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Authors
Karp, Larry
Sacheti, Sandeep

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DEPARTMENT OF AGRICULTURAL AND RESOURCE ECONOMICS AND POLICY
DIVISION OF AGRICULTURE AND NATURAL RESOURCES
UNIVERSITY OF CALIFORNIA AT BERKELEY

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DYNAMICS AND LIMITED COOPERATION IN INTERNATIONAL ENVIRONMENTAL AGREEMENTS

by

Larry Karp and Sandeep Sacheti

California Agricultural Experiment Station
Giannini Foundation of Agricultural Economics
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Dynamics and Limited Cooperation In International Environmental Agreements[1]

Larry Karp[2] and Sandeep Sacheti

Abstract

The amount of cooperation needed to improve the welfare of signatories of International Environmental Agreements (IEAs), in the presence of market imperfections, depends on the characteristics of pollution. In a dynamic model, the conventional wisdom on the effect of free-riding needs to be modified for certain types of pollution problems. For local pollution problems, a sufficient level of free-riding actually promotes signatories' welfare. For global pollution problems, the conventional wisdom is correct insofar as free-riding makes it more difficult to form a successful IEA. However, for some global pollution problems, free-riding may disappear. A static model may overstate or understate the difficulty of forming a successful IEA. The effect of an IEA is sensitive to differences between the duration of the IEA and agents' planning horizon.

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[2] Address correspondence to:
Department of Agricultural and Resource Economics
207 Giannini Hall
University of California
Berkeley CA 94705
email: karp@are.berkeley.edu

1. Introduction

Most environmental problems involve stocks, such as greenhouse gasses or top-soil, which change slowly over time. The existence of these stocks means that policy changes have different effects in the short and the long run. The welfare effects of International Environmental Agreements (IEAs), and therefore the incentives to join these agreements, depend on the dynamics of the environment. Most studies of IEAs use static models or complicated dynamic models that require numerical solutions. Both approaches are valuable, but neither shows clearly the links between dynamics, the characteristics of pollution, and the role of international agreements. We use a simple dynamic model to study these links.

According to conventional wisdom, the incentive to free-ride makes it difficult to form IEAs, and international trade makes the problem worse. These beliefs are based on the observation that pollution abatement by IEA members increases their costs in pollution-intensive industries. This increase shifts comparative advantage in these industries towards non-member countries, increasing output and pollution there. Thus, international trade helps non-member countries earn higher returns by free-riding on the virtuous behavior of nations that sign IEAs. In this situation, a non-member's free riding increases the members' cost of adhering to the IEA.

We examine the relation between the characteristics of pollution and the amount of cooperation needed to improve the welfare of IEA signatories. This model shows that the conventional wisdom on free-riding is incorrect for certain types of pollution problems. There are circumstances where actions that appear to be free-riding improve welfare of IEA signatories. In this case, free-riding may make it easier to form an IEA. In other situations, where free-riding would harm members, non-members may have no incentive to free-ride.

The source of the dynamics in our model is that current actions harm the environment, increasing future production costs. Many current production practices degrade the resource base that is vital for future productivity. Flood irrigation, intensive chemical use and other farming techniques degrade the quality of the top-soil. Over-harvesting of forests can cause soil erosion and flooding. Industrial emissions pollute water and cause acid rain. CFC products harm the ozone layer, increasing ultra-violet radiation exposure. Burning of fossil fuels is a cause of global warming. These production practices may lead to higher future production costs. For example, a lower quality of top-soil requires increased use of fertilizer, and global warming may impose large costs on agriculture due to changes in weather patterns.

Countries have attempted to form IEAs to deal with some transnational environmental problems, e.g. for the management of fisheries, river basins, wildlife, and atmosphere (Barrett, 1991; Enders and Porges, 1992; Blackhurst and Subramanian, 1992). In most agreements cooperation is limited in at least three ways. First, some nations that contribute to the environmental damage do not join the IEA. Second, the goals of IEAs are often quite modest, involving relatively small departures from voluntary levels. Finally, cooperation may eventually end, or the start of cooperation may be delayed. Either there is a possibility that the agreement will fall apart or be weakened, or the negotiation phase takes years, during which time countries are free to choose their own environmental policies. In either case, the duration of the agreement and the planning horizon are different.

The first assumed limitation, i.e., that only a subset of potential members joins the IEA, is an obvious reflection of historical experience. The second and third assumed limitations, i.e. that the goals are modest and that the duration of the agreement and the agents' planning horizon differ, are potentially controversial.

In the absence of an IEA, we assume that every nation takes other nations' environmental policy as given and chooses its optimal policy. The outcome is thus a non-cooperative Nash equilibrium of a simultaneous move game. In describing the IEA as "modest", we mean that the agreement requires members to make small reductions in the amount of environmental damage that they cause. The equilibrium with an agreement is a perturbation of the noncooperative Nash equilibrium that occurs in the absence of an agreement. We explain why we adopt this method of analyzing IEAs in the next section.

The third assumed limitation of the IEA is that the duration of the agreement and agents' planning horizon are different. When agents have a two-period horizon, as in our model, this assumption means that either the agreement comes into effect in the first period but vanishes in the second (the IEA is temporary), or that it is in effect only in the second period (the IEA is delayed). We consider both possibilities, but focus on the former type of IEA. There are two interpretations of the temporary IEA. One interpretation is that agents think that the agreement will literally fall apart. For example, governments may be able to restrain pollution for a short time, while public attention is focused on environmental problems. Over time, however, their collective backbone and the agreement may atrophy. Another interpretation, which would require only minor changes in our analysis, is that agents expect that the requirements of the IEA will not be binding in the future, possibly because of exogenous changes in information or technology. Murdoch et al (1997) explain how the degree to which an IEA is binding changes over time. The second scenario, in which the agreement comes into effect only in the second period, can be motivated if there are costs that cause a delay in successful negotiations.

Historically, IEAs have required substantial time to negotiate.[1] For both types of IEAs, governments with rational expectations correctly anticipate the future.

We hold the second two types of limitations fixed, and allow the number of members of the IEA to vary. Our objective is to understand how characteristics of the pollution problem determine the fraction of countries necessary to make an agreement successful. A "successful" agreement is one which raises signatories' welfare. We consider three characteristics of the pollution problem. The first is the extent to which current production affects future costs via the accumulation of pollution stocks. The second is the degree of myopia among the decision makers. Since environmental externalities are largely felt in the future, the rate of discount affects both the amount of pollution in an equilibrium without an agreement, and the welfare effects of an agreement. The third environmental characteristic is the extent to which the problem is local or global.

There is a large literature on the interaction of trade and the environment and on limited cooperation in environmental agreements. (In addition to the literature already cited, see Dean 1992 for a survey, and Black et al, 1993; Bohm, 1993; Carraro and Siniscalo, 1993; Heal, 1994; Hoel, 1994, 1997; and Karp and Sacheti, 1996). Our paper is also related to the strategic trade literature (Brander and Spencer, 1985) and the application of strategic trade to an environmental setting (Barrett, 1994b; A. Ulph, 1994; D. Ulph, 1994). Since these papers use static models, they cannot examine how the outcome of limited cooperation depends on the importance of the future.

[1] For example, one of the ostensible reasons for the US's reluctance to enter negotiations for a global agreement on forests is that these would provide an excuse for inaction during the lengthy negotiation phase.

In order to analyze the welfare effect of an IEA we need to ask how an agent's welfare depends on a rival's action, and how non-members react to the members' reduction in emissions. The conventional answers are that an agent is harmed by a rival's emissions, and that non-members increase emissions in response to the IEA. We explain why one or both of these answers may be incorrect. In a static framework, free-riding under-cuts member countries' competitive position, making it more costly for a nation to join an IEA. The improvement in global environmental quality is also undermined when non-members increase pollution.

In our dynamic model, an increase in current production increases a stock of pollution, which increases future costs. Here there are circumstances in which free-riding is not detrimental to environmental agreements. Members' lower future production costs may offset the losses they suffer in the current period due to non-members' under-cutting. The future cost advantage that members enjoy is larger, the more that non-members under-cut them in the current period. In this case, members of an IEA may benefit from the non-members' free-riding. In other situations, IEA members would be harmed by free-riding, but the non-members incentive to free-ride vanishes. In intermediate cases, free-riding occurs and harms IEA members. In these cases, consideration of the future may make it more or less difficult to form a successful IEA.

Brander and Taylor (1997) note the difference between instantaneous and long-run effects of heterogenous environmental policies. Other things equal, a laxer environmental policy gives a nation a short run competitive advantage in pollution-intensive industries. However, increased current production in these sectors may degrade their environment and increase their future costs to such a degree that in the long run comparative advantage shifts to nations with more stringent environmental policies. This difference between the short and long run effect on costs is central to our results. The IEA and non-members response to it changes the intertemporal allocation of production. In this sense, the IEA is an implicit market sharing agreement, but the shares are over time, rather than geographical regions or quality characteristics.

The next Section explains why we treat the IEA as a perturbation of a noncooperative equilibrium. Section 3 describes a two-period pollution model and Section 4 studies the non-cooperative equilibrium. In Section 5 we consider limited cooperation in a temporary coalition, and in Section 6 we discuss the incentives to cooperate in a delayed coalition. Section 7 concludes.

2. The Basic Approach to Analyzing an IEA

In the Introduction we explained that we treat an IEA as a perturbation of a symmetric non-cooperative equilibrium to a game with simultaneous moves. Gaudet and Salant (1991) used this approach to study cartels, and many game-theorists find it unexceptionable. Those readers can skip this Section without loss of continuity. However, some environmental economists have objected to our characterization of an IEA, on the grounds that the outcome does not represent an equilibrium to a game. We explain why we consider this objection unimportant. However, to motivate our approach, we first discuss the two most obvious alternatives to it. We then give two reasons for adopting our approach.

First, the signatories to an IEA might become Stackelberg leaders, with non-signatories as followers. That is, creation of an IEA changes the game from one of simultaneous moves to one of sequential moves, in which the IEA chooses its policy first. Barrett (1992, 1994a) uses this assumption to study the (endogenous) number of signatories in a "stable" IEA.[2] He finds that the equilibrium size of the IEA is small in situations where cooperation has the potential to produce large efficiency gains. It is not clear why joining an IEA transforms a "Nash competitor" into a Stackelberg leader. If this transformation were ever to occur, it would be more likely in circumstances when the IEA was *large*, i.e., when it is reasonable for the members to expect to influence non-members' policies. Also, if signatories did become Stackelberg leaders, then in general they would benefit from forming such agreements, and we would see many (possibly small) IEAs. The assumption that signatories become Stackelberg leaders eliminates a major obstacle to the formation of an IEA - the possibility that it harms members. Since our objective is to understand impediments to the formation of IEAs, the Stackelberg assumption may be inappropriate.

The second alternative assumption is that an IEA takes as given non-members' policies and chooses its own policies optimally. The outcome is then the non-cooperative Nash equilibrium to a game with simultaneous moves. In this situation, members' welfare may be lower in an IEA because of the endogenous response of non-members, exactly as in the "disadvantageous cartel" of Salant et al (1983).

We have two reasons for assuming the IEA is "modest", and represents only a perturbation from the original symmetric Nash equilibrium. First, in some cases this assumption appears to describe the world, because negotiators are often willing to consider small but not

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[2] Barrett's definition of stability has been widely used, but has the disadvantage that the "stable equilibrium" is supported by certain beliefs about what would happen following a deviation from equilibrium, and those beliefs are not "rational", so the stable equilibrium is not subgame perfect. Recent alternative approaches to modeling cartel stability, which address this problem, include Chatterjee et al (1993), Bloch and Ghosal (1994), and Ray and Vohra (1994).

large changes in policies. Some agreements do appear to require large changes in behavior, such as the Montreal Protocol on CFCs and the Helsinki Protocol on sulfur emissions. However, in both of these cases improved information might have led to large unilateral policy changes even without the agreement; the additional effect of the agreement might then have been small. (See Barrett (1994a) on the Montreal Protocol and Murdoch et al (1997) on the Helsinki Protocol.)

Our other reason for analyzing the modest IEA rather than the Nash equilibrium to an asymmetric game is even more practical: we can do one but not the other. Even for an extremely simple model, comparing welfare in two equilibria, one of which is asymmetric, requires the use of simulations.[3] Analysis of the perturbed Nash equilibrium, on the other hand, leads to analytic results. These results help our intuition about the formation of IEAs.

We have defended the "modest" assumption on the grounds of plausibility and practicality. There remains the potential objection that our proposed outcome under the IEA does not represent the equilibrium to a game. This objection has superficial appeal. There is an unlimited - probably an uncountable - number of situations we might conceivably study. Restricting attention to equilibrium outcomes imposes discipline on economic research. Our approach appears to violate this restriction, since we analyze a perturbation of the Nash equilibrium, rather than the equilibrium to a perturbed game.

However, a little reflection shows that the distinction between the two is vacuous in many cases. Provided that the equilibrium outcome to the game is differentiable in underlying parameters, there is a one-to-one relation between a perturbation of those parameters and a

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[3] Obviously, it is possible to devise a model which is simple enough to permit analytic comparison of the symmetric and asymmetric Nash equilibria. However, we do not know of such a model which is also rich enough to analyze the situation we are interested in.

perturbation of the equilibrium. Thus, studying the welfare effects of a perturbation of the equilibrium is no less legitimate than studying the welfare effects of a change in the underlying parameters.

In order to see the relevance of this observation, consider a pollution emissions game in which agent i's "intrinsic concern" for the environment is measured by a parameter μ_i. At the initial non-cooperative Nash equilibrium, $\mu_i = 0$ for all i. When country i decides to cooperate (e.g. join an IEA) its preferences do not change, but its behavior changes because it internalizes some effects which it previously ignored. The outcome is observationally equivalent to a situation where country i delegates authority over emissions to a decision-maker with a positive value of the "intrinsic concern" parameter, and that decision-maker then plays non-cooperatively. If the values of μ_i, i = 1,2...S, are chosen appropriately (and given some fairly obvious technical requirements), the Nash outcome under the delegation game where all agents play non-cooperatively, and the outcome under the game in which the S countries form a coalition and play non-cooperatively vis-a-vis the other countries, are identical. The welfare of countries in the delegation game are the same as under the coalition.

Countries in an IEA may not succeed in internalizing all of the costs of their actions. We could analyze a situation with a modest amount of cooperation by considering a coalition that does not achieve full internalization, or equivalently by studying a delegation game in which the "intrinsic concern" parameters are small. There is a straightforward relation between the extent of cooperation amongst the signatories and the "intrinsic concern" parameters.[4] If we want to

[4] Since the two are observationally equivalent, it does not matter which story (delegating to a decision-maker who is more concerned about the environment, or internalizing more externalities as a quid pro quo) is a better description of actual IEAs.

study a small amount of cooperation, we can consider a perturbation of those parameters. However, such a detour would serve no purpose. If we want to study a small amount of cooperation, we might as well cut to the chase and consider a perturbation of the original equilibrium. This perturbation is, of course, *not arbitrary*. If an IEA means anything at all, it must mean that signatories reduce their emissions.

3. A Two-Period Pollution Model

We begin by describing the dynamics of pollution in a two-period model. Country i's pollution stock at the beginning of period 2, before production in that period occurs, is

$$x_2^i = \gamma\left(q_1^i + \alpha Q_1^{-i}\right) \quad \textbf{(1)}$$

where superscript i, {i=1,..,N} denotes the country, and the subscript, {1,2} denotes the time period. Pollution stock in country i, at the beginning of period 2 (x_2^i), is a function of both domestic production (q_1^i) and total foreign production (Q_1^{-i}) in period 1. (Since we have a two period model, we set the initial pollution level to 0, without loss of generality.) The parameter γ measures the strength of current production in contributing to the pollution stock.

Environmental problems can be thought of as existing on a continuum, from local to global. The parameter α in equation (1) measures the level of pollution spillovers. A problem (e.g. soil erosion) is local if production within a country has no effect on the pollution stock elsewhere ($\alpha = 0$). A problem (e.g. global warming) is global if the extent of environmental damage is independent of the source ($\alpha = 1$). In intermediate cases, a unit of output generated abroad contributes less to pollution in a country than does a unit of domestic production ($0 < \alpha < 1$). When we speak of one problem as being "more global" than another, we mean that there is more spillover in the impact of current production on future pollution stocks, so α is larger.

Our formulation treats pollution as a "non-rivalrous public bad" when $\alpha = 1$. If we hold each country's output constant and increase α, the amount of domestically generated pollution is unchanged, but the amount of pollution generated abroad, and thus the total amount of pollution, increases. An increase in α therefore implies not only that spillovers are greater, but also that there is more pollution. (The increase in foreign damages, as α increases, resulting from fixed production, is not associated with a decrease in local damages.) An alternative model, which we do not use, would assume that each unit of output is associated with a certain amount of pollution, the distribution of which depends on a transportation parameter. That formulation means that when domestically created pollution travels abroad, less remains at home.[5]

4. The Non-cooperative Equilibrium

Here we present the subgame-perfect symmetric Nash equilibrium in a two-period, imperfect-competition model with N firms. Each firm is located in a different country. In the next two sections we perturb this equilibrium in order to study the impact of a limited IEA on members' welfare.

We identify a nation's welfare with domestic profits. (More generally, we could include consumer welfare, and allow for the possibility that pollution has a direct effect on welfare.) A nation's production creates a pecuniary externality, via the market price, and possibly a non-pecuniary externality, via increased costs. The model's important features are: (i) Domestic industry profits depend on domestic and aggregate world production and pollution stocks. (ii) The increased cost associated with environmental damage, caused by current production, is felt only

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[5] If we varied γ together with α, holding $\gamma(1+\alpha[N-1])$ constant, the total amount of pollution resulting from a unit of production would be independent of α in a symmetric equilibrium. Our model would then collapse to the alternative model described in the text.

in the future. (iii) The pollution externality may depend on rivals' as well as own production. (iv) In maximizing the stream of discounted welfare (profits), agents recognize that current production decisions affect future costs via the stock of pollution.

The world price net of constant marginal cost (in the absence of environmental damage) is $p(Q_t) = 1 - Q_t$, where $Q_t = \Sigma_i q_t^i$ is aggregate production in period t. In the second period country i chooses q_2^i to solve:

$$\max_{q_2^i} \pi_2^i = q_2^i(1 - Q_2) - x_2^i q_2^i \tag{2}$$

where $x_2^i q_2^i$ is country i's increased cost of production in period 2 due to previous environmental damage. The first order condition is $1 - Q_2 - q_2^i - x_2^i = 0$ and the second order condition, $-2 < 0$, is always satisfied. At an interior solution, the equilibrium level of production is

$$q_2^{i*} = \frac{1 - (N + 1)x_2^i + \bar{x}_2}{N + 1} \qquad Q_2^* = \frac{N - \bar{x}_2}{N + 1}\,. \tag{3}$$

where $\bar{x}_2 \equiv \gamma(1 + \alpha[N-1])Q_1$ is the "world pollution stock" (i.e. the sum of pollution stock over all countries) in a symmetric equilibrium when aggregate output in period 1 was Q_1. We obtain the indirect profit function by substituting the optimal quantities q_2^{i*} into the profit function:

$$\pi_2^{i*} = \frac{\left[1 - (N + 1)x_2^i + \bar{x}_2\right]^2}{(N + 1)^2}\,. \tag{4}$$

In choosing first period production, countries take into account the impact of current production on future pollution stock and thus on future profitability. The first period maximand for country i is $W^i \equiv \pi_1^i + r\pi_2^{i*}(x_2^i, \bar{x}_2)$, where x_2^i is given by (1) and r is the discount factor. With Q_1^{-i} defined as i's rivals' cumulative production in period 1, and using (1) and (4), i's maximization problem is

$$\max_{q_1^i} W^i = q_1^i(1 - q_1^i - Q_1^{-i}) + \frac{r\left[1 - \gamma(N - \alpha[N-1])\,q_1^i + \gamma(1-2\alpha)Q_1^{-i}\right]^2}{(N+1)^2} . \qquad \textbf{(5)}$$

An increase in Q_1^{-i}, decreases i's first period profits, but may increase or decrease second period profits, and therefore has an ambiguous effect on i's total profits. The first order condition to (5) is $F + Gq_1^i + H\,Q_1^{-i} = 0$, where $F \equiv (N+1)^2 - 2r\gamma(N-\alpha[N-1])$, $G = -2(N+1)^2 + 2r\gamma^2(N-\alpha[N-1])^2$ and $H \equiv -(N+1)^2 - 2r\gamma^2(1-2\alpha)(N - \alpha[N-1])$. The symmetric period 1 Nash equilibrium output is

$$q_1^* = \frac{-F}{G + (N-1)H} = \frac{(N+1)^2 - 2r\gamma(N - \alpha[N-1])}{(N+1)^3 - 2r\gamma^2(N - \alpha[N-1])(1 + \alpha[N-1])} . \qquad \textbf{(6)}$$

An increase in the importance of the future decreases the incentive to produce today, so $\partial q_1^*/\partial r < 0$. For a larger discount factor, the stock of pollution has a larger (in absolute value) shadow value. Thus, a firm wants to decrease current production to decrease future pollution stock. We can also show that $(q_1^*)_{|\alpha=0} < (q_1^*)_{|\alpha=1}$. When an increase in domestic production increases rivals' costs, countries have a strategic incentive to produce more in the first period.

We now describe the restrictions on exogenous parameters that ensure that the solution of the first order conditions gives a stable, interior Nash equilibrium. The second order condition in period 1 requires $G < 0$, which is equivalent to $\gamma < \hat{\gamma} \equiv (N+1)/[N - \alpha(N-1)\sqrt{r}]$. The "diagonal dominance condition" is sufficient for stability (Dixit, 1986). This condition requires that $G + (N-1)H < 0$, and is met for $\gamma < \bar{\gamma} \equiv \{(N+1)^3/2r(N-\alpha[N-1](1+\alpha[N-1])\}^{.5}$. From our definitions, we can establish that $\hat{\gamma} \geq \bar{\gamma}$ if and only if $\alpha \geq (N+2)/(N+3)$. For first period production, given by equation (6), to be positive (i.e., for a symmetric interior equilibrium), we need $F > 0$, since $G+(N-1)H < 0$ by the diagonal dominance condition. The inequality $F > 0$ requires $\gamma < \gamma^* \equiv (N+1)^2/2r[N-\alpha(N-1)]$. When we compare γ^* and $\hat{\gamma}$, we find that $\hat{\gamma} > \gamma^*$ if and only if $r > (N+1)^2/4$. In order for second period production to be positive we require $\bar{x}_2 < N$ (equation 3). This inequality implies, after using (6), $\gamma < \dot{\gamma} \equiv (N+1)/[1 + \alpha(N-1)]$. In summary, the feasible region for γ, which satisfies the second order condition for a global maximum, the stability condition, and has positive quantities in both periods is: (i) for $r < (N+1)^2/4$, $\gamma < \min\{\hat{\gamma}, \dot{\gamma}, \bar{\gamma}\}$, and (ii) for $r > (N+1)^2/4$, $\gamma < \min\{\gamma^*, \dot{\gamma}, \bar{\gamma}\}$.[6]

5. Limited Cooperation in a Temporary Coalition

Here we consider the change in the welfare of IEA members, when the IEA requires a small, temporary reduction in pollution (output). In the first period, some countries join the IEA and require their firms to decrease current output, relative to the non-cooperative equilibrium. In the second period the environmental coalition falls apart or ceases to be binding and firms revert to a non-cooperative equilibrium. However, because of the first period IEA, firms no longer have identical stocks in the second period when $\alpha < 1$. At the beginning of the game, agents know that the IEA lasts only for one period.

Let S be the number of IEA member countries. These countries are constrained to choose q_1^m, an amount slightly smaller than the first period symmetric Nash equilibrium quantity. The N-S non-member countries endogenously choose their first period output q_1^n as a best response to the members' output. (The superscript "m" denotes an IEA member, and "n" denotes a non-

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[6] We repeat some notation, in order to help the reader in keeping it straight. The second order condition implies $\gamma < \hat{\gamma}$. The diagonal dominance condition implies $\gamma < \bar{\gamma}$. A positive value of q_1^i implies $\gamma < \gamma^*$. A positive value of q_2^i requires $\gamma < \dot{\gamma}$.

member.) In the second period all N countries simultaneously choose their output q_2^j. Using the first order condition and evaluating the derivative at the symmetric Nash equilibrium, the change in total profits of a member, country j, is

$$\left.\frac{dW^j}{dq_1^m}\right|_{q_1^m=q_1^*} = \frac{\partial W^j}{\partial Q_1^{-j}} \frac{dQ_1^{-j}}{dq_1^m} \tag{7}$$

where $\partial W^j/\partial Q^{-j}$ is the impact on the net present value of domestic profits due to a change in total foreign production, and dQ_1^{-j}/dq_1^m is the equilibrium change in the total foreign production due to the IEA. In the Introduction we mentioned that the welfare effect of an IEA depends on the signs of these two terms.

Players are symmetric, so $Q_1^{-j} = (N\text{-}S)q_1^n + (S\text{-}1)q_1^m$, and

$$\frac{dQ_1^{-j}}{dq_1^m} = (N - S)\frac{dq_1^n}{dq_1^m} + (S - 1)\ . \tag{8}$$

Totally differentiating a non-members' first order condition, $F + Gq_1^n + H(N\text{-}S\text{-}1)q_1^n + HS\ q_1^m = 0$, implies

$$\frac{dq_1^n}{dq_1^m} = \frac{-SH}{G + (N - S - 1)H}\ . \tag{9}$$

Since the denominator in equation (9) is negative[7], $\text{sign}(dq_1^n/dq_1^m) = \text{sign}(H)$. If $H > 0$, a decrease

[7] The denominator is $G + (N\text{-}S\text{-}1)H = G + (N\text{-}1)H - SH$. For $H < 0$ the left side is negative using the second order condition $G < 0$ and $S \leq N\text{-}1$. For $H > 0$ the right side s negative by the diagonal dominance condition.

in member output leads to a decline in the non-member output, and actions are strategic complements. If $H < 0$, a decrease in member output causes the non-members to expand current production, and actions are strategic substitutes. Using the definition of H, we see that $H < 0$ whenever $r\gamma$ is sufficiently small and/or $\alpha < 1/2$. When $\alpha > 1/2$, $H \geq 0$ if and only if $\gamma \geq \tilde{\gamma} \equiv (N+1)/[2r(N-\alpha(N-1)(2\alpha-1))]^{.5}$ By tedious calculation, we can verify that $N^2/2 < r < (N+1)^2/2$ is a sufficient condition for the feasible parameter space (described in Section 4) to include $\tilde{\gamma}$. In summary, we have

Remark 1. *(1) When pollution is fairly local ($\alpha < 1/2$) or the future is not important ($r\gamma = 0$), policies are strategic substitutes. (2) When pollution is fairly global ($\alpha > 1/2$), there exists discount rates ($N^2/2 < r < (N+1)^2/2$) such that policies are strategic complements if and only if the pollution problem is sufficiently important ($\gamma > \tilde{\gamma}$). (3) The strategic substitutability of complementarity of policies is independent of S, the number of IEA members.* •

When pollution is local or not very important for future costs, non-members react to a temporary IEA by relaxing their own environmental restrictions. The non-members take advantage of the increased opportunities for current profits. If, however, pollution is both important and global, stronger environmental policies by IEA members increase future profit opportunities for non-members by enough to cause non-members to reduce current emissions. Whether policies are strategic substitutes or complements depends on the nature of the environmental externality, but not on the number of members in the IEA.

To help interpret these results, we decompose the non-member first order condition as follows:

$$\Delta C\Pi \equiv 1 - 2q_1^n - (N - S - 1)q_1^n - Sq_1^m = \frac{-2r\gamma(N - \alpha[N - 1])}{(N + 1)^2} \times \tag{10}$$

$$\left\{-1 + \gamma(N - \alpha[N-1])q_1^n - \gamma(1-2\alpha)(N-S-1)\,q_1^n - \gamma(1-2\alpha)Sq_1^m\right\} \equiv \Delta F\Pi \,.$$

Here, $\Delta C\Pi$ represents the change in current profits of a non-member due to a change in its current output, q_1^n, for a given level of member output q_1^m and the output of other non-members. Similarly, $\Delta F\Pi$ is the change in future profits of a non-member due to a change in its current output. The equilibrium value of q_1^n balances these two changes in profits. Figure 1 shows the graphs of $\Delta C\Pi$ and $\Delta F\Pi$ as solid lines. The second order condition to the non-member's maximization problem determines the relative slopes of the two graphs. The horizontal component of point A in the figure represents the initial equilibrium level of q_1^n.

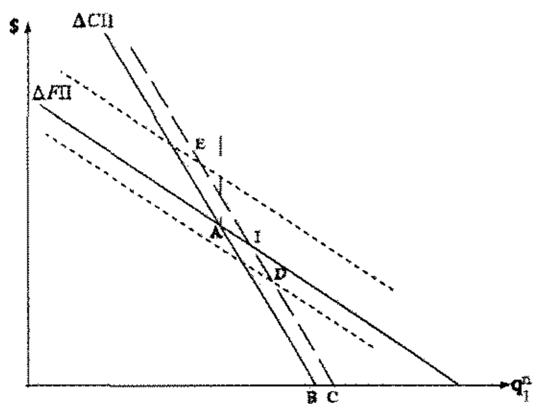

Figure 1 Decomposition of Non-Members' Equilibrium Condition

If the future is not important ($r\gamma = 0$), the $\Delta F\Pi$ line collapses to the horizontal axis and the optimal production level is at point B. Current production is no longer constrained by the existence of pollution and the resulting increase in future costs. When member production, q_1^m, decreases, the graph of $\Delta C\Pi$ shifts out to the dashed line (the coefficient on q_1^m is -S). With a lower member production, marginal profits in the current period increase for a non-member. Therefore, for $r\gamma = 0$, the non-member increases current production to point C. Policies are strategic substitutes and we have Remark 1.1.

However, when the future is important ($r\gamma > 0$) a decrease in current member production may increase or decrease non-member production. As before, a decrease in member production causes $\Delta C\Pi$ to shift out. If a non-member were to consider just the change in current profits, it would expand production to point I. However, the decrease in member production has an impact on future non-member profits, depicted by the movement of $\Delta F\Pi$. The direction of the shift in this line is determined by the sign of the function $2r\gamma^2(1-2\alpha)(N-\alpha[N-1])$, which is positive if and only if $\alpha < 1/2$.

For fairly local pollution ($\alpha < 1/2$) $\Delta F\Pi$ shifts in because the (absolute) shadow value of the stock falls. The intersection of the two curves then implies a larger non-member current production, such as at point D. Actions are strategic substitutes. When pollution is fairly local, a decrease in member production does not change future costs of a non-member by much. However, the current decrease in member production makes the non-members relatively less efficient producers in the future. Thus, a non-member expands first period production.

On the other hand, for fairly global pollution ($\alpha > 1/2$), the (absolute) shadow value of the stock increases with the decrease in member production, so $\Delta F\Pi$ shifts out. If the intersection of the two curves is at a point such as E, actions are strategic complements. (α, γ and r are large.) When pollution is quite global and has a large effect on costs, a decrease in member production decreases future costs of a non-member. A non-member then has a larger incentive to shift production to the future.

Remark 1.1 reproduces a conclusion in Karp and Sacheti (1996): quantity restrictions are always strategic substitutes in a one-period model. However, when the future is important, the intuition obtained from the static model may be incorrect. Quantity restrictions may be strategic complements.

We now analyze the impact on the net present value of domestic profits due to a change in total foreign production. Using equation (5) we find

$$\frac{\partial W^j}{\partial Q_1^{-j}} = -q_1^j + \frac{2r\gamma\left[1 - \gamma(N - \alpha[N - 1])q_1^j + \gamma(1 - 2\alpha)Q_1^{-j}\right]}{(N + 1)^2}(1 - 2\alpha) . \quad \textbf{(11)}$$

Evaluating this expression at the symmetric Nash equilibrium and using equations (3) - (5) to simplify, we obtain

$$\left.\frac{\partial W^j}{\partial Q_1^{-j}}\right|_{q_1^j = q_1^*} = q_1^*\left(\frac{2r\gamma(1-2\alpha)}{N+1} - 1\right). \quad \textbf{(12)}$$

If pollution is fairly global ($\alpha > 1/2$), domestic welfare declines with an increase in total rival current output. If, on the other hand, pollution is fairly local ($\alpha < 1/2$), and in addition $r\gamma > (N+1)/2(1-2\alpha)$, domestic welfare increases with an increase in total rival output. By direct calculation we can show that the critical value of $r\gamma$, $(N+1)/2(1-2\alpha)$, lies in the feasible parameter space which we described in Section 3. In summary, equation (12) implies:

Remark 2. *(1) For $\alpha > 1/2$, $\partial W^j/\partial Q_1^{-j} < 0$. (2) For $\alpha < 1/2$, $\partial W^j/\partial Q_1^{-j} > 0$ if and only if $r\gamma > (N+1)/2(1-2\alpha)$.*•

An increase in current non-member production has two effects on domestic profits. First, higher foreign production decreases price, decreasing members' current profits. The second effect, on future profits, is ambiguous and depends on the type of pollution (measured by α). If the pollution problem is fairly global, an increase in rival production causes future domestic costs to rise due to higher world-wide pollution stock. Consequently, future domestic profits fall. Thus, total domestic profits fall as well (Remark 2.1). However, when pollution is fairly local, an increase in rivals' total current output decreases the member firms' relative costs in the future and thus might increase their future profits. When current profits fall and future profits rise, the impact on total profits is ambiguous. If the future is valued sufficiently highly (r is large) and the pollution problem is significant (γ is large), IEA members' total welfare *increases* with non-members' increased current output.

Using the information on strategic complementarity and substitutability (equations 8 and 9), and the information on the change in domestic profits due to a change in foreign production (equation 12) in equation (7) we obtain

$$\frac{dW^j}{dq_1^m}\bigg|_{q_i^m = q_i^*} \begin{matrix} > \\ = \\ < \end{matrix} 0 \Leftrightarrow \frac{H}{G} \begin{cases} \begin{matrix} < \\ = \\ > \end{matrix} \dfrac{S-1}{N-1} & \text{for } \dfrac{\partial W^j}{\partial Q_1^{-j}} > 0 \\ \begin{matrix} > \\ = \\ < \end{matrix} \dfrac{S-1}{N-1} & \text{for } \dfrac{\partial W^j}{\partial Q_1^{-j}} < 0 \end{cases} \qquad \textbf{(13)}$$

We denote H/G as the "critical fraction" of IEA membership. The welfare effect of the IEA on members depends on the relation between (S-1)/(N-1), the fraction of other countries that actually join (hereafter, the "actual fraction") and the critical fraction. Depending on the type of pollution problem, the actual fraction has to be either larger or smaller than the critical fraction for a member country's total welfare to improve in a temporary IEA. If the actual size of the IEA is not on the "correct side" of the critical size, members of the IEA have lower welfare than in the symmetric non-cooperative Nash equilibrium, without the IEA. Table 1 summarizes the implications of equations (9), (12) and (13). The entry "any size" in the last box of the table, means that for large α and γ, even a unilateral reduction in current output (i.e., S = 1) increases welfare for the country that makes the reduction; therefore, a successful IEA can be "any size".

Extent of spillovers	Sign $\left(\frac{\partial W^j}{\partial Q_1^{-j}}\right)$	Sign $\left(\frac{dq^{n_1}}{dq_1^m}\right)$	Welfare enhancing "actual fraction" relative to "critical fraction"
$\alpha < 1/2$	+ if $r\gamma$ large	-	smaller
	– if $r\gamma$ small	–	larger
$\alpha > 1/2$	–	– if $r = 0$ or $\gamma < \tilde{\gamma}$	larger
		+ if $\gamma > \tilde{\gamma}$	any size

Table 1: Welfare Enhancing Temporary Coalition Size for Different Spillovers

If an increase in total rival production increases domestic profits ($\partial W^j/\partial Q_1^{-j} > 0$), the actual fraction of countries in an IEA has to be smaller than the critical fraction for members' welfare to increase. If there are too many members, current expansion in output of the non-members is too small to give the members a significant cost advantage over the non-members in the future.[8] (The larger is the IEA membership, the more nations there are with lower costs in the future and the fiercer is future competition.) Thus, the members are unable to recoup the loss in current

[8] As a consistency check for this result, suppose that $\partial W^j/\partial Q_1^j > 0$ and consider the limiting case where S = N. From equation (8) $dQ_1^j/dq_1^m = N-1$. Substituting this equation into (7) gives the welfare effect $(N-1)\partial W^j/\partial Q_1^j > 0$.

profits: joining the IEA reduces their welfare. In this case, the conventional wisdom on free-riding is reversed. A "successful" IEA requires a sufficiently large number of free-riders - i.e., a small number of members. Having enough free-riders ensures that member countries gain a large enough competitive advantage to enable them to recover first period lost profits.

On the other hand, if an increase in total rival production decreases domestic welfare ($\partial W^j/\partial Q^{-j}_1 < 0$, which is the "usual case"), the actual fraction of countries in the IEA has to be larger than the critical fraction for member welfare to increase. IEA members want there to be few non-members who expand current production. Here, the conventional wisdom on free-riders is correct: free-riding makes it difficult to form an IEA. However, if policies are strategic complements (H > 0), free-riding does not occur. A coalition of any size is profitable because non-members also contract production along with the member(s). Therefore, a unilateral (S = 1) decrease in output is also beneficial. (Table 1, final row.)

Remark 3 summarizes the effect of exogenous parameters on the critical fraction.[9]

Remark 3. *(1) For $r\gamma = 0$, $H/G = 1/2$. (2) For $r\gamma > 0$, $H/G \geq 1/2$ if and only if $\alpha \leq (N+2)/(N+3)$.*•

When countries ignore the future, the critical IEA size is 1/2; we refer to this as the "myopic fraction". The myopic fraction does not depend on α because the level of pollution can affect behavior only in the second period (Remark 3.1). However, when the future is important, the critical fraction may be larger or smaller than the myopic fraction, depending on the type of pollution problem, characterized by α (Remark 3.2). Table 2 summarizes the

[9] This result can be verified by simplifying the ratio H/G, using the formulae for H and G in Section 3.

comparison between the myopic fraction and the critical size when the future is important.

Extent of Spillovers	Sign $\left(\frac{\partial W^j}{\partial Q_1^n}\right)$	Is a successful coalition that considers the future larger or smaller than the myopic fraction?
$\alpha < \frac{1}{2}$	+	smaller
	–	larger
$\frac{1}{2} \leq \alpha \leq \frac{N+2}{N+3}$	–	larger
$\alpha > \frac{N+2}{N+3}$	–	smaller

Table 2: Comparison of Critical and Myopic Fractions for Different Spillovers

For global problems such as the ozone layer depletion and global warming, consideration of the future decreases the amount of cooperation needed for a successful IEA. Here, even when the conventional wisdom on the detrimental effects of free-riding remains correct, consideration of the future decreases the severity of the problem. The explanation is that if $\alpha \approx 1$, non-members benefit from lower costs when members reduce current emissions. When non-members take the future into account, their incentive to expand current production is smaller, since expansion would decrease their future profits. When non-members have a reduced incentive to expand current production, fewer members are required for an IEA to be successful. Also, as we noted above, if the future is sufficiently important ($r\gamma$ large) policies are strategic complements ($H > 0$) and the problem of free-riding disappears. Non-members respond to the reduction in output by IEA members by decreasing their own output. In this case, an IEA of any size (including one consisting of a single member who unilaterally reduces output) is beneficial to the member(s).

For intermediate pollution problems [$1/2 < \alpha < (N+2)/(N+3)$], successful IEAs require more cooperation in a dynamic, relative to myopic, setting. For problems that are not completely global, the members have a cost advantage over the non-members in the future. Realizing their future cost disadvantage, the non-members have an added incentive to expand current production (relative to the myopic scenario). In this case, to compensate for more severe under-cutting by non-members, a successful IEA requires more members in a dynamic than in a myopic setting.

For fairly local pollution problems ($\alpha < 1/2$), there are two possibilities. When free-riding is "bad" ($\partial W^j/\partial Q_1^{-j} < 0$), consideration of the future makes the critical fraction larger than the myopic fraction. The explanation is as above: since the under-cutting by non-members is more severe, a successful IEA requires more members. However, when free-riding is "good" ($\partial W^j/\partial Q_1^{-j} > 0$), consideration of the future decreases the critical size of the IEA. Here, having too many, as opposed to too few members is a problem. The myopic fraction is not "too large", so an IEA of that size is successful even when the future is very important. However, IEAs smaller than the myopic fraction, which would not have been successful in the static framework, are now beneficial to the members.

6. Limited Cooperation in a Delayed IEA

We briefly consider the effect of limited cooperation in the future. In the first period each country chooses its output non-cooperatively, and in the second period a subset of countries join an IEA that requires their firms to decrease output slightly. In period 1 all agents know which countries will join the IEA.

An appendix, available on request, gives the expression for dW^j/dq_2^m, the equilibrium welfare effect for a member due to an anticipated change in its output in the next period (i.e, as a result of joining the delayed IEA). This expression is analogous to equation (13), which gives the welfare effect in a temporary IEA. Unfortunately we are not able to compare analytically the two equations, so we are unable to determine whether a delayed IEA requires more cooperation than a temporary one. With a delayed IEA, the welfare effect for members depends on the equilibrium ratio of output in the first and second period, and is very complicated.

Despite the lack of analytic results for this case, we can make some comparisons between the two types of IEAs. A temporary IEA tends to shift members' competitive advantage (in the production of the environmentally damaging good) toward the future. This shift encourages non-members to increase their current output. The change in competitive advantage over time is strong when the environmental damage is local, but vanishes in the limiting case where the environmental damage is completely global ($\alpha = 1$). The stability condition insures that if non-members do increase their first-period output, the aggregate increase is smaller than the decrease by members. Thus, the temporary IEA at least improves short run environmental conditions.

A delayed IEA, on the other hand, decreases members' shadow value of the environmental stock, since their future production is restricted. The shadow value of the environmental stock to non-members increases, because their future competition is restricted. Therefore, the delayed IEA tends to increase members' output and market share in the present, and increase non-members output and market share in the future. If many countries anticipate joining the delayed IEA, it is likely that current output, and thus environmental damage, increases.[10]

The effect of the delayed IEA depends on the type of environmental damage. When the environmental damage is quite local, the first-period increased production by (future) members and decreased production by non-members, causes a substantial change in relative costs in the

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[10] However, when S = N we can show that welfare increases.

second period. This change reinforces the direct effects of the requirement that members reduce production in the second period. Consequently, for local environmental problems, we expect the delayed IEA to have a large effect on market shares and inter-temporal reallocation of production.

When the environmental damage is quite global, on the other hand, members and non-members have approximately (or exactly, in the limiting case) the same future costs. Since the future restrictions tend to increase members' first-period production, the restrictions also increase non-members' costs in the second period (for α large). In deciding whether to increase or decrease first-period production, non-members have to balance two considerations. The desire to take advantage of reduced future competition makes the non-members want to reduce current production in order to keep their future costs low. However, members' actions increase non-members' future costs, making future production less attractive to them. The second effect is larger the more global are environmental damages.

Consequently, when α is large, first-period actions can be strategic complements. We established that these actions are strategic complements in a temporary IEA when α and γ are sufficiently large (Remark 1.2b). Strategic complementarity benefits the environment in a temporary IEA, which reduces members' current output. However, strategic complementarity harms the environment in a delayed IEA, which tends to increase members' current output.

7. Conclusion

Most environmental problems involve environmental stocks, causing the effects of international policy coordination to differ in the short and long run. Most previous studies of IEAs have used static models or have studied quite complicated dynamic models using simulation. Although both of these approaches can provide useful insights, neither is very helpful in understanding the basic relations which link together dynamics, the characteristics of pollution, and limited international coordination of policies. We have attempted to take a step toward understanding some of these issues.

We developed a two-period trade model where current production affects future costs via the pollution stock. The domestic pollution stock depends on rivals' as well as own-production, except when pollution is purely local. The conventional wisdom is that free-riding makes it more difficult to form environmental agreements, and that international trade contributes to this problem. This conclusion, which is based on static models, needs to be modified for certain types of pollution problems. In a one-period model, non-members' opportunistic behavior necessarily harms members. Free-riding makes members' current cost disadvantage, caused by adherence to the IEA, more painful to them. The conventional view concentrates on this effect, and therefore concludes that free-riding makes it more difficult to form IEAs.

However, free-riding also contributes to members' future *cost advantage*. When the future is important, free-riding may contribute to the success rather than the downfall of IEAs with limited membership. More stringent environmental standards in the current period can give member nations a relative cost advantage in the future, even when it causes them a cost disadvantage in the current period. Members' future cost advantage can more than offset the temporary competitive disadvantage resulting from adherence to the IEA. This possibility arises for local pollution damages, and seems to us most relevant to the discussion of environmental reform in agricultural sectors of some developing countries. For example, coffee production is concentrated in several Latin American and African countries which may have some market power. Coffee production causes local environmental damage, which countries have been reluctant to control because of the perceived danger of losing market share. This reluctance has led to calls for international policy coordination, and possibly the creation of International Commodity-Related Environmental Agreements. Our model suggests that free-riding may not be a significant problem in such a circumstance.

For fairly global pollution problems such as global warming, when free-riding occurs the conventional wisdom is correct. In this case, non-member current production, and hence pollution, strongly affects the members' future cost. Members are then unable to gain a sufficient future cost advantage to compensate for their current loss of profits due to under-cutting by non-members. However, for very important and global pollution problems, actions are strategic complements, so free-riding may not occur.

Even when free-riding does occur and harms IEA members, consideration of future effects may decrease the amount of cooperation needed for a successful IEA. This possibility is more likely when the environmental problem is quite global. The explanation is simply that members' current reduction of emissions decreases future costs for all countries, making it more attractive for them to shift production to the future, and therefore to protect the current environmental stock.

We concentrated on the temporary IEA. However, the basic mechanism behind our results is simply that current reductions in environmental damages change relative costs across time. The reductions may also change relative costs across countries, depending on the characteristic of pollution. These two effects would be present in a permanent IEA, although to a different degree. Therefore, we doubt that the assumption of a temporary IEA is critical.

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Appendix: Welfare in a Delayed IEA

In the second period S countries are constrained to choose q_2^m, an amount slightly less than the symmetric Nash equilibrium level, and the N-S non-members simultaneously choose q_2^n. In the first period all N countries simultaneously choose output q_1^i. In choosing q_1^i, countries consider the whole profit stream, and (future) members realize that their future output is constrained.

At the second period symmetric Nash equilibrium without the agreement, $q_2^m = q_2^*$, country j's (a member) output is a best reply. Changing j's output by a small amount has no first order effect on its second period profits:

$$\left.\frac{\partial \pi_2^j}{\partial q_2^m}\right|_{q_2^m = q_2^*} = 0. \tag{A1}$$

To find the impact of the second period output restriction on a member's welfare, we totally differentiate $W^j(q_1^j, Q_1^{-j}, q_2^m, Q_2^{-j}) = \pi_1^j + r\pi_2^j$, to obtain

$$\frac{dW^j}{dq_2^m} = \frac{\partial W^j}{\partial q_1^j}\frac{dq_1^j}{dq_2^m} + \frac{\partial W^j}{\partial Q_1^{-j}}\frac{dQ_1^{-j}}{dq_2^m} + \frac{\partial W^j}{\partial q_2^m} + \frac{\partial W^j}{\partial Q_2^{-j}}\frac{dQ_2^{-j}}{dq_2^m} \tag{A2}$$

Evaluating this expression at the symmetric Nash equilibrium ($q_2^m = q_2^*$), using (A1) and $\partial\pi_1^j/\partial q_2^m = 0$, $\partial\pi_1^j/\partial Q_2^{-j} = 0$ and $\partial\pi_1^j/\partial q_1^j + r\partial\pi_2^j/\partial q_1^j = 0$, we obtain

$$\left.\frac{dW^j}{dq_2^m}\right|_{q_2^m=q_2^*} = \left[\frac{\partial\pi_1^j}{\partial Q_1^{-j}} + r\frac{\partial\pi_2^j}{\partial Q_1^{-j}}\right]\frac{dQ_1^{-j}}{dq_2^m} + r\frac{\partial\pi_2^j}{\partial Q_2^{-j}}\frac{dQ_2^{-j}}{dq_2^m}. \tag{A3}$$

Players are symmetric, $Q_1^{-j} = (N\text{-}S)q_1^n + (S\text{-}1)q_1^m$ and $Q_2^{-j} = (N\text{-}S)q_2^n + (S\text{-}1)q_2^m$. Totally differentiating these relations gives

$$\frac{dQ_1^{-j}}{dq_1^m} = (N - S)\frac{dq_1^n}{dq_1^m} + (S - 1)\ ; \quad \frac{dQ_2^{-j}}{dq_2^m} = (N - S)\frac{dq_2^n}{dq_2^m} + (S - 1). \tag{A4}$$

In order to solve for dq_1^n/dq_1^m, consider the first order condition of a non-member i in period 2: $1 - Q_2 - q_2^i - x_2^i = 0$. Totally differentiating this equality gives

$$\frac{dq_2^n}{dq_2^m} = \frac{-S}{N - S + 1}. \tag{A5}$$

We already have an expression for dq_1^n/dq_1^m, equation (9). Thus, we have

$$\left.\frac{dW^j}{dq_2^m}\right|_{q_2^m=q_2^*} \gtreqless 0 \Leftrightarrow -\left(\frac{q_1^j}{rq_2^m} + \alpha\gamma\right)\left[\frac{(S - 1)G - (N - 1)H}{G + (N - S - 1)H}\right] + \frac{N - 2S + 1}{N - S + 1} \gtreqless 0. \tag{A6}$$