima (2017a, 2017b), who employs *Penance-m* and *Regional Cooperative* in the case of symmetric countries. Assuming that there are ancillary benefits that accompany the primary benefits of abatement, Takashima (2017a) shows the effect of ancillary benefits on the condition of full cooperation in a global IEA. Although the condition in Proposition 1 in Takashima (2017a) denotes the number of punishing countries for a WRP equilibrium, as is the case in this study, it depends on the benefit-cost ratio and ancillary benefits. Takashima (2017b) shows the condition that regional IEAs, which include punishment exceptions for accidental deviation, are sustained as a WRP equilibrium. The conditions in Propositions 1 and 2 in Takashima (2017b) denote that the number of participants for a WRP equilibrium is affected by the benefit-cost ratio and the number of participants in other regions. In the case of asymmetric countries, with *Flexible Penance*, our model shows that the number of punishing countries required to sustain full cooperative agreement as a WRP equilibrium depends on the benefit-cost ratios of two types of countries, not on the selection ratio of the punishing countries. In other words, on the condition of the number of punishing countries in Proposition 1 in this study, the punishing countries can be flexibly selected from two types of countries.

4. Contribution of *Flexible Penance*

As explained in Barrett (2001), Biancardi and Villani (2010), and Chou and Sylla (2008), two types of countries are considered to account for the asymmetry among countries: industrially advanced countries, referred to as developed countries, and less industrialized countries, known as developing countries.[10] Barrett (2001), Biancardi and Villani (2010), and Chou and Sylla (2008) assume that the abatement benefits are greater for developed countries than for developing countries. For example, Chou and Sylla (2008) assume that cost functions are identical between developed and developing countries and can be different depending only on the abatement levels established within linear benefit and quadratic cost functions. That is, the benefit-cost ratio of developed countries can be considered to be less than that of developing countries. By assuming that each country faces a binary choice (it plays either abate or pollute), Barrett (2001) notes that developed and developing countries abate at the same costs and that the benefits from global abatement are greater for developed countries than for developing ones. Barrett (2001) also assumes that abatement by a developed country can improve the environment more than abatement by a developing country if each country abates at the same costs. If we adopt Barrett's (2001) model and assume that each country must achieve the same abatement levels, as is the case in Chou and Sylla's (2008) model, the benefit-cost ratio of developed countries is less than that of developing countries.[11]

5. Summary and discussion

This study provides theoretical findings to reach an IEA consisting of asymmetric countries using a repeated game model. For such an IEA to be sustained as a WRP equilibrium, we present the *Flexible Penance* strategy, which enforces compliance. That is, we obtain the condition under which all participants cooperate in accordance with *Flexible Penance*. More precisely, this study shows the method for deciding the

[10] In the two-country model, Niho (1998) examines the impact of a transfer of resources between developed and developing countries related to global environmental qualities.

[11] Biancardi and Villani's (2010) model assumes the costs due to remaining pollution in the cost function. Therefore, their model is not suitable for considering the benefit-cost ratio in this study.

number of punishing countries to reach a WRP equilibrium, depending on the benefit-cost ratios of the two types of countries, not on the selection rate of punishing countries between the two types of countries. Additionally, it is revealed that the number of punishing countries for the WRP equilibrium is decided at the same level between the two types of countries.

The punishment regime within the *Flexible Penance* strategy is likely to have other advantages. Given *Flexible Penance*, punishing countries can be selected after a country deviates. If the punishing countries are selected from among the deviator's neighboring countries, the transaction costs can be reduced because countries within close geographic proximity to each other can gather and negotiate easily.[12]

This study is significant in its development of a process to identify how a future IEA can support international cooperation by developed and developing countries, as has been attempted in the Paris Agreement. Our results show that global cooperation on abatements among asymmetric countries can be achieved by addressing deviation through flexibly selecting punishing countries from developed and developing countries on a specific number of punishing countries depending on the benefit-cost ratio.

Further research into abatement level assumptions is needed. In our model, each country must achieve the same abatement levels. Therefore, each country's deviation has the same impact on other countries' payoffs. This means that each country's payoff depends on the number of cooperating countries. If the abatement targets differ from each other, as in the Kyoto Protocol, a country's payoff depends on the composition of the deviator and punishing countries; therefore, the impact of one country's deviation on other countries can differ. That is, the punishment conditions for a WRP equilibrium can differ compared to the symmetric abatement case. Future research should consider how asymmetry in each country's abatement levels affects the outcome.

Appendix A. Proof of Lemma 1

Consider three conditions to examine the incentive constraints for each country in the following strategy. We consider deviation first by type 1 countries and second by type 2 countries.

(A) The incentive constraint for each country to play *cooperate* when no deviation occurs in any period. A participating country, j, receives $b_1\tilde{n}_1 + b_1\tilde{n}_2 - c_1$ in each period if no deviation occurs in the previous period. If country j deviates in period t and reverts to the strategy in period $t+1$, it receives $b_1(\tilde{n}_1 - 1) + b_1\tilde{n}_2$ in period t and $b_1(\tilde{n}_1 - \theta m) + b_1(\tilde{n}_2 - (1-\theta)m) - c_1$ in period $t+1$. Thereafter, each country receives $b_1\tilde{n}_1 + b_1\tilde{n}_2 - c_1$ from period $t+2$ onward. Each country plays *cooperate* if

$$(1+\delta)(b_1\tilde{n}_1 + b_1\tilde{n}_2 - c_1) \geq b_1(\tilde{n}_1 - 1) + b_1\tilde{n}_2 + \delta(b_1(\tilde{n}_1 - \theta m) + b_1(\tilde{n}_2 - (1-\theta)m) - c_1). \tag{A.1}$$

By rearranging inequality (A.1), we obtain

$$m \geq (c_1 - b_1)/\delta b_1.$$

Given that $\gamma_1 = c_1/b_1$, we have

$$m \geq (\gamma_1 - 1)/\delta. \tag{A.2}$$

Similarly, if a type 2 country deviates, we obtain the lower bound for the number of punishing countries needed to maintain cooperation:

$$m \geq (\gamma_2 - 1)/\delta. \tag{A.3}$$

Inequalities (A.2) and (A.3) represent those conditions under which each signatory plays *cooperate* in every period, provided that the other signatories also *cooperate*. If the number of punishing countries is less than or equal to the right-hand side of inequalities (A.2) or (A.3), a deviating country increases its payoff by deviating. That is, deviation occurs in period t.

(B) The incentive constraint for $\tilde{n}_1 + \tilde{n}_2 - m$ countries to play *cooperate* after a unilateral deviation in period $t-1$. First, we consider deviation by a type 1 country. If countries play *cooperate* in period t, they first receive $b_1(\tilde{n}_1 - \theta m) + b_1(\tilde{n}_2 - (1-\theta)m) - c_1$ and then receive $b_1\tilde{n}_1 + b_1\tilde{n}_2 - c_1$ from period $t+1$ onward. If one country deviates in period t but cooperates in period $t+1$, that country first receives $b_1(\tilde{n}_1 - \theta m - 1) + b_1(\tilde{n}_2 - (1-\theta)m)$ and then receives $b_1(\tilde{n}_1 - \theta m) + b_1(\tilde{n}_2 - (1-\theta)m) - c_1$ in period $t+1$ as a result of punishment by m countries. Thereafter, each country receives $b_1\tilde{n}_1 + b_1\tilde{n}_2 - c_1$ from period $t+2$ onward. Therefore, type 1 countries play *cooperate* after a unilateral deviation if

$$b_1(\tilde{n}_1 - \theta m) + b_1(\tilde{n}_2 - (1-\theta)m) - c_1 + \delta(b_1\tilde{n}_1 + b_1\tilde{n}_2 - c_1) \geq b_1(\tilde{n}_1 - \theta m - 1) + b_1(\tilde{n}_2 - (1-\theta)m) + \delta(b_1(\tilde{n}_1 - \theta m) + b_1(\tilde{n}_2 - (1-\theta)m) - c_1). \tag{A.4}$$

By rearranging inequality (A.4), we obtain

$$m \geq (c_1 - b_1)/\delta b_1.$$

Given that $\gamma_1 = c_1/b_1$, we have

$$m \geq (\gamma_1 - 1)/\delta. \tag{A.5}$$

Second, we consider deviation by a type 2 country. Type 1 countries play *cooperate* after a unilateral deviation if

$$b_2(\tilde{n}_1 - \theta m) + b_2(\tilde{n}_2 - (1-\theta)m) - c_2 + \delta(b_2\tilde{n}_1 + b_2\tilde{n}_2 - c_2) \geq b_2(\tilde{n}_1 - \theta m) + b_2(\tilde{n}_2 - (1-\theta)m - 1) + \delta(b_2(\tilde{n}_1 - \theta m) + b_2(\tilde{n}_2 - (1-\theta)m) - c_2). \tag{A.6}$$

By rearranging inequality (A.6), we obtain

$$m \geq (c_2 - b_2)/\delta b_2.$$

Given that $\gamma_2 = c_2/b_2$, we have

$$m \geq (\gamma_2 - 1)/\delta. \tag{A.7}$$

[12] Asheim et al. (2006) indicate that this factor can also reduce negotiation costs.

Inequalities (A.5) and (A.7) represent those conditions under which each signatory plays *cooperate* in every period, provided that the other signatories also play *cooperate*. If the number of punishing countries is less than or equal to the right-hand side of inequality (A.5) and (A.7), a deviator in period $t-1$ increases its payoff by deviating in period t. That is, the deviator in period $t-1$ deviates again in the next period.

(C) The incentive constraint for m punishing countries to punish a deviation. First, we consider the payoff for a punishing country that fails to punish—that is, when it plays *cooperate* in period t after a deviation in $t-1$. As the country defecting in period t will be punished in period $t+1$, this defection leads to a loss in period $t+1$.

Type 1 punishing countries implement the punishment if

$$b_1(\tilde{n}_1 - \theta m) + b_1(\tilde{n}_2 - (1-\theta)m) \geq b_1(\tilde{n}_1 - \theta m + 1) + b_1(\tilde{n}_2 - (1-\theta)m) - c_1,$$

or

$$c_1 \geq b_1.$$

Type 2 punishing countries implement the punishment if

$$b_2(\tilde{n}_1 - \theta m) + b_2(\tilde{n}_2 - (1-\theta)m) \geq b_2(\tilde{n}_1 - \theta m) + b_2(\tilde{n}_2 - (1-\theta)m + 1) - c_2,$$

or

$$c_2 \geq b_2.$$

From the assumption that $c_i > b_i$ $(i = 1,2)$, the above inequalities always hold.

The definition of subgame perfection requires both types of countries not to deviate. Therefore, from inequalities (A.2), (A.3), (A.5), and (A.7), the condition for subgame perfection is

$$m \geq (\gamma_1 - 1)/\delta \text{ and} m \geq (\gamma_2 - 1)/\delta.$$

This condition can be rewritten as

$$m \geq (\max\{\gamma_1, \gamma_2\} - 1)/\delta.$$

Appendix B. Proof of Lemma 2

We assume that potential renegotiations can occur within a group consisting of all type 1 and type 2 punishing countries as well as sub-groups that consist only of type 1 or type 2 punishing countries. Potential renegotiations under these three scenarios must be considered because the renegotiation-proofness requirement is different for type 1 and type 2 punishing countries and depends on the number of punishing countries.

Given that one country deviates in period $t-1$, an agreement is renegotiation-proof if not all countries' payoffs decrease with punishment. Therefore, the condition for an agreement to be renegotiation-proof is that the payoffs of m countries are at least as great with punishment as with renegotiation. We consider three renegotiation cases: (A) type 1 and type 2 punishing countries (θm and $(1-\theta)m$) renegotiate, (B) only type 1 punishing countries (θm) renegotiate, and (C) only type 2 punishing countries ($(1-\theta)m$) renegotiate.

(A) Consider the case where type 1 and type 2 punishing countries (θm and $(1-\theta)m$) renegotiate in period t. Type 1 punishing countries receive $b_1(\tilde{n}_1-\theta m) + b_1(\tilde{n}_2-(1-\theta)m)$ if they adopt the strategy and $b_1\tilde{n}_1 + b_1\tilde{n}_2-c_1$ if they do not punish by renegotiation. They receive $b_1\tilde{n}_1 + b_1\tilde{n}_2-c_1$ in each period irrespective of their action from period $t+1$ onward. Therefore, renegotiation is deterred if

$$b_1(\tilde{n}_1 - \theta m) + b_1(\tilde{n}_2 - (1-\theta)m) \geq b_1\tilde{n}_1 + b_1\tilde{n}_2 - c_1.$$

Assuming that $\gamma_1 = c_1/b_1$, we have

$$m \leq \gamma_1. \tag{A.8}$$

For type 2 countries, renegotiation is avoided if

$$m \leq \gamma_2. \tag{A.9}$$

(B) Consider that only type 1 punishing countries (θm) renegotiate in period t. The type 1 punishing countries will not renegotiate if

$$b_1(\tilde{n}_1 - \theta m) + b_1(\tilde{n}_2 - (1-\theta)m) \geq b_1\tilde{n}_1 + b_1(\tilde{n}_2 - (1-\theta)m) - c_1.$$

Assuming that $\gamma_1 = c_1/b_1$, we have

$$m \leq \gamma_1/\theta. \tag{A.10}$$

(C) Consider that only type 2 punishing countries ($(1-\theta)m$) renegotiate in period t. The type 2 punishing countries will not renegotiate if

$$b_2(\tilde{n}_1 - \theta m) + b_2(\tilde{n}_2 - (1-\theta)m) \geq b_2(\tilde{n}_1 - \theta m) + b_2\tilde{n}_2 - c_2,$$

or

$$m \leq \gamma_2/(1-\theta). \tag{A.11}$$

For renegotiation to be prevented, (A.8), (A.9), (A.10), and (A.11) are necessary and sufficient. These conditions are summarized as follows:

$$m \leq \min\{\gamma_1,\ \gamma_2,\ \gamma_1/\theta,\ \gamma_2/(1-\theta)\}.$$

This is equivalent to

$$m \leq \min\{\gamma_1,\ \gamma_2\}$$

since $\theta \in [0,1]$. We define $\gamma_1/0 = \gamma_2/0 = \infty$ when $\theta = 0$. Therefore, (A.8) implies (A.10) and (A.9) implies (A.11) for any value of θ.

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