



International environmental agreements with ancillary benefits: Repeated games analysis[☆]



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ABSTRACT

Both ancillary and primary benefits, generated by climate change mitigation, are indispensable key factors to implement the full participation in international environmental agreement (IEA). This paper presents a new IEA model with ancillary benefits, using a repeated game with the linear and quadratic emission abatement cost functions of each country. This study also investigates the effect of ancillary benefits on the condition for full participation in IEA. Ancillary benefits function as a complementary device of punishment scheme for IEA. Our main results show that ancillary benefits can facilitate full participation in IEA, thus suggesting that they should be considered in climate change negotiations.

1. Introduction

International environmental agreements (IEAs) provide public goods such as the mitigation of climate change. The effectiveness of an IEA depends on the number of participating countries and the levels of public goods provisions. A new basic framework aimed at the prevention of global warming was compiled during the twenty-first session of the United Nations Conference of Parties (COP21), held in Paris, France, in 2015. Its scope was to uphold and promote regional and international cooperation to mobilize stronger and more ambitious climate action by all parties and non-party stakeholders.¹ However, each country's greenhouse gases (GHGs) emissions cause environmental damage all over the world, and a single country's public goods provision will benefit all countries in a non-exclusive and non-rival manner. Hence, all countries have an incentive to free ride on other countries' abatement efforts.

Previous research suggests that there are two types of international environmental public goods provision: the provision of *pure* public

goods; and the provision of *impure* public goods (e.g., Aunan et al., 2007; Ekins, 1996a, 1996b; Finus and Rübbelke, 2013; Rive, 2010). The pure type has only public characteristics: climate change mitigation generates global scale public benefits that all countries equally receive by mitigation of climate change (primary benefits). The impure type has public and private characteristics: climate protection generates not only primary benefits, but also private benefits that only abating countries receive by individual climate protection (ancillary benefits). Whereas the primary benefits can be enjoyed globally, the ancillary benefits can only be enjoyed on a local scale. For example, climate protection behaviors reduce not only GHGs emissions but also sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter (PM) emissions simultaneously.² Therefore, if a provision of public goods has private and public characteristics, it may affect the willingness of countries to participate in IEAs.

A considerable number of literatures have addressed the provision of global international pollution controls. Models of cooperation for

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¹ For more details, see UNFCCC (2016).

² For example, the ancillary benefits from reduction of secondary pollutants such as SO₂, NO_x, and PM, resulting from GHGs abatement has been highlighted as a potential catalyst for countries to engage in climate policy (Aunan et al., 2007; Ekins, 1996a, b). Rive (2010) assesses the co-benefit of the point source SO₂, NO_x, and PM emissions associated with regional climate policy in Western Europe. Finus and Rübbelke (2013) describe that many public goods are in fact impure public goods.

climate control can be roughly divided into two groups: a participation game model where compliance is assumed; and repeated game model where compliance is ensured by the threat of future decreased abatement by punishing countries. The participation game model depicts the formation of agreements as a two-stage game. In the first stage, countries decide whether or not to sign an IEA. In the second stage, the signatories jointly choose the abatement levels, while each non-signatory independently chooses its abatement levels (e.g., Barrett, 1994, 2001; Carraro and Siniscalco, 1993; Finus and Rübbelke, 2013; van der Pol et al., 2012).³ In the participation game model, no signatory deviates because we assume that all signatories abate in accordance with the agreement. Early studies of the participation game by Barrett (1994) and Carraro and Siniscalco (1993) demonstrate that the stable agreement is generally small. In summary, these studies demonstrate how difficult it is to forge an agreement with effective abatement levels and full participation under the participation game framework.

In a repeated game model, the game is infinitely repeated and we assume that the participation countries in the IEA are forced to cooperate at subsequent stages through credible threats (e.g., Asheim et al., 2006; Asheim and Holtmark, 2009; Barrett, 1999, 2002, 2003; Froyn and Hovi, 2008).⁴ The punishment is credible if the threats prevent the punishing countries from renegotiating and returning to cooperative behavior after a unilateral deviation. That is, the compliance is ensured by the threat of credible punishment in a repeated game model.

In this game model, agreements must specify a strategy that can enforce the signatories' cooperation. It must be the best interest for each country to individually act in accordance with the strategy (i.e., the subgame perfection requirement). Additionally, renegotiation must be prevented in such an equilibrium agreement (i.e., the renegotiation-proofness requirement). In particular, it must be in the best interest of the punishing countries to collectively punish a non-complying country before restarting the cooperative relationship. If these requirements are satisfied, the IEA can be sustained as a weakly renegotiation-proof equilibrium (in the sense of Farrell and Maskin, 1989).

Barrett (2002) demonstrates that a full participation agreement can be sustained, by limiting the per-country level (a consensus treaty). Asheim et al. (2006) present the *Regional Penance* strategy, which limits the number of punishing countries by only letting a deviation be punished by the other signatories in the same region, whereas signatories in the other region continue to cooperate. The results of Asheim et al. (2006) show that participation can be doubled in a two-region world. Froyn and Hovi (2008) propose a *Penance- m* strategy that specifies that only a subset of the signatories in a global agreement punish a deviator. The results of Froyn and Hovi (2008) show that a full participation agreement can be implemented as a weakly renegotiation-proof equilibrium within the linear abatement benefit and cost functions. Moreover, Asheim and Holtmark (2009) show that full participation is possible using *Penance- m* within linear benefit and quadratic cost functions.

In the climate change context, it has been argued that preventing global warming generates not only primary benefits which all countries receive equally, but also ancillary benefits that the individual climate protecting countries receive privately. The ancillary benefits have attracted much attention in the context of emission abatement for climate change. In reality, the combustion of fossil fuels emits a range of secondary pollutants such as SO₂, NO_x, and PM. When each country reduces their use of fossil fuels with the objective of abating GHGs,

³ To prevent climate change, the two (or more)-stage game is used not only in international policies such as IEAs but also in domestic environmental policies. For example, see Ouchida and Goto (2014, 2016).

⁴ Hovi et al. (2015) categorize Asheim et al. (2006), Asheim and Holtmark (2009), Barrett (1999, 2002, 2003), and Froyn and Hovi (2008) as the studies that demonstrate the IEAs formation within the repeated game framework.

these secondary pollutants are reduced simultaneously (Ekins, 1996a, 1996b; Aunan et al., 2007). Ekins (1996a, 1996b) shows that the consideration of ancillary benefits has a facilitating role for countries engaging in climate policy. Furthermore, Aunan et al. (2007) show the significance of ancillary benefits to China, that is, climate protection will reduce GHGs and local pollutants such as particles and NO_x. Therefore, abatement tends to resolve regional environmental problems such as those associated with domestic air pollution as well as global warming. Rive (2010) shows that considering the ancillary benefits of reducing SO₂, NO_x, and PM when designing policies increases the attainability of the abatement goals and the political feasibility of climate policies. Finus and Rübbelke (2013) investigate the effect of ancillary benefits on IEA participation. They take the pessimistic view that an agreement can be sustained if entered into by a few countries, and that the ancillary benefits have a neutral or negative impact on the number of signatories in a participation game framework.⁵

Although there has been significant analysis regarding the impact of ancillary benefits on international environmental policies and cooperation for mitigating climate change, there has been limited analysis of the strategic implications with respect to the cooperation of all countries. This paper investigates the effects of ancillary benefits of emission abatements on stable IEAs with full participation in a repeated game model, using the *Penance- m* strategy of Froyn and Hovi (2008). We consider two types of payoff functions: linear benefit and cost functions; and linear benefit and quadratic cost functions. An important focus of this study is the effect of ancillary benefits on the conditions leading to the formation of full participation IEAs.

Our main contributions are as follows. Using the two types of payoff functions, we show that full participation is still feasible even if we consider ancillary benefits. That is, this study generalizes the full participation weakly renegotiation-proof equilibria of Froyn and Hovi (2008) and Asheim and Holtmark (2009) to the case of ancillary benefits, where abatement costs functions are linear and quadratic, respectively. Additionally, the results of this study are different from the results of Finus and Rübbelke (2013) and Froyn and Hovi (2008) because we consider a different situation. The negative effect of ancillary benefits on a stable IEA shown by Finus and Rübbelke (2013) disappears, if we consider a different situation where compliance is ensured by credible punishment threats. Compared to Froyn and Hovi (2008), the number of punishing countries decreases because of the ancillary benefits with linear costs, whereas this number remains unchanged with convex costs, if we consider a different situation where ancillary benefits are introduced.

The remainder of the paper is structured as follows. Section 2 presents a brief review of the *Penance- m* strategy. Section 3 describes our models and the weakly renegotiation-proof equilibrium outcomes. Section 4 compares the effect of ancillary benefits on the condition of weakly renegotiation-proof equilibrium for the two cases. Finally, Section 5 provides our concluding remarks and presents future scope for research.

2. The *Penance- m* concept

We assume that the cooperative relationship in the agreement is sustained by the *Penance- m* strategy of Froyn and Hovi (2008), which limits the number of countries that can punish a deviator, and show the feasibility of a weakly renegotiation-proof agreement with full participation and efficient abatement levels. Consider a world with $n \geq 2$ countries, where $N = \{1, \dots, n\}$ denotes the set of all countries, and the grand coalition where all n countries participate. Each country decides

⁵ Finus and Rübbelke (2013) explain that countries that consider the private ancillary benefits to a greater extent will abate more emissions, irrespective of the IEAs. Hence, the relative importance of an IEA for climate protection is reduced.

whether to observe the commitment to undertake an emission abatement. That is, 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).

Based on Froyn and Hovi (2008), we specify *Penance-m* as follows.⁶

- (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 the signatories, excluding the deviator, and they play *defect* ($1 \leq m \leq n - 1$). The $n - m$ other countries play *cooperate*.

The main feature of *Penance-m* is to select m punishing countries. The m punishing countries abandon their abatement action as punishment. If a unilateral deviation occurs from *Penance-m* in period t by playing *defect*, m countries are selected from the signatories (excluding the deviator), and they play *defect*, as punishment, in period $t+1$.

The strategy must satisfy two requirements for IEAs to be weakly renegotiation-proof. The first requirement is that the strategy profile must be a subgame perfect equilibrium, meaning that a player cannot increase its payoff by selecting other behaviors. In a repeated game with discounting, this requires that no player can gain by a one-period deviation after any history.⁷ 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 the same time, instead of carrying out the threatened punishment when a deviation has occurred in the previous period. Punishment in *Penance-m* implies that m countries but the deviator play *defect* after the deviation. This has a negative effect on the deviator and all non-punishing countries because of the m countries' punishing behavior. Renegotiation-proofness thus requires that the punishing countries are at least as well off with punishment as with renegotiation.

3. Models and equilibrium outcomes

This section presents the models and their equilibrium outcomes. Regarding the public benefits from emission abatement, several IEA studies consider that the benefits of countries selecting an abatement action are greater than or equal to the benefits when they select free riding (e.g., Asheim et al., 2006; Barrett, 1994, 1999; Froyn and Hovi, 2008).⁸ However, these studies do not provide definitive reasons for this difference. If an abatement action also has private good characteristics, the benefits may differ. Specifically, a private benefit is a spillover effect that accompanies pollution mitigation. This paper assumes that this difference occurs because cooperating countries receive some additional benefits. One example is the improvement of a domestic environmental problem that occurs by reducing GHGs, such as the reduction of air pollution or an improvement in biodiversity.⁹ Therefore, we adopt the concept that ancillary benefits have the characteristics of private benefits, as per Finus and Rübbelke (2013).

Consider a world with $n (\geq 2)$ identical countries. Let $a \geq 0$ denote the parameter corresponding to ancillary benefits. The total benefit of country i consists of public benefits, private benefits, and private costs. The payoff to country i is

⁶ Froyn and Hovi (2008) use *Penance-m* with $k (1 \leq m < k \leq n)$ signatories. However, we consider *full participation* similar to Asheim and Holtmark (2009) and exclude the behavior of non-signatories.

⁷ We know from the theory of repeated games with discounting that if a player cannot gain by some one-period deviation, then he cannot gain by a multi-period deviation (Abreu, 1988).

⁸ Asheim and Holtmark (2009), Barrett (2001, 2002), McGinty (2010), and Osmani and Tol (2010) consider the case where the benefits of countries selecting an abatement action are equal to the benefits when they select a free ride.

⁹ For other examples, see Aunan et al. (2007) and Finus and Rübbelke (2013).

$$\pi_i = B \left(\sum_{j=1}^n q_j \right) + \alpha B(q_i) - C(q_i) \text{ for } i=1, \dots, n, \tag{1}$$

where q_i is abatement level of country i , $B \left(\sum_{j=1}^n q_j \right)$ is the public good part of the benefits and depends on the total abatement, $\sum_{j=1}^n q_j$; the private good part of the benefits, $\alpha B(q_i)$, and the cost function, $C(q_i)$, depends on the individual abatement, q_i .¹⁰ The public good part of the benefits denotes the reduction of GHGs, which is derived from the abatement behaviors of participating countries, whereas the private good part of the benefits denotes the ancillary benefits with abatement, such as an improvement in domestic air pollution. We assume that an abatement cost is higher than an abatement benefit in the case of solo abatement. If not, every country abates individually irrespective of the agreement. In this paper, each country discounts its future payoffs using a common discount factor, $\delta (0 < \delta < 1)$, which is close to 1.¹¹

Subsequently, we consider the following two types of payoff functions that have been frequently used in the literature:

- Case I: Linear benefit and cost functions; and
- Case II: Linear benefit and quadratic cost functions.

Subsection 3.1 presents the model and equilibrium outcome of Case I, and Subsection 3.2 presents the model and equilibrium outcome of Case II.

3.1. Case I: Linear benefit and cost functions

3.1.1. The model for Case I

We consider a model with linear benefit and cost functions corresponding to emission abatement, which is prominent in recent literature (e.g., Asheim et al., 2006; Barrett, 1999, 2001, 2002, 2003; Froyn and Hovi, 2008). From Eq. (1), the payoff function of country i when the benefit and cost functions are linear is

$$\pi_i = b \sum_{j=1}^n q_j + \alpha b q_i - c q_i \text{ for } i=1, \dots, n, \tag{2}$$

where b is the marginal benefit from abatement, α denotes the parameter corresponding to ancillary benefits, and $c q_i$ represents the total abatement costs of country i .

We assume that $bn > c > b > 0$, and the strategy space for country i is normalized to the decision variable $q_i \in [0, 1]$. The cooperative country i selects $q_i = 1$ as an optimal solution that maximizes coalition payoffs. If country i deviates, it selects $q_i = 0$ as the optimal solution that maximizes its individual payoff because the benefit and cost functions are linear. If the country plays *cooperate*, it chooses abatement level $q_i = 1$. If it plays *defect*, it chooses abatement level $q_i = 0$. Therefore, the payoff of i when all countries abate is $bn + ab - c$. If country i deviates, the payoff of country i is $b(n - 1)$. Similar to Asheim et al. (2006) and Froyn and Hovi (2008), we assume that $(n-1)b > bn + ab - c > 0$, which means that the full participation state Pareto dominates the no participation state. Therefore, we have $b + ab - c < 0$, which means that no country can gain their payoffs by a solo abatement.¹²

3.1.2. Equilibrium outcome of Case I

We examine the conditions of a weakly renegotiation-proof equilibrium under which *Penance-m* satisfies the subgame perfection and

¹⁰ The expression of "public good part" and "private good part" is used in the study of Finus and Rübbelke (2013).

¹¹ This setting indicates the implicit assumption of the folk theory in the repeated game framework. For more details, see Farrell and Maskin (1989).

¹² The assumption $b + ab - c < 0$ means that every country cannot gain their payoffs by a solo abatement because it will abate unilaterally irrespective of an IEA if this assumption is not sustained. We implicitly assume that the countries must cooperate internationally to reduce pollutants.

renegotiation-proofness requirements. Lemma 1 defines the required conditions for the subgame perfection requirement, and Lemma 2 defines the required conditions for the renegotiation-proofness requirement.¹³

Lemma 1. *The subgame perfection requirement holds if there exists m such that $m > c/b - \alpha - 1$.*

(Proof). See Appendix A. □

The right hand side of the above inequality denotes the lower bound of the number of punishing countries, which decreases with an increase in α . The rationale behind this result is that each country's incentive for cooperation increases if they consider ancillary benefits, that is, the incentive for deviation decreases. Therefore, deviation is deterred even if the number of punishing countries decreases.

Lemma 2. *The renegotiation-proofness requirement holds if there exists m such that*

$$m \leq c/b - \alpha.$$

(Proof). See Appendix B. □

The right hand side of the above inequality denotes the higher bound of the number of punishing countries and decreases with increasing α . The intuition behind this lemma is as follows. For punishing countries, the incentive to cooperate increases with ancillary benefits, that is, the incentive to renegotiate also increases. Hence, we need to increase the punishing countries' payoffs by decreasing the number of punishing countries, because their abatement increases the number of countries that play to cooperate during the punishment phase.

Proposition 1 below is directly obtained from Lemmas 1 and 2.

Proposition 1. *There exists a weak renegotiation-proof equilibrium if the number of punishing countries (m) is*

$$c/b - \alpha - 1 < m \leq c/b - \alpha.$$

Two implications can be derived from this proposition. First, the number of punishing countries decreases with increasing ancillary benefits. The number of punishing countries in our result is less than that of Froyn and Hovi's (2008) study because of the ancillary benefits, although our model also achieves a full participation agreement. That is, the ancillary benefits do not affect the number of participating countries but do affect the number of punishing countries.

Second, in this paper, we simplify the different benefit effects of cooperate and defect obtained based on previous studies. Froyn and Hovi (2008) consider that the slope of the benefit function of a country playing cooperate is steeper than or equal to the slope of the benefit function of the country playing defect. If these benefit slopes are calculated, m becomes less than that stated in Froyn and Hovi's (2008) study.¹⁴ The difference between these benefit parameters has a similar effect to α , because the number of punishing countries decreases with an increase in α . Essentially, a larger payoff difference between cooperation and deviation corresponds to a smaller stipulated number of punishing countries. The effect of the difference in the payoff between cooperate and defect is simply expressed as parameter α .

3.2. Case II: Linear benefit and quadratic cost functions

3.2.1. The model for Case II

The payoff function with linear benefit and quadratic cost has been considered in several studies (e.g., Asheim and Holtmark, 2009; Finus

¹³ The expressions "subgame perfection" and "renegotiation-proofness" are used in the study by Asheim et al. (2006).

¹⁴ In Froyn and Hovi (2008), the range of punishing countries is $[c - d - (d - b)(n - 1)] / [\delta d - (d - b)] \leq m \leq [c - (d - b)n] / b$. Given that δ is close (but not equal) to 1 and $d = b$, we have $(c - b) / b \leq m \leq c/b$.

and Rübbelke, 2013; Osmani and Tol, 2010). In this case, it is generally assumed that the marginal cost of pollution control increases with higher environmental quality and treatment activities. For instance, marginal costs increase because subsequent improvements in quality gradually require more investment in technology. Therefore, the cost function is quadratic, because we presume that the marginal costs of abatement are increasing. We examine the range of the punishing countries.

From Eq. (1), the payoff function of country i when the benefit function is linear and the cost function is quadratic is

$$\pi_i = b \sum_{j=1}^n q_j + abq_i - cq_i^2/2 \text{ for } i=1, \dots, n, \tag{3}$$

where the ancillary benefit is expressed as abq_i when the abatement levels that country i chooses are non-negative real numbers, $q_i \in [0, 1]$. Following Finus and Rübbelke (2013), we assume an interior solution to solve the country's optimization problem. We assume $nb + ab - c/2 < 0$, meaning the situation where all countries take abatement $q_i = 1$ is not profitable for any country. The intuition behind this assumption is that the marginal cost of pollution control increases with higher environmental quality when using the quadratic cost function.

Differentiating π_i with respect to q_i , and from the assumption of an interior solution, the first-order condition for maximizing the individual country's payoff is

$$\partial \pi_i / \partial q_i = b + ab - cq_i = 0.$$

From the above equation, the optimal abatement level q_u when each country plays defect is

$$q_u = (\alpha + 1)b/c.$$

The value of q_u corresponds to a unique Nash equilibrium strategy taken by each country at the stage game. From the assumption of an interior solution and $nb + ab - c/2 < 0$, we have $b + ab - c < 0$. Therefore, $0 < q_u < 1$.

Differentiating $\sum_{i=1}^n \pi_i$ with respect to q_i , the first-order condition for maximizing the total payoff is

$$\partial \left(\sum_{i=1}^n \pi_i \right) / \partial q_i = bn + ab - cq_i = 0. \tag{4}$$

In Eq. (4), the optimal abatement level q_c when all the countries play cooperate is

$$q_c = (n + \alpha)b/c.$$

The value of q_c represents the unique Pareto-efficient abatement level. From the assumption of an interior solution and $nb + ab - c/2 < 0$, we have $bn + ab - c < 0$. Therefore, $0 < q_c < 1$.

Hence, the Pareto-efficient abatement is n times the abatement level in the Nash equilibrium. Substituting q_c into (3), we have

$$\pi_c = (n + \alpha)^2 b^2 / 2c.$$

3.2.2. Equilibrium outcome of Case II

We now examine the weakly renegotiation-proof condition. Lemma 3 gives the required conditions for the subgame perfection requirement, and Lemma 4 gives the required conditions for the renegotiation-proofness requirement.

Lemma 3. *The subgame perfection requirement holds if there exists m such that*

$$m > (n - 1)/2.$$

(Proof). See Appendix C. □

The right hand side of the above inequality is the lower bound of the number of punishing countries and is only dependent on parameter n .

Lemma 4. *The renegotiation-proofness requirement holds if there exists m such that*

$$m \leq (n+1)/2.$$

(Proof). See Appendix D. \square

The right hand side of the above inequality is the higher bound of the number of punishing countries and is only dependent on parameter n .

Proposition 2 is directly obtained from Lemmas 3 and 4.

Proposition 2. *There exists a weak renegotiation-proof equilibrium if the number of punishing countries (m) satisfies*

$$(n-1)/2 < m \leq (n+1)/2.$$

Proposition 2 shows that the effect of α disappears in Case II. In other words, the ancillary benefits do not affect the agreement size under the *Penance- m* strategy in Case II. Additionally, the number of punishing countries only depends on the number of countries, n . The value of m is close to $n/2$. For this payoff function, ancillary benefits have no impact on the condition of a stable agreement.¹⁵ Therefore, the result in Proposition 2 is a generalization of the analysis of Asheim and Holtmark (2009).¹⁶

Propositions 1 and 2 imply that full participation is still feasible even when ancillary benefits are considered in a repeated game framework. The results of Finus and Rübbelke (2013) suggest that ancillary benefits have a neutral or negative impact on the formation of stable coalitions in a participation game framework. That is, the positive effect of *Penance- m* on the participation of countries dominates the negative effect of ancillary benefits on the formation of a stable coalition. The intuition behind this result is as follows. *Penance- m* specifies that all countries participate, and they play *cooperate* because of the existence of the punishing countries. In other words, all countries cooperate for fear of the punishment levels. That is, the sustainability of the agreement depends on the number of punishing countries. Considering this punishment rather than other elements such as ancillary benefits, all countries choose the equilibrium where all countries play *cooperate* through pre-play communication.¹⁷ Consequently, the ancillary benefits do not affect the agreement size under the *Penance- m* strategy. However, the effect on the numbers of punishing countries using Cases I and II is different. In the next section, we explain why ancillary benefits have an effect in Case I but not Case II.

4. A comparison of the impact of ancillary benefits on a weakly renegotiation-proof equilibrium with respect to Case I and Case II

This section reveals why the effects of ancillary benefits differ between the two types of payoff functions: Case I, where the benefit and cost functions are linear, and Case II, where the benefit function is linear but the cost function is quadratic. We have the following results from Section 3.

Result I: In Case I, the number of punishing countries reduces with an increase in the ancillary benefits.

Result II: In Case II, the ancillary benefits have no impact on the number of punishing countries. Therefore, the effect of the ancillary benefits disappears.

Comparing the effect of ancillary benefits between the two cases leads to Proposition 3:

¹⁵ Finus and Rübbelke (2013) show a similar result in the case of linear benefit and quadratic cost functions.

¹⁶ For more details, see Asheim and Holtmark (2009).

¹⁷ The rules of the repeated game implicitly permit pre-play communication. For more details, see Barrett (2003).

Proposition 3. *If an agreement where all n countries participate and employ *Penance- m* is in a weakly renegotiation-proof equilibrium, the ancillary benefits decrease the number of punishing countries with linear benefit and cost functions, whereas the number of punishing countries remains unchanged with linear benefit and quadratic cost functions.*

Subsections 4.1 and 4.2 explain why the negative impact of ancillary benefits in Case I, obtained by Finus and Rübbelke (2013), disappears when using the *Penance- m* strategy in a repeated game framework, whereas, in Case II, the impact of ancillary benefits remains constant. To explain these results, we investigate the effect of ancillary benefits on the subgame perfection and renegotiation-proofness requirements considering three factors: (i) the gain from deviating, (ii) the loss from punishment, and (iii) the gain from renegotiation. (i) and (ii) consider that the effect of ancillary benefits on the deviation incentive, and (iii) considers the effect of ancillary benefits on the renegotiation incentive.

4.1. Case I

4.1.1. The impact of ancillary benefits on the subgame perfection requirement: Case I

We consider the impact of ancillary benefits on the subgame perfection requirement in Case I by investigating the signatories' incentive for deviation.

From Eq. (2), the payoff function of Case I is

$$\pi_i = b \sum_{j=1}^n q_j + abq_i - cq_i \text{ for } i=1, \dots, n.$$

The abatement levels for the *cooperate* and *defect* cases are, respectively,

$$q_c = 1 \text{ and } q_u = 0.$$

(i) The gain from deviating

A signatory's payoff is denoted by $\pi_c(n)$ and a deviator's payoff is denoted by $\pi_n(n-1)$. Substituting these abatement levels into the payoff function results in

$$\pi_c(n) = bn + ab - c, \tag{5a}$$

and

$$\pi_n(n-1) = bn - b. \tag{5b}$$

From Proposition 1, the subgame perfection requirement is $m > c/b - 1 - \alpha$. Therefore, the lower bound of the number of punishing countries decreases with an increase in α . The intuitive explanation behind Eqs. (5a) and (5b) is that ancillary benefits only increase the payoffs to signatories, $\pi_c(n)$, not the payoffs to deviators, $\pi_n(n-1)$. In other words, the incremental benefit of a deviation from *Penance- m* $c - (1 + \alpha)b$ suggests that the incentive for deviation is reduced by ancillary benefits. Consequently, a deviation can be prevented even if the magnitude of punishment is weakened because there are less punishing countries.

(ii) The loss from punishment

We compare the payoffs in the punishment phase (i.e., cooperating or receiving a punishment). The payoff when no country deviates is denoted by $\pi_c(n)$, and if one country deviates, the payoff of a deviator in the punishment phase is denoted by $\pi_c(n-m)$. That is, $n-m$ countries (including the deviator play *cooperate*) and m punishing countries play *defect*. Substituting these abatement levels into the payoff function results in

$$\pi_c(n) = bn + ab - c, \tag{6a}$$

and

$$\pi_c(n-m) = b(n-m) + \alpha b - c. \tag{6b}$$

From (6a) and (6b), the loss from punishment equals $-mb$. Therefore, ancillary benefits have no effect on the loss of a deviator's payoff in the punishment phase. From (i) and (ii), ancillary benefits reduce the incentive for deviation because the ancillary benefits reduce the gain from deviating.

4.1.2. The impact of ancillary benefits on the renegotiation-proofness requirement: Case I

The effect of ancillary benefits on the renegotiation-proofness requirement in Case I is explained by investigating the punishing countries' incentive for renegotiation.

(i) The gain of renegotiation

A punishing country's payoff of punishment, $\pi_n(n-m)$, and the payoff of renegotiation, $\pi_c(n)$, are denoted as

$$\pi_n(n-m) = bn - bm, \tag{7a}$$

and

$$\pi_c(n) = bn + \alpha b - c. \tag{7b}$$

The requirement for the renegotiation-proofness is $m \leq c/b - 1 - \alpha$. This higher bound on the number of punishing countries decreases with increasing α . Eqs. (7a) and (7b) state that the payoff of punishment, $\pi_n(n-m)$, is not dependent on ancillary benefits, but the payoff of renegotiation, $\pi_c(n)$, is dependent on ancillary benefits. In other words, the incremental benefit of punishing countries by renegotiation $b(m + \alpha) - c$ depends on the ancillary benefits. To deter renegotiation, the payoff per punishing country must be increased by decreasing the number of punishing countries. Therefore, an ancillary benefit has a positive impact on the payoff when renegotiation is chosen.

4.2. Case II

From Proposition 2, the number of punishing countries is constant even if there are ancillary benefits. We analyze this result similarly to Subsection 4.1.

4.2.1. The impact of ancillary benefits on the subgame perfection requirement: Case II

This subsection reveals the effect of ancillary benefits on the subgame perfection requirement in Case II in a manner similar to Subsubsection 4.1.1.

From Eq. (3), the payoff function of Case II is

$$\pi_i = b \sum_{j=1}^n q_j + \alpha b q_i - c q_i^2 / 2 \text{ for } i=1, \dots, n,$$

In Case II, the abatement levels for the cooperate and defect cases are defined as, respectively:

$$q_c = (n + \alpha)b/c \text{ and } q_u = (\alpha + 1)b/c.$$

(i) The gain from deviating

The signatory's payoff is denoted by $\pi_c(n)$, and the deviator's payoff is denoted by $\pi_n(n-1)$. Substituting these abatement levels into the payoff function gives

$$\pi_c(n) = (n^2 + 2\alpha n + \alpha^2)b^2/2c, \tag{8a}$$

and

$$\pi_n(n-1) = (2n^2 - 2n + 1 + 2\alpha n + \alpha^2)b^2/2c. \tag{8b}$$

From Proposition 2, the requirement for subgame perfection is $m > (n + 1)/2$, which is unaffected by ancillary benefits. The intuitive explanation behind Eq. (8a) and (8b) is that the ancillary benefits increase the payoffs to signatories, $\pi_c(n)$, by the same amount as the

payoffs to deviators, $\pi_n(n-1)$.¹⁸ The incremental benefit of deviation from *Penance-m* is not dependent on the ancillary benefits; it is equal to $b^2(n-1)^2/2c$. That is, an ancillary benefit has no impact on a deviator's payoff. Therefore, the incentive for deviation remains constant irrespective of the ancillary benefits.

(ii) The loss from punishment

The payoff when no country deviates is denoted by $\pi_c(n)$, and if one country deviates, the payoff of a deviator in the punishment phase is $\pi_c(n-m)$. Substituting these abatement levels into the payoff function results in

$$\pi_c(n) = (n^2 + 2\alpha n + \alpha^2)b^2/2c, \tag{9a}$$

and

$$\pi_c(n-m) = (n^2 + 2\alpha n + \alpha^2 + 2m - 2mn)b^2/2c. \tag{9b}$$

From the above equations, the loss from punishment is $-b^2m(n-1)/c$. Therefore, ancillary benefits have no effect on the loss of the deviator's payoff in the punishment phase. From (i) and (ii), ancillary benefits have no effect on the deviation incentive.

4.2.2. The impact of ancillary benefits on the renegotiation-proofness requirement: Case II

We investigate the effect of the ancillary benefits on the renegotiation-proofness requirement in Case II in a similar way to Subsubsection 4.1.2.

(xxix) The gain of renegotiation

A punishing country's punishment payoff, $\pi_n(n-m)$, and the payoff of renegotiation, $\pi_c(n)$, are

$$\pi_n(n-m) = (2n^2 - 2mn - 1 + 2m + 2\alpha n + \alpha^2)b^2/2c, \tag{10a}$$

and

$$\pi_c(n) = (n^2 + 2\alpha n + \alpha^2)b^2/2c. \tag{10b}$$

The renegotiation-proofness requirement, $m \leq (n + 1)/2$, is unaffected by ancillary benefits. Equations (10a) and (10b) state that the ancillary benefits increase the punishing country's payoffs, $\pi_n(n-m)$, by the same amount as the renegotiation payoffs, $\pi_c(n)$. Therefore, the incremental benefit of punishing countries by renegotiation is $-(n-1)(n+1-2m)b^2/2c$. In other words, an ancillary benefit has no impact on the payoff increases when punishment is chosen.

From Subsections 4.2.1 and 4.2.2, we see that ancillary benefits have no role on the weakly renegotiation-proofness requirement in the case of linear benefit and quadratic cost functions. Because the ancillary benefits have no role, the results of [Asheim and Holtmark \(2009\)](#) remain unchanged.

5. Summary and discussion

This paper presents new theoretical findings on the effect of ancillary benefits on IEAs with full participation. We investigate the effect of ancillary benefits in a repeated game framework, applying *Penance-m* to two types of payoff functions: Case I with linear benefit and cost functions, and Case II with linear benefit and quadratic cost functions.

This study draws the following conclusions. First, the results of our study generalize the findings of [Asheim and Holtmark \(2009\)](#) and [Froyn and Hovi \(2008\)](#). That is, full participation is feasible in Cases I and II, even when ancillary benefits are taken into consideration. Second, our research demonstrates how the different results compare to the results of [Finus and Rübbelke \(2013\)](#) and [Froyn and Hovi \(2008\)](#), which consider a different situation. [Finus and Rübbelke](#)

¹⁸ [Finus and Rübbelke \(2013, p. 218\)](#) show a similar result.

(2013) show that ancillary benefits have a negative or neutral impact on a stable coalition in a participation game model. Compared to Finus and Rübhelke (2013), our situation is different because we do not assume compliance. If the ancillary benefits are newly taken into consideration using our framework, the negative effect disappears. Froyen and Hovi (2008) show that a full participation agreement can be sustained as a weakly renegotiation-proof equilibrium under *Penance-m*. Compared to Froyen and Hovi (2008), our situation is different because we introduce ancillary benefits. If the ancillary benefits are considered in our framework, the number of punishing countries can decrease because of the ancillary benefits while achieving a full participation agreement. Third, this study reveals that, although full participation is achieved for two types of payoff functions, the effect of ancillary benefits differs between the two cases. The number of punishing countries decreases with an increase in ancillary benefits

in Case I and remains unchanged in Case II. In other words, the ancillary benefits affect the incentive for deviation and renegotiation in Case I, whereas the ancillary benefits have no impact on these incentives in Case II.

The directions for future research are promising. First, we should explore the impact of international trade on full participation IEAs. For instance, Cai et al. (2013) reveal that international trade enhances the incentive for participation in agreements. Therefore, it is important to consider a cooperative coalition formation in the event that one country's provision of public goods encourages abatement in another country. Second, we should study IEAs with domestic environmental policies and the concept of environmental R&D. Finally, we should also analyze the full participation agreement for heterogeneous countries.¹⁹

Appendix A. Proof of Lemma 1

We examine the subgame perfection of *Penance-m* for the following three cases.

- (a) Consider the incentive constraint that $n - m$ countries adopt *Penance-m* after a unilateral deviation becomes a unique binding constraint. Therefore, this study verifies the payoff of $n - m$ countries after a deviation. If these countries play *cooperate* in periods t and $t+1$, the country receives $b(n - m) + ab - c + \delta(bn + ab - c)$. If the country deviates in period t and returns to *Penance-m* in the next period, it receives $b(n - m - 1) + \delta[b(n - m) + ab - c]$. Thereafter, each country receives $n + ab - c$ from period $t + 2$ onwards. Therefore, we compare the payoffs in periods t and $t + 1$. Consequently, it is individually rational for $n - m$ countries to adopt *Penance-m* in period t if

$$b(n-m)+ab-c+\delta(bn+ab-c) \geq b(n-m-1)+\delta[b(n-m)+ab-c].$$

Solving the above inequality for m , we obtain

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

If δ is close (but not equal) to 1, we obtain

$$m > c/b - 1 - \alpha. \tag{A.1}$$

- (b) Consider the incentive constraint that each country plays *cooperate* when there is no deviation at any period. A participating country i receives $bn + ab - c$ in each period if no deviation has occurred in the previous period. If country i deviates in period t and returns to *Penance-m* in period $t + 1$, it receives $b(n - 1)$ in period t and $b(n - m) + ab - c$ in period $t + 1$. Thereafter, each country receives $n + ab - c$ from period $t + 2$ onwards. It is individually rational for each country to stick to *Penance-m* in periods t and $t + 1$ if

$$(1 + \delta)(n+ab-c) \geq b(n-1)+\delta[b(n-m)+ab-c].$$

If δ is close (but not equal) to 1 in the above inequality, we obtain

$$m > c/b - 1 - \alpha. \tag{A.2}$$

- (c) Consider the incentive constraint that m countries punish a deviation. First, 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 $b(n - m + 1) + ab - c$. The country defecting in period t will be punished in period $t + 1$, so this defection leads to a loss in period $t - 1$. Hence, it suffices to check that the m punishing countries that are prescribed by *Penance-m* to play *defect* as punishment in period t have no incentive to play *cooperate*. Because $b + ab - c < 0$ always holds,

$$b(n-m) > b(n-m+1)+ab-c.$$

Therefore, the incentive constraints correspond to (A.1) and (A.2). The right hand side of inequalities (A.1) and (A.2) is the lower bound of the number of punishing countries.

Appendix B. Proof of Lemma 2

Consider the constraint for an agreement to be renegotiation-proof. The payoff of m punishing countries when punishment is applied should be greater than or equal to those with renegotiation.

Subsequently, assume that one country deviates in period $t-1$. The payoff of the punishing countries is $b(n - m)$ if they adopt *Penance-m* in period t and they receive $bn + ab - c$ if they play *cooperate* by renegotiation. The countries receive the same payoff regardless of their action from period $t+1$ onward. Therefore, we consider the payoff in period t . Thus, renegotiation-proof requires that

¹⁹ The heterogeneity of countries has been considered in several fields. For example, McGinty (2007) considers the asymmetric case of a country's benefit function in the participation game model in the field of pollution abatement in IEAs. Zhuang et al. (2007) and Zhuang (2010) consider the heterogeneity of countries in the field of investment in homeland security.

$$bn+ab-c \leq b(n-m),$$

or

$$m \leq c/b - \alpha. \tag{A.3}$$

The right-hand side of Eq. (A.3) is the upper bound of the punishing countries.

Appendix C. Proof of Lemma 3

We examine the subgame perfection as follows.

- (a) Consider the incentive constraints that $n-m$ countries adopt *Penance-m* after a unilateral deviation. Let us examine the behaviors of country i in period t when one country deviates from *Penance-m* in period $t-1$. Deviation in this case means that they choose the abatement level q_u . If a country in $n-m$ plays *cooperate* in period t and returns to full participation, the payoff is $b[(n-m)q_c + mq_u] + abq_c - cq_c^2/2 + \delta\pi_c$. If a country in $n-m$ countries deviates in period t and plays *cooperate* in period $t+1$, the payoff is $b[(n-m-1)q_c + (m+1)q_u] + abq_u - cq_u^2/2 + \delta[b[(n-m)q_c + mq_u] + abq_c - cq_c^2/2]$. Thereafter, each country receives π_c from period $t+2$ onwards. Therefore, we compare the payoffs in periods t and $t+1$.

Now, each country plays *Penance-m* in all periods if

$$b[(n-m)q_c + mq_u] + abq_c - cq_c^2/2 + \delta\pi_c \geq b[(n-m-1)q_c + (m+1)q_u] + abq_u - cq_u^2/2 + \delta[b[(n-m)q_c + mq_u] + abq_c - cq_c^2/2].$$

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

$$m > (n-1)/2. \tag{A.4}$$

- (b) Consider the incentive constraint that each country plays *cooperate* when there is no deviation in any period. A participating country i receives $\pi_c + \delta\pi_c$ in each period if no deviation has occurred in the previous period. If country i deviates in period t and return to *Penance-m* in period $t+1$, it receives $b[(n-1)q_c + q_u] + abq_u - cq_u^2/2$ in period t and $b[(n-m)q_c + mq_u] + abq_c - cq_c^2/2$ in period $t+1$. Thereafter, each country receives π_c from period $t+2$ onwards. It is individually rational for each country to stick to *Penance-m* in periods t and $t+1$ if

$$(1 + \delta)\pi_c \geq b[(n-1)q_c + q_u] + abq_u - cq_u^2/2 + \delta[b[(n-m)q_c + mq_u] + abq_c - cq_c^2/2].$$

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

$$m > (n-1)/2. \tag{A.5}$$

- (c) Consider the incentive constraint that m punishing countries punish a deviation. First, 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 $b[(n-m+1)q_c + (m-1)q_u] + abq_c - cq_c^2/2$. The country defecting in period t will be punished in period $t+1$, so this defection leads to a loss in period $t-1$. Hence, it suffices to check that the m punishing countries that play *defect* as punishment in period t have no incentive to deviate from *Penance-m* by playing *cooperate*. Because $n > 1$ always holds,

$$b[(n-m)q_c + mq_u] + abq_u - cq_u^2/2 > b[(n-m+1)q_c + (m-1)q_u] + abq_c - cq_c^2/2.$$

Therefore, the incentive constraint is derived from (A.4) and (A.5). The right hand side of these inequalities is the lower bound of the number of punishing countries.

Appendix D. Proof of Lemma 4

To consider the conditions that ensure an agreement adopting *Penance-m* is renegotiation-proof, we examine the payoff to the punishing countries. After a unilateral deviation, the punishing countries behave in two ways: (i) if they punish in period t , the payoff is $b[(n-m)q_c + mq_u] + abq_u - cq_u^2/2$; (ii) if they return to the *Penance-m* strategy and play *cooperate*, the payoff is π_c . *Penance-m* is renegotiation-proof if the former is greater than or equal to the latter. The punishing countries receive the same payoff regardless of their action from period $t+1$ onward. Therefore, we compare the payoffs in period t . Solving this inequality for m , we obtain

$$b[(n-m)q_c + mq_u] + abq_u - cq_u^2/2 \geq \pi_c,$$

or

$$m \leq (n+1)/2.$$

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