Overlapping International Green R&D Agreements*

By

Emilson Caputo Delfino Silva
Department of Marketing, Business, Economics & Law
3-30M Business Building, University of Alberta, Edmonton, AB, Canada
Tel: 1-780-248-1312; Fax: 1-780-492-3325; E-mail: emilson@ualberta.ca

And

Chikara Yamaguchi
Faculty of Economic Sciences, Hiroshima Shudo University
1-1-1, Ozukahigashi, Asaminami-ku, Hiroshima, 731-3195, Japan,
Tel: 81-82-830-1238; Fax: 81-82-830-1313; E-mail: chikara@shudo-u.ac.jp

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Abstract: We examine the formation of multilateral, hub-and-spoke and bilateral green technology international agreements. Green R&D provision produces two types of positive externalities: a global public good (i.e., reduction of CO_2 emissions) and knowledge spillovers in technology agreements. We utilize the perfectly-coalition-proof-Nash equilibrium (PCPNE) concept to refine the set of Nash equilibria. Multilateral and hub-and-spoke coalitional structures are PCPNE, even in large economies, in the absence of income transfers for different values of attrition costs. Fully participated multilateral coalitional structures are not stable in the presence of income transfers; however, the size of the stable coalition increases as the economy expands.

Keywords: coalition-proof equilibrium; overlapping coalitions; green technology; hub-and-spoke; international environmental agreements.

JEL Classification: C7, D6, D7, H4, H7, Q4, R5

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1. Introduction

Carbon Capture and Storage (CCS) has tremendous potential to reduce global carbon emissions (see, e.g., de Coninck et al. (2009), Herzog (2011) and Leach et al. (2011)). However, there are also substantial barriers that need to be overcome in order for this technology to be widely deployed; namely, the technology requires the financing of very large upfront costs (building the facilities and transportation networks), regulatory incentives (e.g., carbon pricing), coordination between public and private sectors in research development and demonstration (RD&D), and coordination between public and private sectors in the various issues associated with storage activities (see, e.g., de Coninck et al. (2009), Herzog (2011) and The Royal Society (2011)). Given the large dimensions of the tasks that must be accomplished, it is not surprising that Australia, Canada, China, the EU, India, Japan, Korea, Norway, South Africa, the UK and the USA, regions that are heavily dependent on energy produced from fossil fuels, are forming international partnerships to share efforts to enable them to eliminate obstacles and further develop and deploy CCS (see, e.g., the Asia-Pacific Partnership on Clean Development and Climate and the International Energy Agency's Greenhouse Gas R&D Centre). Notably, China and the EU are "hubs" in the international CCS network, since they have entered into multiple bilateral and multilateral international agreements. For example, China has bilateral agreements with Australia, the EU, Japan and the USA and a multilateral agreement with the EU and Norway (see, e.g., Hagemann et al. (2011)).

The strategy chosen by China and the EU in becoming hubs in a network of overlapping bilateral and multilateral international agreements in CCS may, in part, be motivated by the disappointing performance of the Kyoto Protocol in effectively guiding its members to fulfill their commitments in terms of reductions in greenhouse gas emissions or to effectively address technological cooperation and transfers. The inherent fragmentary nature of a global agreement, characterized by a gamma of disparate and conflicting interests and bargaining and coordination costs, as it has been observed in the annual meetings of the United Nations Framework Convention on Climate Change (UNFCC), will likely undermine a global CCS agreement's performance in promoting incentives for effective CCS deployment (see, e.g., de Coninck and Backstrand (2011)). The Chinese and European hub-and-spoke CCS networks, as well as similar future networks, may prove to be more efficient (i.e., characterized by lower bargaining and coordination costs) and effective (i.e., self-enforcing) in executing the essential activities for widespread CCS utilization.

The fact that China and the EU have entered into several bilateral and multilateral CCS agreements may also be illustrating another type of advantage of such strategy. A large research network may enable China or the EU to have access to new as well as complementary pieces of knowledge and reduce the likelihoods of inertia and redundancy in its R&D process. The amount of R&D spillovers enjoyed by a nation may significantly increase as it forms new bridges across nations. The Chinese and European hub-and-spoke networks may yet provide empirical support to "chance combination theory" (see, e.g., Simonton (2004)) in that creative ideas emerge from combination of various pieces of knowledge in original and useful ways, and the expansion of a research network is known to produce more knowledge.[1]

However, in the case of CCS, there appear to be important factors that limit the efficient size of the international research network. The inherent interdependency of the various research tasks in CCS (i.e., carbon capture, logistics and storage) implies that research teams need to be very cohesive in order to effectively solve the intertwined complex problems that they face.[2] Cohesive research teams are those in which research collaborators are prone to cooperate in knowledge creation and diffusion

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[1] Several studies find that the size of a research team (i.e., research network size) is positively correlated to various types of indicators of number and quality of publications (see, e.g., Defazio et al (2009)).

[2] The knowledge underlying CCS projects seem to fit well the description of complex knowledge in Sorenson et al. (2006). Complexity is defined "…in terms of the level of interdependence inherent in the subcomponents of a piece of knowledge…Interdependence arises when a subcomponent significantly affects the contribution of one or more other subcomponents to the functionality of a piece of knowledge. When subcomponents are interdependent, a change in one may require the adjustment, inclusion or replacement of others for a piece of knowledge to remain effective." (Sorenson et al (2006), p. 995)

because they have a great deal of trust on each other.[3] But, trust among research collaborators builds slowly because collaborators give preference to past and existing relationships to engaging in new collaborations.[4] The argument is that researchers who contemplate new collaborations face substantial informational asymmetries with respect to each other's skills, expertise and research effort. Therefore, the existence of informational asymmetries may reduce the impetus for continual expansion of research networks brought up by R&D sharing.

In this paper, we consider benefits and costs associated with production of green R&D by international research collaborators in order to examine the efficiency and stability of hub-and-spoke, multilateral and isolated bilateral agreements. We focus on R&D that is produced by interactions among researchers. Specifically, we examine situations in which researchers' interactions produce what Fershtman and Gandal (2011) call "direct project spillovers" and "indirect project spillovers."[5] We follow the basic premise of the "coauthor model" developed by Jackson and Wollinsky (1996) that the benefits of the interaction between a pair of research collaborators are both the benefit that each collaborator puts into the project and the benefit associated with synergy. The more time the collaborators spend together, the greater the amount of synergy and thus the greater the collective benefit from collaboration.

[3] See, e.g., Forti et al. (2013). These authors find that research teams are more productive the more cohesive they are. This finding gives support to the idea that strong ties among research collaborators promote trust and cooperation and these factors enable these researchers to effectively enhance mutual exchange of highly sensitive and fine-grained information. Their result adds to the controversy of which weak or strong ties among researchers are more important for knowledge creation and diffusion. As hypothesized by Granovetter (1973), weak ties among individuals may facilitate bridge formation and information diffusion.

[4] See, e.g., Goyal (2007), pp. 259-261.

[5] In Fershtman and Gandal (2011), direct project spillovers "exist whenever there are knowledge spillovers between projects that are directly connected, that is they have common contributors" and indirect project spillovers "exist whenever there are knowledge spillovers between projects that are not directly connected, that is, projects for which there are no common contributors." In our multilateral R&D agreements there exist direct project spillovers only. In our hub-and-spoke R&D agreements, there are both direct and indirect project spillovers. Fershtman and Gandal find evidence of direct and indirect project spillovers in their analysis of open-source software.

As for the costs of R&D production faced by international collaborators, we consider both the cost of hiring inputs (labor and capital) in optimal quantities as well as the costs associated with relative efficiency losses, measured in terms of potential R&D product foregone, which may emerge in international research collaboration. We account for two potential sources of relative efficiency losses. First, international research interactions may be less efficient than domestic ones due to weaker ties between any pair of researcher collaborators, since moral hazard and adverse selection issues are likely to be more severe.[6] We call the loss of efficiency due to weaker ties "relational attrition" cost. Second, the total relational attrition cost faced by any researcher should be proportional to the number of international collaborators that this individual possesses, since coordinating relational issues becomes more complex as the number of partners expands.[7] We call the loss of efficiency associated with the size of one's research network "congestion cost."

We follow Silva and Zhu (2013), who extend the concept of perfectly coalition-proof Nash equilibrium (PCPNE) advanced by Bernheim et al. (1987) to settings in which overlapping coalitions may coexist in the Nash equilibrium for multistage games. The extension is presented in Appendix A. It consists of employing the perfectly coalition-proof concept to the sets of players produced by the union of intersecting (i.e., overlapping) sets of players. Suppose, for example, that $N = \{1,2,3\}$ denotes the set of all players. In addition to N, the subsets of the set of all players are the singletons, $\{1\},\{2\},\{3\}$ and the pairs $\{1,2\},\{1,3\},\{2,3\}$. Let $(\{1\},\{2\},\{3\}),(\{1,2\},\{3\}),(\{1,3\},\{2\})$, $(\{1\},\{2,3\})$, $(\{1,2\},\{1,3\})$, $(\{1,2\},\{2,3\})$, $(\{1,3\},\{2,3\})$ and $(\{1,2,3\})$ be the relevant

[6] International research collaboration is also more likely to be less efficient than domestic research collaboration because of the extra burden faced by researchers in traveling long distances and dealing with differences in time zones (which affect the proper times for one-on-one communication over the internet) and in culture and social working habits.

[7] This is a particular form of crowding cost, which is commonly studied in both club theory (see, e.g., Cornes and Sandler (1996)) and theoretical models of network formation (see, e.g., Goyal (2007) and Jackson (2008)). This type of crowding cost is different from the one that emerges with allocation of *productive* research time across multiple research tasks (or collaborators) in the coauthor model of Jackson and Wollinsky (1996).

coalitional structures that may be produced by the coalition-proof refinement. The standard coalition-proof concept is applicable to all coalitional structures except to the overlapping ones, $(\{1,2\},\{1,3\})$, $(\{1,2\},\{2,3\})$, $(\{1,3\},\{2,3\})$. The extended concept of Silva and Zhu (2013) is applicable to the overlapping coalitional structures in that it is employed over the union of the overlapping bilateral coalitions; namely the set $\{1,2,3\}$. Consider, for example, the coalitional structure $(\{1,2\},\{1,3\})$. The Nash equilibrium for this structure is coalition-proof if and only if there is no individual nor collective incentive to deviate; that is, player 1 has no incentive to exit either coalition, and players 2 and 3 have no incentives to exit their respective coalitions in order to stand alone or to form the bilateral coalition $\{2,3\}$. The latter is one of the possible self-enforcing sub-coalitions that can be produced from the set $\{1,2,3\}$.

The game considered here is a strategic network formation game (see, e.g., Furusawa and Konishi (2011)). We follow Furusawa and Konishi (2011) in formulating a multistage game, in which the first stage is a participation stage. When transfers are prohibited, the game contains two stages: following the participation stage, there is a contribution stage. When transfers are allowed within coalitions, the game also includes a third stage in which transfers are made. Formally, the participation stage can be described as follows. For a game where $N=\{1,2,3\}$, a pointing game Γ is a list $\left(N,(S_i)_{i\in N},U_i\right)$, where $S_i=\{0,1\}^{N\setminus\{i\}}=\{0,1\}\times\{0,1\}$ for each $i\in N$ (a representative element $s_i=\{s_{ij},s_{ik}\}\in S_i$ describes the countries that country i is pointing towards to initiate an agreement, and $s_{ij}=1$ means that country i selects country j while $s_{ij}=0$ means that country i does not select country j) and $U_i(s_i,s_{-i})=u_i\left(\{i,j\}\subset N: s_{ij}=s_{ji}=1\right)$ for each $i\in N$. For $N=\{1,2,3,....,Z\}$, where $Z\geq 4$, and multiple coalitions $\{T_1,T_2,...,T_K\}$, let $S_i=\{0,1,2,...\}$ and $T_k(s)=\{W\subseteq N: i\in T\Leftrightarrow s_i=k\}$ for all $k=\{1,2,...\}$. As in Furusawa and Konishi (2011), the equilibrium concept is PCPNE.

Our paper differs from Silva and Zhu (2013) and Furusawa and Konishi (2011) in many respects. Unlike Silva and Zhu (2013), we consider the incentives for coordination promoted by R&D sharing and the fact that we examine coalition-proof for agreements that prohibit transfers and for agreements in which transfers are allowed. The existence of a transfer mechanism in the Kyoto Protocol is our main motivation to examine agreements that allow transfers. Unlike Furusawa and Konishi (2011), all players can contribute to the global public good, there are excludable knowledge spillovers, public good provision is subject to attrition and congestion costs, the players' payoffs are strictly concave on the global public good and, as the economy grows, there is always a PCPNE for the game without transfers in which all players participate in the contribution group.

We show that if transfers are not allowed, knowledge spillovers flow freely within agreements but research collaborators do not internalize externalities. One important result is that a nation that stands alone in an isolated bilateral arrangement necessarily enjoys an equilibrium payoff that is lower than the common equilibrium payoff earned by the bilateral research collaborators. Even though the stand-alone nation "free rides" on the emission reductions produced by the bilateral research collaborators, it does not partake on the benefits produced by R&D sharing. When transfers are allowed within agreements, they align the incentives of research collaborators: research collaborators find it desirable to choose green R&D products that internalize both types of positive externalities. In contrast to the important result mentioned above, a nation that stands alone in an isolated bilateral arrangement now enjoys an equilibrium payoff that is higher than the common equilibrium payoff earned by the bilateral collaborators. The reason for this is that the benefits from free riding enjoyed by the stand-alone nation outweigh the benefits produced by R&D sharing. In addition, conditional on whether transfers are allowed within agreements, one obtains significantly different equilibrium payoff rankings and PCPNE for large economies.[8]

Green technology deployment is just one of the motivations behind the emergence of hub-and-spoke networks among nations. Indeed, perhaps, the greatest motivation for the development of such

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[8] For a comprehensive analysis of network formation in the presence of transfers, see Bloch and Jackson (2007).

networks is trade expansion: Hur et al (2010) find that nations experience a significant increase in the volume of exports when they become hubs in overlapping free trade agreements (FTAs). Not surprisingly, some nations have been very active in establishing bilateral FTAs with several nations, and hence effectively becoming hubs in networks of overlapping bilateral free trade agreements. Consider, for example, Canada and China. Canada has bilateral FTAs with Chile, Colombia, Costa Rica, Honduras, Israel, Jordan, Panama and Peru. China has bilateral FTAs with Chile, Costa Rica, New Zealand, Peru and Singapore. The existence and growth of overlapping free trade agreements have generated a sizable literature in international economics.[9]

Mukunoki and Tachi (2006) study sequential negotiations of bilateral free trade agreements and show that hub-and-spoke networks are likely to be more effective in delivering multilateral free trade than the alternative system of customs unions. They also show that there is incentive for a nation to be a hub, since the hub nation enjoys greater welfare than the spoke nations in equilibrium. Like Mukunoki and Tachi (2006), we show that the hub nation in a green technology agreement without income transfers fares better than the spoke nations. Unlike Mukunoki and Tachi (2006), we also consider a setting in which income transfers are allowed. We show that the 'hub-incentive effect' disappears when income transfers are allowed, since hub and spoke nations get the same level of welfare in equilibrium. Our paper differs from Mukunoki and Tachi (2006) in many other significant respects, including the existence of crowding costs in green technology agreements and the employed equilibrium concept.

Our paper contributes to the vast literature on international environmental agreements (see, e.g., Carraro and Siniscalco (1993), Barrett (1994), Eyckmans and Tulkens (2003), Diamantoudi and

[9] See, e.g., Mukunoki and Tachi (2006), Furusawa and Konishi (2005), Furusawa and Konishi (2007), Saggi and Yildiz (2010). Furusawa and Konishi (2005) and Furusawa and Konishi (2007) consider such games in which transfers are allowed and not allowed, respectively. Furusawa and Konishi (2005) shows that the global network of FTAs is pairwise-stable in the presence of transfers. Furusawa and Konishi (2007) show that the global network of FTAs is pairwise-stable in the absence of transfers if countries are symmetric or if their products are highly substitutable. For additional references, see these papers and Hur et al. (2010).

Sartzetakis (2006), Chander (2007) and Osmani and Tol (2009)) and to the literature on environmental R&D (see, e.g., Greaker and Hoel (2011) and Golombek and Hoel (2011)). The approach we utilize here deviates from the ones utilized in the literature on international environmental agreements because coalition formation fully accounts for individual and collective deviations in the presence of perfect foresight in a setting where players are able to have unlimited pre-communication and to establish non-binding agreements. Coalition-proofness is a refinement of Nash equilibrium. As for our key contributions to the literature on environmental R&D, to the best of our knowledge, we are the first ones to model the production of collaborative R&D in overlapping international research networks and therefore consider the efficiency and stability of multilateral and hub-and-spoke international green R&D agreements.

The paper is organized as follows. Section 2 builds the basic model for an economy featuring three nations. Section 3 determines PCPNE for settings in which R&D agreements prohibit or allow transfers. Section 4 provides an analysis of global welfare. Section 5 examines PCPNE with and without transfers for large economies. Section 6 concludes the paper.

2. Economy with three nations

We consider an economy consisting of three identical nations, with each nation being indexed by i, $i=1,2,3$. There is one consumer in each nation. The utility consumer i gets from consumption of x_i units of a numeraire good and $G=\sum_{j=1}^{3} g_j$ units of a pure public good (say, reduction in global carbon dioxide emissions through CCS technology) is $u_i = x_i + v(G) = x_i + G(1-G/2)$, $i=1,2,3$. The budget constraint for consumer i is $x_i + c(q_i) = I$, where $c(q_i)$ is nation i's cost of contributing q_i units of R&D utilizing its own resources (net of R&D spillovers) and $I>0$ is nation i's total income. We assume that $c(q_i) = q_i^2/2$. We also assume that I is sufficiently large so that all Nash equilibria examined below are characterized by strictly positive consumption of the numeraire good.[10]

One unit of carbon emission can be reduced with the production of one unit of green R&D. We assume that nation i produces g_i units of green R&D according to the following technology: $g_i = e(a, n_i - 1)\left(q_i + \sum_{j \neq i} g_j / n_i\right)$, where $\sum_{j \neq i} g_j / n_i$ represents the total amount of R&D spillovers received by nation i from its research partners, $a \in [0,1]$ denotes the relational attrition rate faced by a nation when it collaborates with another nation,[11] $n_i \geq 1$ denotes the size of nation i's R&D network (including self) and $e_i = e(a, n_i - 1)$ is nation i's "efficiency rate" function; namely, a function that transforms nation i's potential green R&D output (i.e., the amount of green R&D output this nation can produce in the absence of friction costs) into nation i's actual green R&D output. We assume that $e(a, n_i - 1)$ decreases in both arguments at increasing rates and satisfies $e(a, n_i - 1) \in [0,1]$ for all $a \in [0,1]$ and $n_i \geq 1$, and $e(0, n_i - 1) = e(a, 0) = 1$. In the absence of attrition, coordination is costless, and attrition matters only when a nation does not stand alone in the R&D production process. We assume that $e(a, n-1) = [1 + a(n-1)]^{-1}$.[12]

3. PCPNE analysis

The participation stage may produce several coalitional structures depending on the values of the

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[10] These details of our basic model are widely used in the environmental economics literature which examines transboundary pollution issues (see, e.g., Diamantoudi and Sartzetakis (2006), Nagase and Silva (2007), Silva and Yamaguchi (2010), Silva and Zhu (2009)).

[11] In this paper, the attrition rate is exogenous. Motivated by the discussion in Goyal (2007, pp. 259-261), we believe that an interesting avenue for future work is to consider an asymmetric information model (see, e.g., Cornes and Silva (2000, 2002) and Nagase and Silva (2000)) in which the attrition rate is endogenous. In this richer setting, high attrition rates in the steady state may result from free rider problems in the research teams.

[12] We have considered different specifications for the efficiency function, but the qualitative results regarding payoff rankings remain the same. Hence, we chose the specification that is used in the text because of its simplicity and its intuitive appeal since $e^{-1}(a,2) - e^{-1}(a,1) = a$; that is, the marginal efficiency loss associated with increasing a nation's network size from two to three nations is equal to the attrition rate. As one nation is added to the network with two nations, it makes sense to think that the implied efficiency loss is equal to the additional loss that the extra nation imposes in terms of attrition; namely, a quantity equal to the attrition rate.

parameters of the model. We need to consider all possible coalitional structures that may result in the participation stage and then compare the equilibrium payoffs in order to determine the PCPNE. We examine two different settings: (i) when transfers are not allowed within coalitions; and (ii) when transfers are allowed within coalitions.

3.1. PCPNE without transfers

The coalitional structures that may be produced in the Nash equilibrium for the participation stage are $\left(\{1\},\{2\},\{3\}\right)$, $\left(\{1,2\},\{3\}\right)$, $\left(\{1,3\},\{2\}\right)$, $\left(\{1\},\{2,3\}\right)$, $\left(\{1,2\},\{1,3\}\right)$, $\left(\{1,2\},\{2,3\}\right)$, $\left(\{1,3\},\{2,3\}\right)$ and $\left(\{1,2,3\}\right)$. Consider the multilateral network, $\left(\{1,2,3\}\right)$. In our framework, this network is equivalent to a network of bilateral agreements in which each nation forms a bilateral agreement with the other two nations, that is, $\left(\{1,2\},\{1,3\},\{2,3\}\right)$. Hence, the multilateral network permits each nation to interact with all other nations in the production of green R&D. In the Nash equilibrium for the contribution game, contributions are determined according to the first order conditions, $v'\left(G^M\right)=e^{-1}(a,2)c'\left(q_1^M(.)\right)$, where q_i^M, $i=1,2,3$, denotes nation i's own R&D contribution, net of R&D spillovers, $G^M=\sum_{i=1}^{3}g_i^M$ denotes the total amount of the global public good and g_i^M, $i=1,2,3$, represents nation i's total R&D contribution, including R&D spillovers. The symmetry in interactions implies that all nations earn the same payoff in the Nash equilibrium for the contribution game, $u_i^M=I+v\left(G^M\right)-c\left(q_i^M\right)$, $i=1,2,3$.

In a hub-and-spoke network – i.e., $\left(\{1,2\},\{1,3\}\right)$, $\left(\{1,2\},\{2,3\}\right)$ or $\left(\{1,3\},\{2,3\}\right)$ – only the hub interacts directly with the other nations (the spokes). In this case, there is asymmetry in interactions, since the hub enjoys R&D spillovers from both spokes and each spoke enjoys R&D spillovers from the hub only. The asymmetry in interactions implies that in the Nash equilibrium for the contribution game the hub earns a higher payoff than the spokes. This important result is gathered in the following proposition:

Proposition 1. *For all* $a>0$*, a hub nation's welfare is higher than a spoke nation's welfare.*

Proof. Consider the hub-and-spoke network $\left(\left\{1,2\right\},\left\{1,3\right\}\right)$. Let g_i^H, $i=1,2,3,$ denote the Nash equilibrium R&D output levels. Let q_i^H, $i=1,2,3,$ denote the nations' own R&D contributions in the Nash equilibrium. The conditions that characterize the Nash equilibrium are

$$v'\left(G\right)=e^{-1}\left(a,2\right)c'\left(q_1^H\left(.\right)\right), \tag{1a}$$

$$v'\left(G\right)=e^{-1}\left(a,1\right)c'\left(q_m^H\left(.\right)\right),\ \ m=2,3. \tag{1b}$$

Equations (1b) imply that $q_2^H=q_3^H$. Equations (1a) and (1b), the crowding properties of the efficiency function and the strict convexity of the cost function imply that $q_1^H<q_m^H$, $m=2,3$. To see this, note that $c'\left(q_1^H\right)e^{-1}\left(a,2\right)=c'\left(q_m^H\right)e^{-1}\left(a,1\right)$ is implied by equations (1a) and (1b). Hence, $c'\left(q_1^H\right)/c'\left(q_m^H\right)=e\left(a,2\right)/e\left(a,1\right)<1$ for all $a>0$. Since this implies that $c'\left(q_1^H\right)<c'\left(q_m^H\right)$ for all $a>0$ and $c''\left(\cdot\right)>0$, we obtain $q_1^H<q_2^H=q_3^H$ for all $a>0$. The equilibrium payoff earned by the hub nation is $u_1^H=I+v\left(G^H\right)-c\left(q_1^H\right)$, where $G^H=\sum_{i=1}^{3}g_i^H$. The equilibrium payoff for a spoke nation is $u_m^H=I+v\left(G^H\right)-c\left(q_m^H\right),\ \ m=2,3.$ It follows that $u_1^H>u_m^H$ for all $a>0$ because $q_m^H>q_1^H$ for all $a>0$ and $c'\left(\cdot\right)>0$.■

The hub premium follows from the fact that the hub nation spends less resources to produce R&D than the spoke nations when the attrition rate is positive. This result is consistent with the result obtained by Mukunoki and Tachi (2006) in that a hub enjoys a premium relative to a spoke, even though the essential details that generate our result are quite different from the essential details that lead to their result.

In any isolated bilateral network, the stand-alone nation does not enjoy R&D spillovers. The nations that form a bilateral agreement enjoy R&D spillovers from each other. Thus, in the Nash equilibrium for the contribution game, the equilibrium payoffs for the nations that form a bilateral agreement are always the same. The following proposition informs us that in the Nash equilibrium for the contribution game the stand-alone nation is never better off than the nations that form a bilateral agreement:

Proposition 2. *The equilibrium payoff for the stand-alone nation in the contribution game is never greater than the equilibrium payoffs for the nations that belong to the bilateral technological agreement. The stand-alone nation is worse off than the other nations whenever* $a > 0$.

Proof. Consider the isolated bilateral network $(\{1,2\},\{3\})$. Let g_i^P, $i = 1,2,3$, denote the Nash equilibrium green R&D product levels. Let q_i^P, $i = 1,2,3$, denote the nations' own R&D contributions in the Nash equilibrium. The first-order conditions that characterize the Nash equilibrium are

$$v'(G) = e^{-1}(a,1)c'(q_h^P(.)), \quad h,m = 1,2, \quad m \neq h, \tag{2a}$$

$$v'(G) = c'(q_3^P(.)). \tag{2b}$$

The equilibrium payoffs are $u_h^P = I + v(G^P) - c(q_h^P)$, $h = 1,2$, and $u_3^P = I + v(G^P) - c(q_3^P)$. Hence, $u_h^P \geq u_3^P$ if and only if $q_3^P \geq q_h^P$, $h = 1,2$. But, $q_3^P \geq q_h^P$, $h = 1,2$, because $c' > 0$. If $a = 0$, $e^{-1}(a,1) = 1$ and $q_3^P = q_h^P$, $h = 1,2$. If $a > 0$, $e^{-1}(a,1) > 1$ and $q_3^P > q_h^P$, $h = 1,2$.■

Let us now determine the PCPNE. Anticipating the Nash equilibria payoffs for the contribution games, each nation decides whether or not to make or accept offers in the network formation stage. To determine the PCPNE, we must compare the Nash equilibria payoffs for the contribution games.

The direct R&D spillovers in the multilateral network should provide each nation with an equilibrium payoff that is greater than the lowest equilibrium payoff that is produced by any hub-and-spoke arrangement – namely, the common payoff earned by the spokes – for a sufficiently small attrition rate. This is the relevant condition because two nations can effectively deny another nation a high payoff in a particular equilibrium by selecting another equilibrium in which both are better off. By a similar argument, the hub-and-spoke arrangement becomes superior to the multilateral arrangement for the spokes if the attrition is sufficiently high. The equilibrium for the hub-and-spoke arrangement then becomes coalition proof if the common equilibrium payoffs earned by the spokes are higher than the payoffs that these nations obtain in the equilibrium for the setting with one isolated bilateral agreement. This should be possible since the hub-and-spoke agreement provides direct (for the hub) and indirect R&D spillover benefits relative to the restricted direct bilateral R&D spillover benefits enjoyed by the members of the isolated bilateral agreement. This is indeed the case for an interval of attrition rates, as the proposition below demonstrates. Finally, by continuity, the bilateral arrangement is coalition proof for another interval of attrition rates. The upper attrition rate of this interval is the level at which the equilibrium payoff for the nations in the bilateral agreement is just equal to the equilibrium common equilibrium payoff that each nation can earn in the arrangement in which all nations stand alone. Figure 1 illustrates the results.

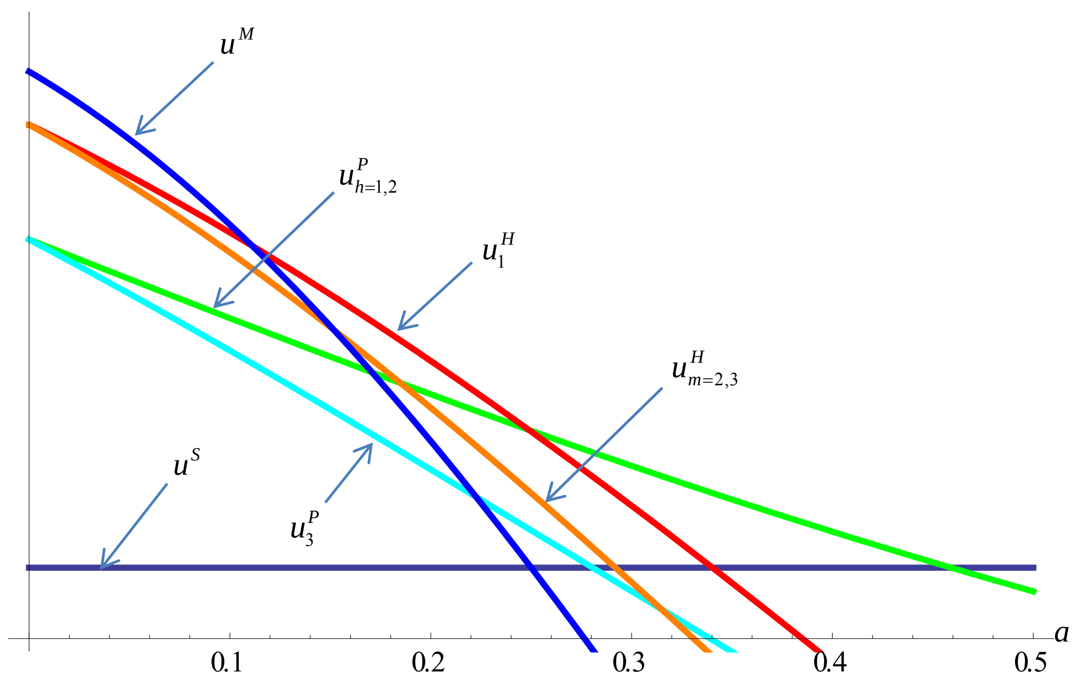

Figure 1. Nash equilibrium payoff levels without transfers

Proposition 3. *For an interval of sufficiently small attrition rates, the perfectly coalition-proof Nash equilibrium is the equilibrium for the multilateral arrangement. For an interval of higher attrition rates, the perfectly coalition-proof Nash equilibrium is the equilibrium for the hub-and-spoke arrangement. For another interval of even higher attrition rates, the perfectly coalition-proof Nash equilibrium is the equilibrium for the arrangement containing an isolated bilateral arrangement.*

Finally, for an interval of sufficiently high attrition rates, the perfectly coalition-proof Nash equilibrium is the equilibrium for the arrangement in which all nations stand alone.

Proof. Let u^M and u^S denote the Nash equilibrium payoffs in the multilateral and stand-alone networks, respectively. From Proposition 1, $u_1^H = u_2^H = u_3^H$ for $a = 0$, and $u_1^H > u_2^H = u_3^H$ for $a \in (0,1]$. From Proposition 2, $u_1^P = u_2^P = u_3^P$ for $a = 0$, and $u_1^P = u_2^P > u_3^P$ for $a \in (0,1]$. Combining the various Nash equilibria payoffs, it follows that the coalition-proof Nash equilibrium is: (i) the Nash equilibrium for the multilateral coalition structure for $a \in [0, 0.152027]$, since $u^M > \max[u_1^H, u_2^H, u_3^H, u_1^P, u_2^P, u_3^P, u^S]$ for $a \in [0, 1/9)$, $u^M = u_1^H$ for $a = 1/9$, $u_1^H > u^M$ for $a \in (1/9, 1]$, $u^M > \max[u_2^H, u_3^H, u_1^P, u_2^P, u_3^P, u^S]$ for $a \in [1/9, 0.152027)$, $u^M = u_2^H = u_3^H > \max[u_1^P, u_2^P, u_3^P, u^S]$ for $a = 0.152027$; (ii) the Nash equilibrium for the hub-and-spoke arrangement for $a \in [0.152027, 0.185142]$, since $u_2^H = u_3^H > \max[u^M, u_1^P, u_2^P, u_3^P, u^S]$ for $a \in (0.152027, 0.185142)$ and $u_2^H = u_3^H = u_1^P = u_2^P$ for $a = 0.185142$; (iii) the Nash equilibrium for the arrangement containing an isolated bilateral agreement for $a \in [0.185142, 0.459224]$, since $u_1^P = u_2^P > \max[u_2^H, u_3^H, u^M, u_3^P, u^S]$ for $a \in (0.185142, 0.459224)$ and $u_1^P = u_2^P = u^S$ for $a = 0.459224$; and (iv) the Nash equilibrium for the arrangement containing singletons for $a \in [0.459224, 1]$ since $u^S > \max[u_1^H, u_2^H, u_3^H, u^M, u_1^P, u_2^P, u_3^P]$ for $a \in (0.459224, 1]$ (see Figure 1 and Appendix B). ■

3.2. PCPNE with transfers

We now determine the PCPNE for international agreements in which international income transfers are feasible. We allow the international transfers to be determined endogenously. We follow the Kyoto Protocol in that the responsibility for the implementation of international transfers within an agreement lies with an outside agency, which we shall refer to as 'international arbitrator.' The rules that govern the arbitrator's choices are that the transfers should be implemented after the nations choose their green R&D outputs (i.e., nations commit to green R&D policies because they are politically powerful vis-à-vis international arbitrators) and the transfers should obey pre-established

Nash bargaining conditions. This is equivalent to saying that in the agreement's non-binding contract it is established that the international transfer mechanism is to be delegated to an international arbitrator and the agreement's total surplus is to be split according to Nash bargaining rules.

Formally, we consider three-stage games of complete but imperfect information. The first and second stages are as before. In the third stage, transfers are implemented within coalitions (see Appendix E for details). All players know that international transfers within any agreement will be implemented in the third stage of the game, after all green R&D levels are observed, in order to satisfy well-known Nash bargaining rules. We assume that the bargaining rules are such that the nations that belong to an agreement receive equal weights. Thus, transfers are chosen in the third stage to equalize payoffs within any coalition. Knowing this, each nation that belongs to an agreement has an incentive to make choices that internalize all externalities within the coalition.

The highest aggregate payoffs are obtained in the arrangements in which both types of externalities are fully internalized by all nations. These are the multilateral and hub-and-spoke arrangements. The critical difference between these arrangements is the fact that in the multilateral arrangement all nations are directly connected to each other while in the hub-and-spoke arrangement the spokes are not directly connected. This implies that for sufficiently small attrition rates, the equilibrium for the multilateral arrangement is Pareto superior to the equilibrium arrangement for the hub-and-spoke arrangement.

But, the equilibrium for the multilateral arrangement is not self-enforcing because for an interval of sufficiently low attrition rates a single nation benefits from deviating from this arrangement and the remaining nations also benefit from sticking together because the common equilibrium payoffs earned by the nations in the isolated bilateral agreement is at least as high as the payoffs these nations obtain in the equilibrium for the setting in which all nations stand alone. But, interestingly, when the common equilibrium payoff for the nations in the isolated bilateral agreement becomes smaller than the common equilibrium payoff these nations can obtain in the setting with all nations standing alone, it becomes individually rational for the free riding nation to "broker" an agreement with the other two nations in which all three nations select the hub-and-spoke arrangement. Due to the fact that all nations in the hub-and-spoke arrangement internalize externalities, the common equilibrium payoff for such an arrangement falls less quickly with the attrition rate than the common equilibrium payoff earned by the nations that belong to the isolated bilateral agreement. Hence, all three nations find it advantageous to select the equilibrium for the hub-and-spoke arrangement for an interval of attrition rates. Once the benefits from R&D sharing are completely eroded by efficiency losses due to an increase in the attrition rate, the coalition-proof Nash equilibrium becomes the equilibrium for the setting in which all nations stand alone in R&D production. Figure 2 illustrates the results.

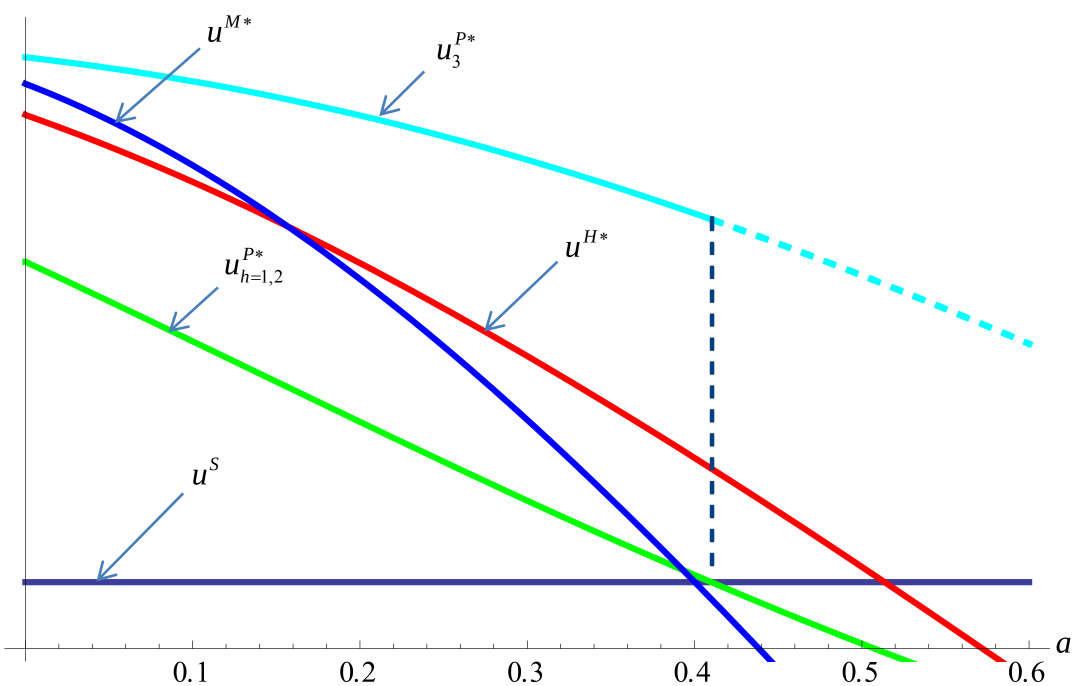

Figure 2. Nash equilibrium payoff levels with transfers

Proposition 4. *For sufficiently small attrition rates, the perfectly coalition-proof Nash equilibrium is the equilibrium for the setting in which there is an isolated bilateral agreement. As attrition rates increase, the perfectly coalition-proof equilibria are first the equilibrium for the hub-and-spoke* *arrangement and later the equilibrium for the setting in which all nations stand alone.*

Proof. Let u^{M*}, u^{H*} and u^{P*} denote the Nash equilibrium payoffs for the multilateral, hub-and-spoke and isolated bilateral networks, respectively. Consider the isolated bilateral network $(\{1,2\},\{3\})$ in what follows. Combining the perfect Nash equilibria payoffs for the relevant structures, we find that the perfect coalition-proof Nash equilibrium structure is: (i) the perfect Nash equilibrium for the setting in which there is an isolated bilateral agreement for $a \in [0, 0.41018]$ since $u_3^{P*} > \max[u^{H*}, u^{M*}]$ for $a \in [0,1]$, $u_3^{P*} > (\leq) u^S$ for $a < (\geq) 0.914214$, $u_1^{P*} = u_2^{P*} > u^S$ for $a \in [0, 0.41018)$ and $u_1^{P*} = u_2^{P*} = u^S$ for $a = 0.41018$; (ii) the perfect Nash equilibrium for the hub-and-spoke arrangement for $a \in (0.41018, 0.513799]$, since $u^{H*} > \max[u^{M*}, u_1^{P*}, u_2^{P*}, u^S]$ for $a \in (0.41018, 0.513799)$ and $u^{H*} = u^S > u^{M*}$ for $a = 0.513799$; (iii) the Nash equilibrium for the arrangement with singletons for $a \in [0.513799, 1]$ since $u^S > \max[u^{H*}, u^{M*}, u_1^{P*}, u_2^{P*}]$ for $a \in (0.513799, 1]$(see also Figure 2 and Appendix C). ■

4. Global Welfare Analysis

We now consider global welfare levels when transfers are not allowed and when agreements allow transfers. We let superscript C index the global welfare level for each relevant coalition structure, $C = H, M, P, S$ when agreements do not allow transfers and $C = H^*, M^*, P^*, S^*$ when agreements allow transfers. The global welfare level is denoted by $W^C \equiv \sum_{i=1}^{3} u_i^C$.

We compute the global welfare levels as functions of the attrition rate. Figure 3 provides the global welfare curves and enables us to derive the following ranking of global welfare levels:

(i) $W^M > \max[W^S, W^P, W^H]$ for $a \in [0, 0.135793)$;

(ii) $W^H > \max[W^S, W^P, W^M]$ for $a \in (0.135793, 0.238574)$;

(iii) $W^P > \max[W^S, W^H, W^M]$ for $a \in (0.238574, 0.371021)$;

(iv) $W^S > \max[W^H, W^M]$ for $a \in (0.371021, 1]$.

When agreements allow transfers, the ranking of global welfare levels is as follows:

(i) $W^{M*} > \max\left[W^{S}, W^{P*}, W^{H*}\right]$ for $a \in \left[0, 0.157355\right)$;

(ii) $W^{H*} > \max\left[W^{S}, W^{P*}, W^{M*}\right]$ for $a \in \left(0.157355, 0.391117\right)$;

(iii) $W^{P*} > \max\left[W^{S}, W^{H*}, W^{M*}\right]$ for $a \in \left(0.391117, 0.41018\right)$;

(iv) $W^{H*} > \max\left[W^{S}, W^{M*}\right]$ for $a \in \left(0.41018, 0.513799\right)$;

(v) $W^{S} > \max\left[W^{H*}, W^{M*}\right]$ for $a \in \left(0.513799, 1\right]$.

The ranking of global welfare levels when agreements do not allow transfers capture the advantage of teamwork for sufficiently small attrition rates. As expected, the greatest benefit from teamwork is in the setting in which all nations are connected. The second-best and third-best situations are the hub-and-spoke network and the isolated bilateral agreement, respectively. When agreements allow transfers, on the other hand, we observe a surprise sort of events. Unlike the well-behaved ranking order for the settings without transfers, we now see that the global welfare level in the setting with an isolated bilateral agreement exceeds the global welfare level in the hub-and-spoke network for an interval of attrition rates, even though for smaller attrition rates the reverse is true. The reason for this is the fact that the stand-alone nation in the setting with an isolated bilateral agreement enjoys an equilibrium payoff that is larger than the common payoff earned by all nations in the hub-and-spoke network and, for an interval of attrition rates, the difference between the equilibrium payoff for the stand-alone nation and the equilibrium payoff earned by the average nation in the hub-and-spoke exceeds the difference between the sum of equilibrium payoffs for the remaining hub-and-spoke nations and the sum of equilibrium payoffs for the bilateral collaborators in the isolated bilateral agreement.

The welfare analysis so far can be understood in terms of what can be achieved if a global planner has the power to command the nations to collaborate or not in green R&D production and, when collaboration is welfare-enhancing, which form of collaboration network (i.e., multilateral, hub-and-spoke or isolated bilateral depicted) should be formed to take advantage of knowledge spillovers. But, in a more realistic scenario, when nations are free to make their own coordination decisions, the coalition structures that materialize are those that are predicted by Propositions 3 and 4. Hence, a non-interventionist global planner would have to be content with the global welfare levels that result from the set of coalition-proof Nash equilibria.

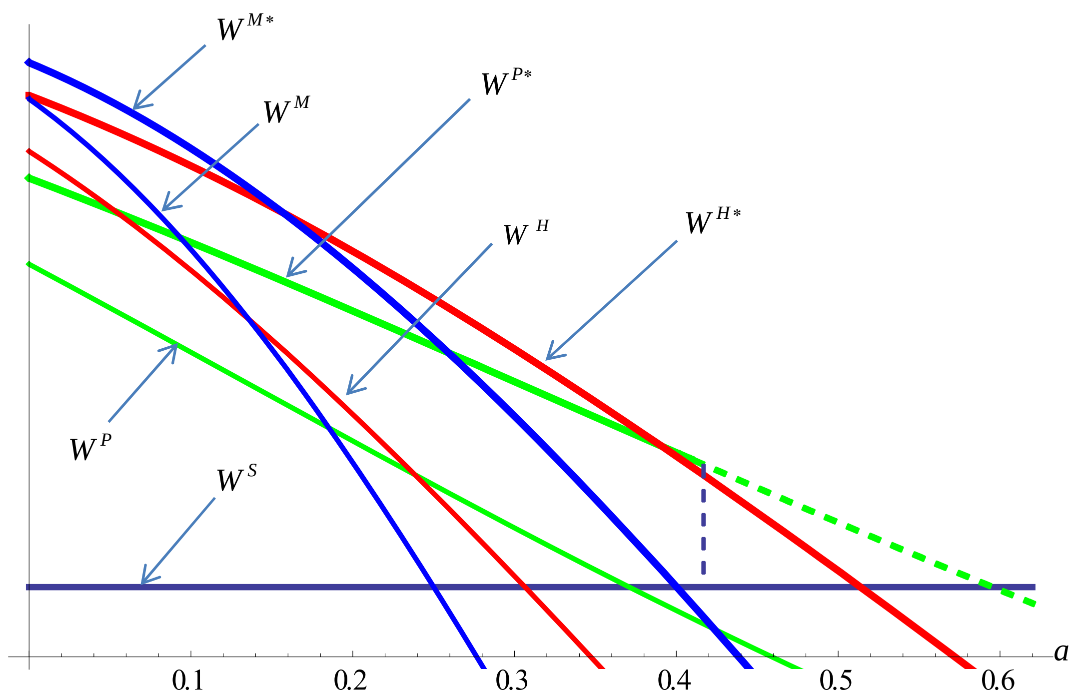

Figure 3. Total welfare

However, close inspection of Figure 3 reveals an interesting, welfare-enhancing, avenue for policy intervention by a global planner, which does not violate the nation's ability to make own coordination choices. Proposition 4 informs us that the Nash equilibrium for the setting with multilateral agreements is not coalition proof. Proposition 3, on the other hand, tells us that for sufficiently small attrition rates the Nash equilibrium for the setting with multilateral agreements is coalition proof. Hence, if a global planner is capable of deciding whether transfers within agreements should be allowed, he or she will have a window of opportunity to exercise his/her power for sufficiently small attrition rates. By prohibiting transfers for an interval of sufficiently small attrition rates, the planner induces the nations to select the Nash equilibrium for the setting with multilateral agreements without transfers. The global welfare improvement resulting from this smart prohibition choice can be clearly seen in Figure 3 (see also Appendix D): it is equal to the horizontal distance between the thin-blue curve and the thick-green curve for sufficiently small attrition levels (i.e., those at which the height of the thin-blue curve is at least as large as the height of the thick-green curve). This occurs for $a < 0.0938257$. Figure 3 also makes it clear that the global planner should allow transfers within agreements for large values of the attrition rate.

Proposition 5. *For sufficiently small attrition rates, constrained global welfare levels improve when transfers are prohibited in green R&D agreements because multilateral agreements without transfers are self-enforcing. For larger attrition rates, constrained global welfare levels are maximal when transfers are allowed in green R&D agreements.*

5. Large economies

In this section, we extend our analysis to settings in which $N = \{1, 2, 3, ..., Z\}$, where there are $Z \geq 4$ nations. We consider both green R&D agreements in which transfers are allowed and in which transfers are prohibited. Due to its ubiquity in the literature and to its symmetric features, we first examine large economies in the presence of income transfers.

5.1. Large economies with transfers

Let $Z - D$ be the number of nations that collaborate in green R&D production by being members of either hub-and-spoke or multilateral international research networks, where D, $1 \leq D < Z$, is the number of stand-alone nations. We allow the formation of multiple coalitions.

Table 1 shows the results of our analysis under the assumption that there is no attrition. For economies of sizes 3 to 6, the PCPNE feature bilateral agreements and 1 to 4 stand-alone nations. For economies of sizes 7 to 13, the PCPNE are characterized by trilateral agreements and 4 to 10 stand-alone nations. Finally, for economies of sizes 173 to 204, the PCPNE feature multilateral agreements containing 12 nations and 161 to 192 stand-alone nations.

Table 1. Stable Agreements for *a* = 0

Z	3 ~ 6	7 ~ 13	14 ~ 23	24 ~ 36	37 ~ 51	52 ~ 70
$Z - D$	2	3	4	5	6	7
Z	71 ~ 91	92 ~ 115	116 ~ 142	143 ~ 172	173 ~ 204	⋯
$Z - D$	8	9	10	11	12	⋯

One important result of the analysis is that at most one coalition is formed. We also find that the sizes of the stable multilateral agreements increase at a decreasing rate as the size of the global economy increases. These implications follow from the fact that technological spillovers associated with collaborative R&D products are enjoyed by nations that join R&D agreements only. In other words, the collaborative R&D output produced by R&D agreements generates a nonrivalrous and nonexcludable knowledge public good for the members of an agreement, but outsiders do not enjoy access to this public good.[13] Outsiders, on the other hand, enjoy the by-product, which results from knowledge creation in green R&D agreements. This by-product is the collective carbon emission reductions promoted by the members of the green R&D agreement. Therefore, there is a tension between the incentive of being a member in a multilateral agreement and the incentive to free ride (i.e., to stand alone) on the emission reductions promoted by the collective efforts of the multilateral agreement.

The analysis demonstrates that the tension between the incentive to join the "club" and the incentive to free ride produces the unconventional finding that the size of a stable multilateral coalition increases with the size of the economy. Diamantoudi and Sartzetakis (2006), whose model builds on the model advanced by Barrett (1994), demonstrate that the stable coalition involves no more than four countries. We must also emphasize that our stable coalitions emerge from a refinement

[13] See Silva and Kahn (1993) for an early analysis of exclusion incentives in voluntary public good provision in which coalition proofness is utilized to select a stable Nash equilibrium.

of Nash equilibrium. This method is quite distinct from the most common notions of coalition stability used in the literature, such as the notion of 'internal and external stability' originated by d'Apremont et al. (1983). Different methods should generate different outcomes.

We summarize our finding with respect to the effect of an expansion in the number of nations on the size of a stable multilateral coalition in the absence of attrition in the following proposition:

Proposition 6. *In the absence of attrition, the larger the global economy is, the larger will be the size of the stable multilateral green R&D agreement.*

Table 2. Stable coalition structures

(ranges for the attrition rate in parentheses)

Z	Bilateral or Multilateral	Hub-and-Spoke
4	$D = 2$ (0 ~ .256)	$D = 1$ (~ .397)
5	$D = 3$ (0 ~ .126) $D = 2$ (~ .157)	$D = 2$ (~ .296) $D = 1$ (~ .388)
6	$D = 4$ (0 ~ .003) $D = 3$ (~ .157)	$D = 3$ (~ .214) $D = 2$ (~ .307) $D = 1$ (~ .383)
7	$D = 4$ (0 ~ .151)	$D = 3$ (~ .241) $D = 2$ (~ .312) $D = 1$ (~ .38)
8	$D = 5$ (0 ~ .114)	$D = 4$ (~ .189) $D = 3$ (~ .255) $D = 2$ (~ .316) $D = 1$ (~ .378)
9	$D = 6$ (0 ~ .083) $D = 5$ (~ .112)	$D = 5$ (~ .146) $D = 4$ (~ .209) $D = 3$ (~ .264) $D = 2$ (~ .319) $D = 1$ (~ .377)
10	$D = 7$ (0 ~ .058) $D = 6$ (~ .112)	$D = 5$ (~ .171) $D = 4$ (~ .221) $D = 3$ (~ .27) $D = 2$ (~ .321) $D = 1$ (~ .377)

For $a \in [0,1]$, the sets of coalition-proof equilibria for $Z \geq 4$ are shown in Table 2 above. Table 2 shows that the types of stable coalition structures depend crucially on both the number of nations, Z, and the attrition rate, a. As demonstrated above, if $a = 0$, the resulting stable coalition structures will consist of a mix of multilateral and stand-alone nations, except for isolated bilateral agreements for $Z < 7$; that is, $(Z, D) =$ (3,1), (4,2), (5,3), and (6,4). The equilibrium payoff for a stand-alone nation in the singleton coalition structure increases with Z: it becomes larger than the common equilibrium payoff earned by bilateral nations in isolated bilateral agreements for all $Z \geq 7$.

For the interval of positive attrition rates, we see that as the attrition rate increases, the stable coalition structures contain initially a mix of multilateral and stand-alone nations. Then, for higher attrition rates, it becomes a mix of hub-and-spoke agreements and stand-alone nations. For still higher attrition rates, it features a mix of isolated bilateral agreements and stand-alone nations. Finally, for sufficiently high attrition rates, it consists of stand-alone nations only.

5.2. Large economies without transfers

If income transfers are not allowed within coalitions, the number and types of PCPNE increase because there are several Nash equilibrium with asymmetric outcomes. The analysis is more complex, but we are able to provide some coherent results for the PCNPE and for the "second-best" structures for sufficiently low attrition rates. The purpose of this exercise is to illustrate that the stable coalition structures can indeed be very large, encompassing all the nations in globe, and that there are multiple types of stable coalition structures depending on the value of the attrition parameter.

Table 3. Attrition Ranges for the Top 3 PCPNEs

Z	Multilateral	2nd Formation	3rd Formation
4	0 ~ .0691	Circle of 4 (~ .1319)	2 Bilateral (~ .3659)
5	0 ~ .0442	Hub & Circle of 4 (~ .0626)	Circle of 5 (~ .1751)
6	0 ~ .0290	Circle of 6 + 6 Bilateral (~ .0425)	Circle of 6 + 3 Bilateral (~ .0687)

Figures 4-6 illustrate the Nash equilibrium payoffs as functions of the attrition rate. The results are also gathered in Table 3. Figure 4 clearly shows that the second-best-stable formation is the "circle of four" in which all nations have two links, one link to each of its two neighbors. If $Z = 5$, Figure

5 shows that the second-best-stable formation is characterized by one nation being a hub (linked to the other four nations) and the other four nations having two links. If $Z = 6$, Figure 6 shows that in the second-best-stable formation each nation is linked to four other nations.

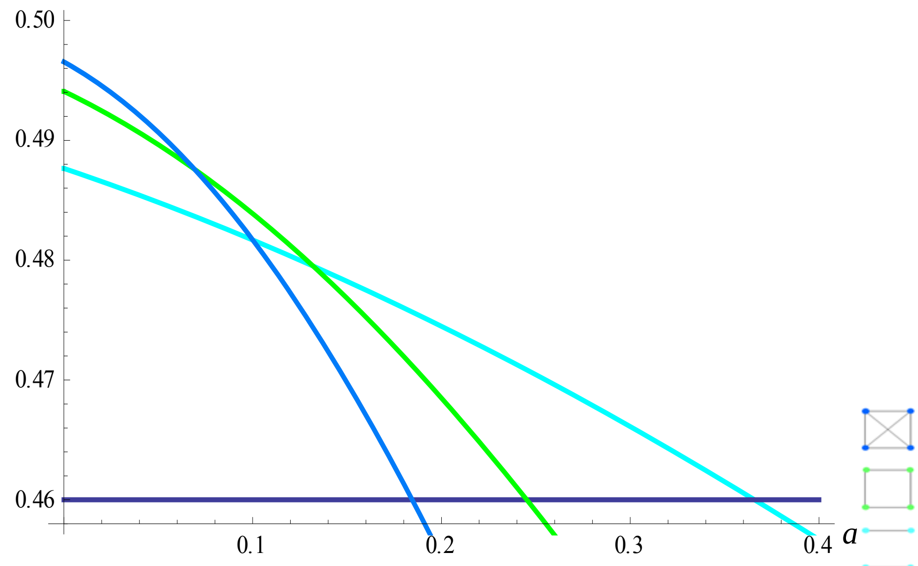

Figure 4: PCPNE for Z = 4

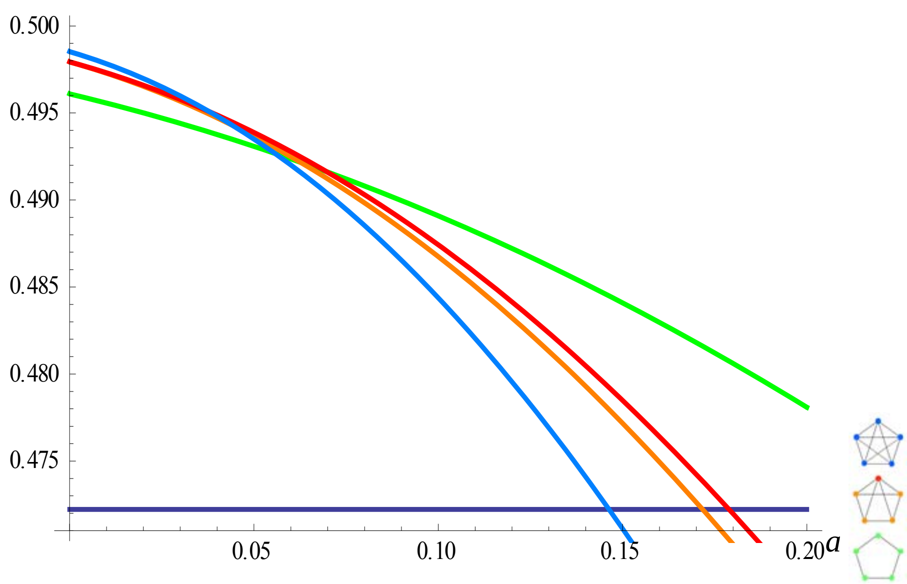

Figure 5: PCPNE for Z = 5

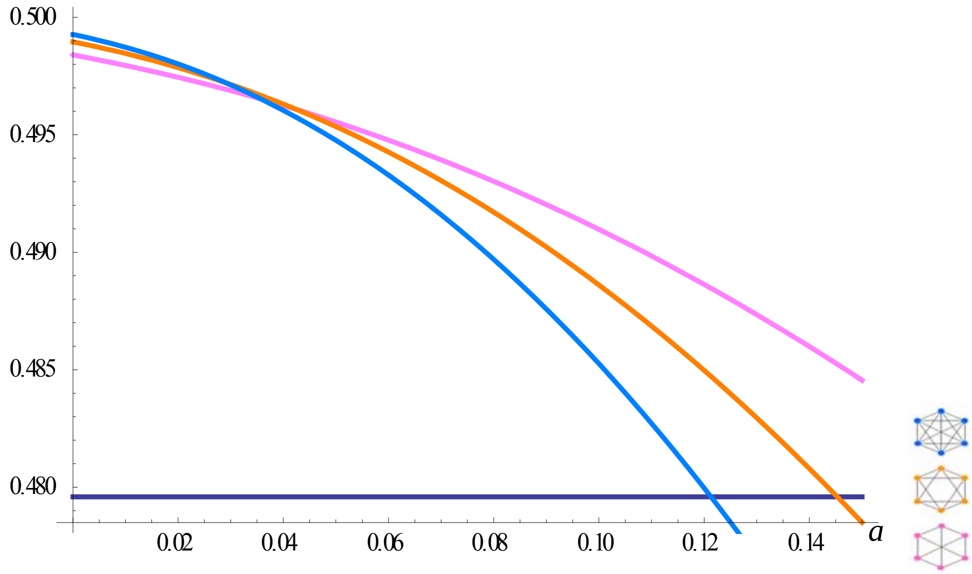

Figure 6: PCPNE for Z = 6

First, it is important to note that the multilateral arrangement containing all nations is a PCPNE for sufficiently low attrition rates for economies with four, five and six nations. It also appears that if the total number of nations is odd, the second-best-stable formation is characterized by a hub with a larger number of links than the spokes, and if the total number of nations is even, the second-best-stable formation is characterized by a symmetric composition where all nations have the same number of links.

By considering larger economies, with up to 197 nations, we see that the two main findings described above are consistent throughout. If the attrition is sufficiently small, say $a \leq 0.0000257689$, the PCNPE will always involve all nations in the globe! This is good news for international R&D agreements in which the benefits from R&D spillovers are perfectly excludable. In addition, the second-best PCPNE alternates depending on whether or not the total number of nations is odd – see Table 4 and Appendix F.

Table 4. Cut-off attrition values

Z	2nd Formation	Cut-off value
4	Circle of 4	0.0690696
5	Hub & Circle of 4	0.0441995
6	Circle of 6 + 6 Bilateral	0.0290215
7	H&C of 6 + 6 Bilateral	0.0214552
8	Circle of 8 + 16 Bilateral	0.0160121
9	H&C of 8 + 16 Bilateral	0.0127239
10	Circle of 10 + 30 Bilateral	0.0101571
11	H&C of 10 + 30 Bilateral	0.00843318
…		
196	Circle of 196 + 18816 Bilateral	0.0000260318
197	H&C of 196 + 18816 Bilateral	0.0000257689

6. Concluding Remarks

We derive our main motivation from the fact that several nations are currently engaged in the production of CCS research in collaborative R&D networks. These networks are bilateral, multilateral and hub-and-spoke. Such networks may be promising alternatives to global R&D agreements in that they are likely to be more effective (i.e., self-enforcing). Hub-and-spoke networks, in particular, may allow the hub nation to partake on knowledge spillovers from several partners and thus increase the hub's potential to benefit from novel and non-redundant pieces of knowledge.

Our theoretical model also builds on recent empirical findings of studies of collaborative R&D that demonstrate that the productivity of R&D collaborations may crucially depend on some aspects related to social interactions among researchers. There is evidence that productivity in research teams is positively correlated to team cohesiveness. A team is more cohesive the stronger are the ties among its team members. There is also evidence that cohesive R&D collaborations are developed in order to alleviate or resolve problems of informational asymmetries within research teams. Thus, there appears to be a chain linking team efforts to alleviate inherent problems of informational asymmetries to the level of trust shared by team members and the latter to team's research productivity. We incorporate these notions in our model in a synthetic form. We assume that international research collaborations are typically subject to relational attrition, which erodes their efficiency rate. We also allow efficiency to be eroded by the size of a nation's research network.

We demonstrate that, conditional on the magnitude of the attrition rate, multilateral, hub-and-spoke and isolated bilateral agreements can be stable if income transfers are not allowed in such agreements. Since the benefits generated by R&D sharing are larger the larger it is the number of nations that collaborate (directly or indirectly), multilateral agreements are Pareto superior for sufficiently small attrition rates, with hub-and-spoke agreements being second best and isolated bilateral agreements being third best.

If transfers are allowed within agreements, multilateral agreements are never coalition-proof. However, hub-and-spoke and isolated bilateral agreements are stable for different attrition rates. Given the stability results for agreements in which transfers are prohibited and for agreements in which transfers are allowed, we demonstrate that global welfare improves if transfers are prohibited for sufficiently low attrition rates because multilateral agreements without transfers are stable for an interval of sufficiently low attrition rates.

We also considered the effects associated with enlarging the global economy. The findings depend on whether or not transfers are allowed within coalitions. If transfers are allowed, we find that the size of a stable multilateral agreement increases as the size of the global economy expands in the absence of attrition. We also demonstrate that for positive attrition rates all types of coalition structures can be stable as the size of the global economy expands. However, a stable agreement will never involve full participation. On the other hand, if transfers are not allowed, the stable agreement will involve all nations in the globe provided the attrition rate is small enough. Several other arrangements, with participation of almost all nations in the globe, are shown to be stable depending on the value of the attrition rate. The type of "second-best" stable arrangement depends on whether or not the number of nations in the globe is even or odd. If it is even, the second-best stable arrangement involves. If it is odd, the second-best arrangement involves. Overall, one can clearly see that the potential benefit of prohibiting transfers, which is already present in a setting with three nations only, should become larger, for sufficiently low attrition rates, as the number of nations in the globe increases. The number of nations that will find it desirable to enter into an international green R&D agreement when transfers are prohibited relative to the number that will enter into a similar agreement when transfers are allowed increases with the total number of countries in the world.

Our findings enable us to conjecture that the current international green R&D networks may be self-enforcing and may still increase in size, even in the presence of significant attrition.

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Appendices

Appendix A: Extension of Perfectly Coalition-Proof Equilibria (Silva and Zhu (2013))

"For the n-player game $\Gamma = \left[\left\{ u_i \right\}_{i=1}^{n}, \left\{ S_i \right\}_{i=1}^{n} \right]$, let $\boldsymbol{J}$ be the set of subsets of $\left\{ 1,...,n \right\}$. For $h \geq 1$, $m \geq 1$ and $n \geq h+m$, let $J_{\{h,...,h+m\}} \equiv \left\{ h, h+1,...,h+m \right\} \in \boldsymbol{J}$. For $h=1$ and $m=n-1$, we have $J_{\{1,...,n\}} \equiv \left\{ 1,...,n \right\}$. Hence, $J_{\{h,...,h+m\}}$ is a consecutively ordered subset of $J_{\{1,...,n\}}$. Let $\boldsymbol{J}_{(h,m)}$ be the set of subsets of $J_{\{h,...,h+m\}}$. An element of $\boldsymbol{J}_{(h,m)}$ is denoted $J_{(h,m)}$. Let $S_{J_{(h,m)}} \equiv \prod_{i \in J_{(h,m)}} S_i$. For the case $\left\{ 1,...,n \right\}$, we will write S. Let $-J_{(h,m)}$ be the complement of $J_{(h,m)}$ in $\left\{ 1,...,n \right\}$. For every $s^o_{-J_{(h,m)}} \in S_{-J_{(h,m)}}$, let $\Gamma / s^o_{-J_{(h,m)}} \equiv \left[\left\{ \bar{u}_i \right\}_{i \in J_{(h,m)}}, \left\{ S_i \right\}_{i \in J_{(h,m)}} \right]$ be the game induced on coalition $J_{(h,m)}$ by the actions $s^o_{-J_{(h,m)}}$ for coalition $-J_{(h,m)}$, where $\bar{u}_i : S_{J_{(h,m)}} \rightarrow R$ is given by $\bar{u}_i \left(s_{J_{(h,m)}} \right) \equiv u_i \left(s_{J_{(h,m)}}, s^o_{-J_{(h,m)}} \right)$ for every $i \in J_{(h,m)}$ and $s_{J_{(h,m)}} \in S_{J_{(h,m)}}$.

BPW (p.6) defines self-enforceability and coalition-proofness recursively as follows:

Definition 2. (i) In a single player game Γ, $s^* \in S$ is a *Coalition-Proof Nash equilibrium* if and only if s^* maximizes $u_1(s)$.

(ii) Let $n > 1$ and assume that Coalition-Proof Nash equilibrium has been defined for games with fewer than n players. Then,

(a) For any game Γ with n players, $s^* \in S$ is *self-enforcing* if, for all $J_{(h,m)} \in \boldsymbol{J}$, $s^*_{J_{(h,m)}}$ is a Coalition-Proof Nash equilibrium in the game $\Gamma / s^*_{-J_{(h,m)}}$.

(b) For any game Γ with n players, $s^* \in S$ is a *Coalition-Proof Nash equilibrium* if it is self-enforcing and if there does not exist another self-enforcing strategy vector $s \in S$ such that $u_i(s) > u_i(s^*)$ for all $i = 1,...,n$.

We now turn to our extension of BPW's self-enforceability and coalition-proofness concepts. Let $o \geq 2$ denote the number of coalitions in a particular collection of overlapping coalitions, $J_{(h_1,m_1)}$, $J_{(h_2,m_2)}$, …, $J_{(h_o,m_o)}$, where $h_l \geq 1,\ m_l \geq 1,\quad n \geq h_l + m_l,\ l = 1,...,o$. Without loss of generality, assume that $J_{(h_k,m_k)} \cap J_{(h_{k+1},m_{k+1})} \neq \emptyset,\ k = 1,...,o-1$. Let $J_{\bigcup_{l=1}^{o} J_{(h_l,m_l)}} \equiv J_{(h_1,m_1)} \cup J_{(h_2,m_2)} \cup ... \cup J_{(h_o,m_o)}$. Let $-J_{\bigcup_{l=1}^{o} J_{(h_l,m_l)}}$ be the complement of $J_{\bigcup_{l=1}^{o} J_{(h_l,m_l)}}$ in $\{1,...,n\}$. Since $S_{J_{(h_l,m_l)}} \equiv \prod_{i \in J_{(h_l,m_l)}} S_i$, let $S_{\bigcup_{l=1}^{o} J_{(h_l,m_l)}} = \prod_{l=1}^{o} S_{J_{(h_l,m_l)}}$. For every $s^o_{-J_{\cup_{l=1}^{o} J_{(h_l,m_l)}}} \in S_{-J_{\cup_{l=1}^{o} J_{(h_l,m_l)}}}$ let $\Gamma / s^o_{-J_{\cup_{l=1}^{o} J_{(h_l,m_l)}}} \equiv \left[\{\bar{u}_i\}_{i \in J_{\cup_{l=1}^{o} J_{(h_l,m_l)}}}, \{S_i\}_{i \in J_{\cup_{l=1}^{o} J_{(h_l,m_l)}}} \right]$ be the game induced on coalition $J_{\bigcup_{l=1}^{o} J_{(h_l,m_l)}}$ by the actions $s^o_{-J_{\cup_{l=1}^{o} J_{(h_l,m_l)}}}$ for coalition $-J_{\bigcup_{l=1}^{o} J_{(h_l,m_l)}}$, where $\bar{u}_i : S_{J_{\cup_{l=1}^{o} J_{(h_l,m_l)}}} \to R$ is given by $\bar{u}_i\left(s_{J_{\cup_{l=1}^{o} J_{(h_l,m_l)}}}\right) \equiv u_i\left(s_{J_{\cup_{l=1}^{o} J_{(h_l,m_l)}}}, s^o_{-J_{\cup_{l=1}^{o} J_{(h_l,m_l)}}}\right)$ for every $i \in J_{\bigcup_{l=1}^{o} J_{(h_l,m_l)}}$ and $s_{J_{\cup_{l=1}^{o} J_{(h_l,m_l)}}} \in S_{J_{\cup_{l=1}^{o} J_{(h_l,m_l)}}}$. Our extension of **Definition 2** is limited to imposing an additional restriction on the concept of self-enforceability (i.e., replacing (ii.a) with (ii.a')):

(a') For any game Γ with n players, $s^* \in S$ is *self-enforcing* if, for all *non-overlapping* $J_{(h,m)} \in \boldsymbol{J}$, $s^*_{J_{(h,m)}}$ is a Coalition-Proof Nash equilibrium in the game $\Gamma / s^*_{-J_{(h,m)}}$, and for *any collection of overlapping coalitions*, $J_{(h_l,m_l)}$, $l = 1,...,o$, $s^*_{J_{\cup_{l=1}^{o} J_{(h_l,m_l)}}}$ is a Coalition-Proof Nash equilibrium in the game $\Gamma / s^*_{-J_{\cup_{l=1}^{o} J_{(h_l, m_l)}}}$.

In words, for a strategy vector to be self-enforcing it needs to "pass" two tests: (i) the Nash equilibrium for any partition of non-overlapping coalitions must be coalition proof, just like in BPW; and (ii) for any partition containing overlapping coalitions, the Nash equilibrium for a partition consisting of two relevant sets – namely, a coalition produced by the union of overlapping coalitions and the complement of such a coalition – must be coalition proof. When coalitions overlap, the players who belong to a particular set of overlapping coalitions make strategic choices taking the strategic choices of all players who do not belong to this set of overlapping coalitions (i.e., players who belong to the complement of the union of the overlapping coalitions) as given, and vice-versa. The equilibrium strategies are determined according to two relevant coalitions, the superset formed by the union of the overlapping coalitions and its complement. Given such sets, the self-enforceability concept of BPW is readily applicable." (Silva and Zhu (2013), pp. 9-11)

Silva and Zhu also extend the concept of perfectly coalition-proof Nash equilibrium.

"**Definition 3.** (i) In a single player, single stage game Γ, $s^* \in S$ is a *Perfectly Coalition-Proof Nash* equilibrium if and only if s^* maximizes $u_1(s)$.

(ii) Let $(n,t) \neq (1,1)$. Assume that Perfectly Coalition-Proof Nash equilibrium has been defined for all games with ν players and τ stages, where $(\nu,\tau) \leq (n,t)$, and $(\nu,\tau) \neq (n,t)$.

(a) For any game with n players and t stages, $s^* \in S$ is *perfectly self-enforcing* if:

(1) for all *non-overlapping* $J_{(h,m)} \in \boldsymbol{J}$, $s^*_{J_{(h,m)}}$ is a Perfectly Coalition-Proof Nash equilibrium in the game $\Gamma / s^*_{-J_{(h,m)}}$; (2) for *any collection of overlapping coalitions*, $J_{(h_l,m_l)}$, $l = 1,...,o$, $s^*_{J_{\cup_{l=1}^{o} J_{(h_l, m_l)}}}$ is a Coalition-Proof Nash equilibrium in the game

$\Gamma / s^*_{-J_{\cup_{l=1}^{o} J(h_l, m_l)}}$; and (3) the restriction of s^* to any proper subgame forms a Perfectly Coalition-Proof Nash equilibrium in that subgame.

For any game with n players and t stages, s^* is a *Perfectly Coalition-Proof Nash equilibrium* if it is perfectly self-enforcing, and if there does not exist another perfectly self-enforcing strategy vector $s \in S$ such that $u_i(s) > u_i(s^*)$ for all $i = 1,...,n$.” (Silva and Zhu (2013), pp. 15-16)

Appendix B: Proof of Proposition 3

From Proposition 2, we know that $u_1^P = u_2^P > u_3^P$ for $a \in (0,1]$ and from Proposition 1, we know that $u_1^H > u_2^H = u_3^H$ for $a \in (0,1]$. From the conditions that determine the Nash equilibria for the contribution games, we obtain

$$g^S = 1/4,\ \ g_1^P = g_2^P = (3+3a+2a^2)^{-1},\ \ g_3^P = (1+a)(1+2a)/[2(3+3a+2a^2)],$$
$$g_1^H = (5+10a+3a^2)/(4\Delta_1),\ \ g_2^H = g_3^H = 3(3+9a+8a^2)/(8\Delta_1),\ \ g^M = 3/(10+8a+12a^2),$$

where $\Delta_1 \equiv 4+13a+16a^2+9a^3+3a^4$. From these results, we have

$$u^S = w + \frac{7}{16},\ \ u^M = w + \frac{49+66a+90a^2}{4(5+4a+6a^2)^2},\ \ u_{h=1,2}^P = w + \frac{34+62a+67a^2+36a^3+12a^4}{8(3+3a+2a^2)^2},$$

$$u_3^P = w + \frac{17+30a+29a^2+12a^3+4a^4}{4(3+3a+2a^2)^2},\ \ u_{m=2,3}^H = u_1^H - \frac{a(2+3a)(2+9a+6a^2)^2}{32\Delta_1^2},$$

$$u_1^H = w + (124+780a+2099a^2+3100a^3+2685a^4+1326a^5+306a^6)/(16\Delta_1^2).$$

Comparing these outcomes yields that: $u_1^P = u_2^P > (\le) u^S$ if $a < (\ge) 0.459224$, $u_3^P > (\le) u^S$ if $a < (\ge) 0.280776$, $u_1^H > (\le) u_1^P = u_2^P$ if $a < (\ge) 0.248912$, $u_2^H = u_3^H > (\le) u_1^P = u_2^P$ if $a < (\ge) 0.185142$, $u^M > (\le) u_1^H$ if $a < (\ge) 1/9$, $u^M > (\le) u_2^H = u_3^H$ if $a < (\ge) 0.152027$, $u_2^H = u_3^H > (\le) u^S$ if $a < (\ge) 0.292069$. These results are in the proof and summarized in Figure 1.

Appendix C: Proof of Proposition 4

The Nash equilibria for the contributions games yield

$$g_1^{P*} = g_2^{P*} = 4/(9+4a+4a^2),\ \ g_3^{P*} = (1+4a+4a^2)/[2(9+4a+4a^2)],$$

$$g_1^{H*} = 3(26+39a+9a^2)/(4\Delta_2), g_2^{H*} = g_2^{H*} = 9(14+31a+24a^2)/(8\Delta_2),$$
$$g^{M*} = 27/[2(41+6a+18a^2)],$$

where $\Delta_2 \equiv 52+108a+87a^2+27a^3+9a^4$. From these results, we have

$$u_1^{P*} = u_2^{P*} = w + \frac{307+216a+264a^2+96a^3+48a^4}{8(9+4a+4a^2)^2},$$

$$u_3^{P*} = w + \frac{161+136a+152a^2+32a^3+16a^4}{4(9+4a+4a^2)^2},$$

$$u^{H*} = w+3(68+132a+81a^2)/8\Delta_2, \quad u^{M*} = w+81/[4(41+6a+18a^2)].$$

By comparing these payoffs, we obtain that: $u_3^{P*} > (\leq) u^S$ if $a < (\geq) 0.914214$, $u_1^{P*} = u_2^{P*} > (\leq) u^S$ if $a < (\geq) 0.41018$, $u^{H*} > (\leq) u^S$ if $a < (\geq) 0.513799$, $u^{H*} > (\leq) u_1^{P*} = u_2^{P*}$ if $a < (\geq) 0.642148$, $u^{H*} < u_3^{P*}$ $\forall a \in [0,1]$, $u^{M*} < u_3^{P*}$ $\forall a \in [0,1]$, $u^{M*} > (\leq) u^{H*}$ if $a < (\geq) 0.157355$. These results are in the proof and summarized in Figure 2.

Appendix D: Proof of Proposition 5

By utilizing the results in Appendix B and C, we obtain that: $W^S = 3w + 21/16$, $W^P = 3w + (51+92a+96a^2+48a^3+16a^4)/[4(3+3a+2a^2)^2]$, $W^H = 3w + (372+2332a+6213a^2+8982a^3+7524a^4+3582a^5+810a^6)/[16(\Delta_1)^2]$, $W^M = 3w + 3(49+66a+90a^2)/[4(5+4a+6a^2)^2]$, $W^{M*} = 3w + 243/[4(41+6a+18a^2)]$, $W^{P*} = 3w + (13+4a+4a^2)/(9+4a+4a^2)$, $W^{H*} = 3w + 9(68+132a+81a^2)/(8\Delta_2)$, which yield that: $W^M > W^H$ if $a < 0.135793$, $W^H > W^P$ if $a < 0.238574$, $W^H > W^S$ if $a < 0.30648$, $W^{M*} > W^{H*}$ if $a < 0.157355$, $W^{H*} > W^S$ if $a < 0.513799$, $W^{H*} > W^{P*}$ if $a < 0.391117$, $W^M > W^{P*}$ if $a < 0.0938257$. Since $u_1^{P*} = u_2^{P*} > u^S$ for $a < 0.41018$, we are able to summarize the results in Figure 3.

Appendix E: Large economies without Transfers

Solving the system of first order conditions for the structure with stand alone nations yields the Nash equilibrium payoffs for the contribution game: $\tilde{u}^S = w - c(\tilde{q}^S) + v(Z\tilde{q}^S)$.

In the hub-and-spoke partial coalitional structure, the hub nation 1 forms $Z-D-1$ bilateral coalitions, while $1 \le D < Z$ nation(s) form singleton coalition(s). In the third stage, the international arbitrator implements intra-coalitional transfers for all $\{1,i\}$, $i = 2,\cdots,Z-D$ coalitions. The first order conditions to the optimization problems imply that all transfers satisfy $u_1 = u_i$ and $t_{1i} + t_{i1} = 0$ for $i = 2,\cdots,Z-D$, which yields

$$t_{1i}^H(g_1,\cdots,g_{Z-D}) = \frac{1}{(Z-D)}\left[\sum_{j=1,\, j\neq i}^{N-D} c\left(q_j^H\right) - (Z-D-1)c\left(q_i^H\right)\right],\ i = 2,\cdots,Z-D.$$

The first order conditions for the hub 1 and spoke $i = 2,\cdots,Z-D$ in the first stage are

$$v'(G) = \frac{1}{(Z-D)}\left[c'\left(q_1^H\right)e^{-1}(a, Z-D-1) - \sum_{i=2}^{Z-D} c'\left(q_i^H\right)\Big/2\right], \tag{A.1}$$

$$v'(G) = \frac{1}{(Z-D)}\left[c'\left(q_i^H\right)e^{-1}(a,1) - c'\left(q_1^H\right)\big/(Z-D)\right]. \tag{A.2}$$

Summing (A.1) and (A.2) in the symmetric equilibrium with $q_1^H = \tilde{q}_1^{H*}$, and $q_i^H = \tilde{q}_s^{H*}$ for $i = 2,\cdots,Z-D$, yields the Samuelson condition for $Z-D$ nations' hub-and-spoke structure; i.e., the sum of nations' MRS's of the public good in the LHS should equal to its MRT in the RHS:

$$(Z-D)v'(G) = \frac{1}{(Z-D)}\left\{\begin{matrix} c'\left(\tilde{q}_1^{H*}\right)\left[e^{-1}(a, Z-D-1) - (Z-D-1)/(Z-D)\right] \\ +(Z-D-1)c'\left(\tilde{q}_s^{H*}\right)\left[e^{-1}(a,1) - 1/2\right] \end{matrix}\right\}.$$

In the multilateral partial coalitions, the solution to the arbitrator's problem in the second stage satisfies that $u_1 = \cdots = u_{Z-D}$ and $\sum_{i=1}^{Z-D} t_i = 0$, which yields the intra-coalition income transfers for $i = 1,\cdots,Z-D$ as follows:

$$t_i^M(g_1,\cdots,g_{Z-D}) = \frac{1}{Z-D}\left[(Z-D-1)c\left(q_i^M\right) - \sum_{j\neq i} c\left(q_j^M\right)\right].$$

The first order condition for $i = 1,\cdots,Z-D$ in the second stage is

$$v'(G) = \frac{1}{(Z-D)}\left[c'\left(q_i^M\right)e^{-1}(a, Z-D-1) - \frac{1}{Z-D}\sum_{j\neq i} c'\left(q_j^M\right)\right], \tag{A.3}$$

which yields $q_i^M = \tilde{q}^{M*}$ since $g_i^M = \tilde{g}^{M*}$ for $i = 1, \cdots, Z - D$. Summing (A.3) yields the Samuelson condition for $Z - D$ members' multilateral coalitions structure as follows:

$$(Z-D)v'(G) = c'\left(\tilde{q}^{M*}\right)\left[e^{-1}(a, Z-D-1) - (Z-D-1)/(Z-D)\right].$$

Setting $e(a, n-1) = \left[1 + a(n-1)\right]^{-1}$ and $v(G) = G(1 - G/2)$ with the first order condition for Z members' multilateral coalitions structure: $Zv'(G) = c'\left(\tilde{q}^{M*}\right)\left[e^{-1}(a, Z-1) - (Z-1)/Z\right]$, (2b) for $i = 1, \cdots, D$, (A.1), (A.2), and (A.3) yields Z nations economy's outcomes summarized in Table 1 and 2.

Appendix F: Large economies without transfers

In multilateral networks containing Z nations, each nation forms $Z - 1$ bilateral coalitions. The first order conditions are as follows:

$$v'(G) = c'\left(q_i^M\right)e^{-1}(a, Z-1), \quad i = 1, \cdots, Z, \tag{A.4}$$

which yields $q_i^M = \hat{q}^M$ since $g_i^M = \hat{g}^M$ for $i = 1, \cdots, Z$. Since the maximum number of links for Z members is $Z(Z-1)/2$, subtracting 1 link between nations 1 and 2 from the multilateral coalitions structure (i.e., $Z(Z-1)/2 - 1$ bilateral agreements) can be characterized by equations (A.4) for $i = 3, \cdots, Z$, and the following first order conditions:

$$v'(G) = c'\left(q_j\right)e^{-1}(a, Z-2), \quad j = 1, 2. \tag{A.5}$$

Setting $e(a, n-1) = \left[1 + a(n-1)\right]^{-1}$ and $v(G) = G(1 - G/2)$ in equations (A.4) and (A.5) and comparing the resulting utilities yield the corresponding cut-off attrition value. By subtracting another link from the above coalitions' structure, comparing all the corresponding utilities, and repeating a similar way, we obtain the PCPNE for $Z = 4, 5, 6$ nations. The results are summarized in Table 3 and Figures 4-6.

Furthermore, if $Z \geq 4$ is an even number, the second-best stable formation is characterized by the equations (A.5) for $i = 1, \cdots, Z$, which implies that each nation forms $Z - 2$ bilateral coalitions and hence the total number of links is $Z(Z-2)/2$ in the second-best coalitional structure. For an odd number: $Z \geq 5$, it is impossible that each nation links up with an identical number of nations. In this case, the second-best stable formation becomes hub-and-spoke structure; i.e., one country is a hub, linking with $Z-1$ nations, and each spoke nation forms $Z-2$ bilateral agreements. The corresponding equilibria can be characterized by the equations (A.4) for the hub nation and (A,5) for the other $Z-1$ members. In this case, the total number of links is $(Z-1)^2/2$. These second-best stable formations and those cut-off attrition values are summarized in Table 4.

Appendix G: Second-Order Conditions for the Maximization Problems

Singleton: $\partial^2 u_i / \partial g_i^2 = -c''(g_i) + v''(G) < 0$, $i = 1,2,3$.

Partial: $\partial^2 u_i / \partial g_i^2 = \left[-c''(q_i) e^{-1}(a,1) + v''(G)\right] e^{-1}(a,1) < 0$, $i = 1,2$.

Hub-and-Spoke: $\partial^2 u_1 / \partial g_1^2 = \left[-c''(q_1) e^{-1}(a,2) + v''(G)\right] e^{-1}(a,2) < 0$.

Partial with Transfers: $\partial^2 (u_1 - \bar{u})(u_2 - \bar{u}) / \partial t_i^2 = -2 < 0$, $i = 1,2$,

$$\frac{\partial^2 u_i}{\partial g_i^2} = -\frac{1}{2}\left\{c''(q_i)\left[e^{-1}(a,1)\right]^2 + \frac{1}{4}c''(q_j)\right\} + v''(G) e^{-1}(a,1) < 0.$$

Hub-and-Spoke with Transfers: $\partial^2 (u_1 - \bar{u})(u_i - \bar{u}) / \partial t_{1i}^2 = -2 < 0$, $i = 2,3$,

$$\frac{\partial^2 u_1}{\partial g_1^2} = -\frac{1}{3}\left\{c''(q_1)\left[e^{-1}(a,2)\right]^2 + \frac{1}{4}\sum_{j\neq 1} c''(q_j)\right\} + v''(G) e^{-1}(a,2) < 0,$$

$$\frac{\partial^2 u_i}{\partial u_i^2} = -\frac{1}{3}\left[c''(q_i)\left[e^{-1}(a,1)\right]^2 + \frac{1}{9}c''(q_1)\right] + v''(G) e^{-1}(a,1) < 0, \quad i = 2,3.$$

Multilateral Coalition with Transfers:

$$\partial^2 \prod_{h=1}^{3} (u_h - \bar{u}) / \partial t_i^2 = -2(u_j - \bar{u}) < 0, \quad i, j = 1,2,3, \quad i \neq j,$$

$$\frac{\partial^2 u_i}{\partial g_i^2} = -\frac{1}{3}\left\{c''(q_i)\left[e^{-1}(a,2)\right]^2 + \frac{1}{9}\sum_{j\neq i} c''(q_j)\right\} + v''(G) e^{-1}(a,2) < 0, \quad i = 1,2,3.$$