Anticipated International Environmental Agreements*

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Abstract

Consider a two-period transboundary stock pollution game in which countries anticipate an international environmental agreement (IEA) to be in effect in the future (i.e., in period 2). What will be the impact of the future IEA on current emissions (i.e., in period 1)? We show that the answer to this question is ambiguous.

We examine a first type of IEA where countries anticipate that the level of emissions in period 2 will be set at an agreed upon target. Assuming that the countries can commit to this policy, we show that when this target is set close to the business-as-usual (BAU) level of emissions, the equilibrium level of emissions in period 1 falls below its BAU level. However, the emission level in period 1 is a decreasing function of the target that will prevail in period 2, hence, the impact of this policy on period 1 emissions may be ambiguous, and in general depend on the targeted emission level. We also examine other types of IEAs where countries cannot commit to an emission level but rather commit to an emission *policy rule* that depends on the level of pollution stock.

Keywords: International environmental agreements; Climate agreement; Future Agreements; Transboundary Pollution; Dynamic Games.

JEL: Q53; Q54; Q58; Q59.

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1 Introduction

Transboundary pollution problems give rise to prisoners' dilemma type of situations that are particularly difficult to resolve due to the absence of a supra-national authority that can impose an allocation of pollution rights, or enforce agreed upon contracts. Any agreement between the parties involved needs to be self-enforcing. The difficulty of reaching an agreement can in principle be overcome by an ad-hoc system of transfers and incentives to prevent free-riding.[1] In practice, the number of international treaties to protect the environment or resources has been steadily increasing since the second half of the twentieth century. The International Environmental Agreements (IEA) Database Project[2] lists environmental agreements from 1800 to 2013. In the project, agreements are defined as environmental "if they seek, as a primary purpose, to manage or prevent human impacts on natural resources; plant and animal species (including in agriculture, since agriculture modifies both); the atmosphere; oceans; rivers; lakes; terrestrial habitats; and other elements of the natural world that provide ecosystem services. " Daily (1997). The project lists over 1200 multilateral environmental agreements, more than half of which were signed after 1990, 1500 bilateral environmental agreements, and 250 "other" environmental agreements. The "Other" category includes environmental agreements between governments and international organizations or non-state actors. The list includes conventions, treaties, protocols, amendments, modifications.

The process of defining precise commitments for each member of an agreement, the ratification and the passing of domestic legislation to enforce the agreement's commitments is often very tedious and lengthy. An interesting feature of many such agreements is that there is a substantial period of time that separates the date of adoption and the date of entry into force.[3 4] For example, in the case of climate change, the United Nations Framework Convention on Climate Change (UNFCCC) was signed by 154 countries in the Earth Summit in Rio de Janeiro in 1992 and entered into force in 1994. However, binding limits on greenhouse gases emissions, in the case of developed countries[5], were only defined in 1997 under the Kyoto Protocol; a protocol that entered into force in 2005.[6] Even bilateral

[1] See e.g., Germain, Toint, Tulkens and de Zeeuw (2003) or Petrosyan and Zaccour (2003) for the case of stock pollution game and Calvo and Rubio (2013) for a recent survey.

[2] http://iea.uoregon.edu/page.php?file=home.htm&query=static
Version 2013.2, July 2013.

[3] Barrett (1998) breaks down the process of treaty making into five stages: pre-negotiation, negotiation, ratification, implementation and renegotiation. Congleton (2001) identifies four phases of IEAs. The first stage is the recognition of the benefits from cooperation and gives rise to "Symbolic Treaties", in the second stage parties sign a "Procedural Treaty" defining procedures to evaluate alternative policy targets, in the third stage parties agree on specific targets and sign a "Substantive" treaty and in the fourth "Domestic" stage each party passes legislation to conform with its treaty obligations.

[4] Barrett (2003), in the appendix of Chapter 6, gives a list of multilateral environmental agreements and provides the date of adoption and the date of ratification.

[5] Canada withdrew in 2011 and the US did not ratify the treaty.

[6] Other examples of delayed entry into force of environmental treaties include The Convention for the Protection of the Marine Environment of the North-East Atlantic which was opened for signature in 1992 and entered into force in

environmental treaties can take decades to be finalized (see Congleton (2001) for examples).

In the case of stock pollutants, where countries take into account the accumulation process of pollution, such delays and the anticipation of cooperation influences the level of emissions over the pre-cooperation phase: the decisions on the level of emissions at different points in time are interrelated. We examine, in this paper, the impact of an anticipated IEA on the emission levels over the pre-cooperation phase. To this end, we consider a transboundary stock pollution game in which countries will adopt an emission policy that is more environmentally friendly than the business-as-usual (BAU) policy. For the sake of simplicity, we abstract from modeling the political process by which a cooperative solution is reached. In this environment, a number of countries produce homogeneous products, and pollution is emitted as a by-product. Emissions of pollution accumulate, constituting a transboundary stock of pollution which damages all countries in the same way. It is well known that a Markov Perfect Nash Equilibrium (MPNE) of the game when countries behave non-cooperatively results in larger emissions of pollution than the socially efficient level, i.e. where each country adopts the pollution strategy that maximizes the joint welfare of all countries.[7]

To provide a benchmark case, following the literature, we first determine the equilibrium under the BAU scenario, where the countries behave non-cooperatively over the two periods. This is contrasted with the first-best cooperative equilibrium where countries follow a profile of emissions strategies for each period that maximizes the aggregate welfare. This is followed by our main thought experiment where we consider the case in which countries adopt an IEA in period two that is fully anticipated in period one. We examine the effect of four different types of IEAs on the emission level over the pre-cooperation phase.

In the first type of IEA, countries anticipate that the level of emissions in period 2 will be set at an agreed upon target, independent of the pollution stock, assuming that the countries can commit to this level. In the other three IEAs, countries cannot commit to an emission *level*, but rather commit to an emission *policy rule* that depends on the level of pollution stock. In the second (third) type of IEA, the anticipated emission policy represents a percentage (constant) cut of future emissions vis-à-vis BAU. In the fourth type of IEA the anticipated emission policy is the ex-post first-best emission policy, i.e., the policy which maximizes the joint welfare of all countries (in period 2).

In the first type of anticipated IEA, where countries can commit to a target level of emissions, we show that a cap in period 2, set exactly at the BAU emission level, results in a decrease of current emissions with respect to the BAU emission level. However, emissions in period 1 is a decreasing

1998. The Convention on Long-Range Transboundary Air Pollution, CLRTAP, open for signature in 1979 and entered into force in 1983, Marpol 73/78 ("Marpol" is short for marine pollution and 73/78 short for the years 1973 and 1978) the International Convention for the Prevention of Pollution From Ships was signed in 1973. The current convention entered into force in 1983.

Even the Vienna Convention on the Law of Treaties (VCLT), a treaty on the international law on treaties between states was adopted in 1969 and entered into force in 1980.

[7] See the surveys of dynamic pollutions games in Jorgensen, Martin-Herran and Zaccour (2010) or Long (2011).

function of the target level for period 2: A tighter target in period 2 results in larger emissions in period 1. Therefore, the overall impact of a cap on emissions is ambiguous.

For an anticipated IEA of type 2, we show that it results in an increase (a decrease) of current emissions when the elasticity of marginal utility with respect to emission level is larger (smaller) than one. In the linear-quadratic framework, we show that anticipation of an IEA results in a decrease of current emissions if the damage from pollution is sufficiently large. Otherwise, the impact of an IEA is ambiguous, and typically depends on the level of the stock of pollution. A future IEA of type 3 unambiguously results in an increase in current emissions.

For the fourth type of IEA, where countries adopt the ex-post first best emission policy, we give a necessary condition under which the future IEA results in a decrease of current emissions with respect to their BAU level. We show that this necessary condition is never satisfied in the linear-quadratic case, and in the case where utility function is logarithmic.

It is widely recognized that the actual policies ratified, by domestic legislatures, diverge from policies prescribed under an 'ideal' scenario (IEA of type 4 in our context) or policies that are economically efficient. The reality of policy making is that the final legislation that will be implemented is the outcome of an interaction of several interest groups.[8] In this sense, we view IEAs of type 1, 2 and 3 to be potentially more relevant for policy implications. Indeed, an IEA of type 2 or 3 can be explained by the fact that the larger the decrease of emissions with respect to the BAU scenario, the larger the resistance of interest groups in the economy.

The fact that the impact of an IEA in period 2 on current emissions can be ambiguous is *prima facie* puzzling. One may expect that future cooperation decreases the shadow cost of the stock of pollution in the future. As a best response, countries are expected to increase their current emissions. This is what happens under an IEA of type 3 and 4. However this intuition does not carry over to the case of a type 1 and type 2 IEA. To understand the contrast between the effects of the IEAs of type 1, 2 and 3, it is important to note that all three impose lower emission *levels* compared to the BAU scenario, but only an IEA of type 1 and 2 affect the *slope* of the emission policy. In the presence of a stock pollution, the slope of the emission policy generates a feedback effect in the pollution game. In equilibrium, the emission policy is a downward sloping function of the stock of pollution. This property generates an additional incentive for each country to raise its emissions, since an increase in its emissions will raise the stock of pollution, which will ultimately be met by a reduction of emissions of the other countries. While an IEA of type 3 leaves the slope of the emission policy unchanged, an IEA of type 1 and 2 reduces the slope of the emission policy and therefore diminishes (in the case of an IEA of type 2) or eliminate (in the case of an IEA of type 1) the feedback effect. This is why even a marginal reduction of emissions with respect to the BAU policy, as in an IEA of type 1 and 2, can result in a decrease of emissions in period 1.

While we assume throughout the paper, for simplicity, that the 'environmentally friendly' policy

[8] See Oates and Portney (2003) or Wangler, Altamirano-Cabrera and Weikard (2011).

will be adopted in period 2 with certainty, our analysis extends to the case where there is uncertainty about whether the 'environmentally friendly' policy will actually be adopted (i.e. where the probability of adoption of the cooperative solution is positive and less than one). For example, in the US, a treaty is negotiated by the administration and ratified by the US senate where a sixty percent majority is required. In the UK, the Constitutional Reform and Governance Act 2010 gave a statutory footing to the Ponsonby Rule, a convention that treaties be laid before Parliament before ratification.[9] The need of the approval of a legislative body often casts a significant amount of uncertainty on the actual ratification of a treaty signed by the executive branch of government.[10] Our analysis shows that even a treaty that may end up being rejected at the ratification stage will have an impact on the current policy (i.e., policy during the phase between adoption and the date of the ratification decision) as long as there is a positive probability of ratification in the future. Depending on the nature of the externality, and on the form of the anticipated future 'friendly' policy, the expectation of the ratification alone can alleviate or worsen the tragedy of the commons.

1.1 Literature Review

The possibility that an environmental friendly policy may end-up having negative environmental consequences, as is the case under all four types of IEAs considered, is by now well-established: see e.g., Hoel (1991 and 1992) or Eichner and Pethig (2011) in the case where environmentally friendly policies are unilaterally adopted by a sub-group countries or Benchekroun and Ray Chaudhuri (2014) in the case where countries adopt a cleaner technology.[11] A related literature that highlights the role of fossil fuels in the climate change problem examines the role of environmentally friendly policies on the intertemporal extraction of fossil fuels. Within this framework, the unintended negative impact of environmentally friendly policies (such as subsidy to cleaner energies) on the environment was coined 'the green paradox' (see e.g., Sinn (2012), Ploeg and Withagen (2012), Grafton, Kompas and Long (2012) or for surveys, Werf and Di Maria (2012), Ploeg and Withagen (2013) or Long (2014)). However, none of these papers examines the impact of an anticipated agreement on the current emissions. Smulders, Tsur and Zemel (2012) study the impact of announcing a carbon tax to be implemented in the future. They show that this announcement results in an increase of carbon emissions in the period that precedes the implementation of the tax, compared to the BAU scenario. The result is driven by an increase in savings and the accumulation of capital, which in turn translates into more production and emissions. Di Maria, Smulders and Werf (2012) examine the effectiveness of environmental policy under the presence of an implementation lag within the confines of a non-renewable resources model. They show that an implementation lag can result in an increase of emissions during the period that

[9] In Australia, the Federal Government does not need parliamentary approval to enter a binding treaty. However, legislation by Federal parliament is needed for the implementation of treaties.

[10] For example: the Kyoto Protocol was signed but not ratified by the US; the initial 1973 Convention for the Prevention of Pollution From Ships (Marpol 73) did not come into force for lack of ratifications.

[11] or Benchekroun (2003) in the context of international fisheries.

precedes implementation. This result is driven by the scarcity of the available resources. In our model, it is the countries' strategic response to the anticipation of an IEA that potentially leads the countries to cut back on the current emissions.

Harstad (2015) considers a model of formation of consecutive IEAs. Countries are assumed to be able to contract over emissions; however the length of the contract is finite. Along with the choice of emissions, each country chooses a level of investment in a technology that reduces its 'need for pollution'. When choosing its investment and emission levels, each country anticipates that there will be future negotiations. It is shown that IEAs may result in a smaller welfare than under the BAU scenario, where no IEA is signed. This is because when countries anticipate future negotiations, the hold-up problem diminishes the incentives to investment in the technology. This negative outcome is more likely to arise, the weaker the intellectual property rights, the shorter the length of the agreement, and the larger the number of countries. In contrast with Barstad (2015), where IEAs start at time zero, we have an explicit pre-agreement period where emissions are decided non-cooperatively, and we focus on emission decisions only. An important difference in Harstad (2015) and Harstad (2012) is that the equilibrium in the BAU case is not affected by the IEA that will prevail in the future. This feature is due to (i) the possibility to invest in technology and (ii) the fact that the investment costs are linear.[12]

Our paper is closely related to Beccherle and Tirole (2011), which also examines the impact of the announcement of a future environmental agreement within a two-period game between two countries. In their framework, the damage from pollution is generated in period 2, and depends only on the environmental policies adopted in period 2. However, in period 1, each country can adopt an environmental policy that will impact its private utility in period 2. The paper examines the impact of delaying an agreement on the bargaining outcome between the two countries, focusing on the environmental policies adopted in period 2. While their public good framework is quite general, a crucial assumption of their model is that a more lax environmental policy in period 1 results in a more lax environmental policy in period 2. Such an assumption makes their analysis not applicable to the case of a transboundary stock pollution game, where the emission policies in period 1 and period 2 are typically negatively related. Indeed, in our model, an increase in emissions in period 1 increases the stock of pollution in period 2, resulting in a decrease in period 2 emissions. Another contrast with Beccherle and Tirole (2011) is that we do not explicitly model the bargaining taking place in period 2. Rather, we assume that in period 2, the emission policy is fixed through an agreement and is independent of emissions in period 1.[13]

[12] Our result also contrasts with Harstad (2014) which shows in the case of a game between the owner of a fossil fuel deposit and a player seeking to prevent the use of fossil fuels, that the prospect of future compensation for conservation (in period 2) leads to more present conservation (in period 1). The contrast is due to the nature of the goods considered, i.e., "conservation goods" defined as goods where the buyer does not consume the good but only seeks "to prevent the seller from consuming it in the future."

[13] However, in the case of IEAs of type 2, 3 and 4 in our game, the outcome of the agreement in period 2 still depends on decisions made in period 1 since those decisions impact the stock of pollution in period 2 and therefore impact the outcome of the agreement.

In the following section, we present the model and analyze the benchmark BAU, and the first-best equilibrium. In section 3, we examine the impact of four different types of anticipated future agreements on the current emissions. Section 4 includes a discussion of optimal choice of emissions strategies and section 5 offers concluding remarks.

2 Model

There are two periods $t \in \{1,2\}$, and n identical countries $i \in I \equiv \{1,...,n\}$. Let P_t denote the initial stock of pollution at time t. Each country $i \in I$ emits pollution $E_{t,i}$ at time t.

The sequence of events in each period is as follows:

- given an initial stock P_t, countries choose their emissions $(E_{t,1},..,E_{t,n})$,
- the sum of the current emissions and the inherited stock cause a damage $D\left(P_t+\sum_{k=1}^{n} E_{t,k}\right)$.
- natural decay of pollution (current emissions plus the initial stock of pollution) occurs. We have

$$P_2=\left(P_1+\sum_{k=1}^{n} E_{1,k}\right)(1-\delta)$$

where $\delta \in [0,1]$ represents the natural rate of decay of the stock of pollution.

Countries derive utility $u(E)$ from emission.[14] We assume that $u'>0$ and $u''<0$ and $D'>0$ and $D''>0$. We assume that agents discount future utility and damage by a factor $\beta \in [0,1]$.

In the non-cooperative setup, each country i chooses an emission strategy, taking the profile of emission strategies of the other countries as given. We seek a Markov perfect Nash equilibrium of this game. In the cooperative setup, countries choose a vector of emissions in each period that maximize the joint discounted sum of welfare. We solve this problem backwards, starting from the strategies in period 2.

2.1 Period 2

Given a stock of pollution P_2, under the non-cooperative scenario, country i takes $E_{2,-i}$, the vector of emissions of all the countries except country i, as given and chooses its emissions $E_{2,i}$ as solution to the following problem:

$$E_{2,i} \in \arg\max_{E}\left(u(E)-D\left(P_2+E+\sum_{k\in I\backslash\{i\}} E_{2,k}\right)\right)$$

The first order condition (at an interior solution) gives

$$u'(E_{2,i})-D'\left(P_2+E_{2,i}+\sum_{k\in I\backslash\{i\}} E_{2,k}\right)=0.$$

[14] Utility is obtained from consumption. For simplicity we assume that production of one unit of consumption good causes one unit of pollutant.

Since countries are identical, we limit the attention to a symmetric equilibrium, $E_{2,NC}$ is a function of the initial stock P_2 and solves

$$u'\left(E_{2,NC}\right) - D'\left(P_2 + nE_{2,NC}\right) = 0 \tag{1}$$

Observe that if $u'(0) < \infty$, then for P_2 such that $u'(0) - D'(P_2) < 0$ we have $E_{2,NC} = 0$. On the other hand, if $u'(0) \geq D'(P_2)$, there exists a unique interior solution $E_{2,NC} > 0$ to equation (1). Similarly, If $\lim_{E\to 0^+} u'(E) = \infty$ and $\lim_{E\to\infty} u'(E) = 0$, then for each $P_2 > 0$ there exists a unique interior solution $E_{2,NC} > 0$ to equation (1). We further make the relationship between emissions and the stock of pollution more explicit and denote the equilibrium emission policy by $E_{2,NC}(P_2)$.

Total differentiation of expression (1) with respect to P_2 gives

$$u''\left(E_{2,NC}\left(P_2\right)\right) E'_{2,NC}\left(P_2\right) - \left(1 + nE'_{2,NC}\left(P_2\right)\right) D''\left(P_2 + nE_{2,NC}\left(P_2\right)\right) = 0 \tag{2}$$

which implies

$$E'_{2,NC}\left(P_2\right) = \frac{D''\left(P_2 + nE_{2,NC}\left(P_2\right)\right)}{u''\left(E_{2,NC}\left(P_2\right)\right) - nD''\left(P_2 + nE_{2,NC}\left(P_2\right)\right)} < 0 \tag{3}$$

If countries were to choose a vector of emission strategies that maximize their joint welfare, they would choose the emission strategy $E_{2,Coop}(P_2)$ solution to

$$u'\left(E_{2,Coop}\left(P_2\right)\right) - nD'\left(P_2 + nE_{2,Coop}\left(P_2\right)\right) = 0 \tag{4}$$

2.2 Period 1

We now consider the problem of Country i in period 1 under the non-cooperative scenario. Given an initial stock of pollution in period 1, country i takes $E_{1,-i}$, the vector of emissions in period 1 of all the countries except country i, as given. It also takes the Nash equilibrium policy in period 2, $E_{2,NC}(P_2)$, as given and solves the following problem

$$E_{1,i} \in \arg\max_E \left(u(E) - D\left(P_1 + E + \sum_{k\in I\setminus\{i\}} E_{1,k}\right) + \beta\left(u\left(E_{2,NC}\left(P_2\right)\right) - D\left(P_2 + nE_{2,NC}\left(P_2\right)\right)\right)\right)$$

where

$$P_2 = \left(P_1 + E + \sum_{k\in I\setminus\{i\}} E_{1,k}\right)(1-\delta)$$

The first order condition gives

$$\begin{aligned} & u'(E) - D'\left(P_1 + E + \sum_{k\in I\setminus\{i\}} E_{1,k}\right) \\ & +\beta\left(u'\left(E_{2,NC}\left(P_2\right)\right) E'_{2,NC}\left(P_2\right) - \left(\left(1 + nE'_{2,NC}\left(P_2\right)\right)\right) D'\left(P_2 + nE_{2,NC}\left(P_2\right)\right)\right) \frac{dP_2}{dE} \\ = \; & 0 \end{aligned}$$

Using the facts that $E_{2,NC}$ satisfies equation (1) and that $\frac{dP_2}{dE} = 1 - \delta$, at a symmetric equilibrium, period 1 emissions (as a function of pollution stock), $E_{1,NC}(P_1)$, solves

$$u'(E_{1,NC}(P_1)) - D'(P_1 + nE_{1,NC}(P_1)) - \beta(1-\delta)\left(1 + (n-1)E'_{2,NC}\right)u'(E_{2,NC}(P_2)) = 0 \qquad (5)$$

We assume that such a solution exists and is unique for each P_1. We refer to the emission policies $E_{1,NC}(P)$ and $E_{2,NC}(P)$ as the business-as-usual (BAU) policies in period 1 and 2 respectively. Condition (5) represents the usual balance of the marginal benefit from current emissions with the present and future marginal damages from pollution. We would like to draw the attention of the reader to the term $(n-1)E'_{2,NC}$. The presence of this term captures the impact of a given country's current emissions on the future emissions of other countries. In period 1, while any given country takes the strategies of the other countries as given, if the strategies are stock dependent, by affecting the stock of pollution, a country can manipulate the emission of other countries: in the dynamic games literature, this channel of interaction is referred to as the feedback effect. This term $(n-1)E'_{2,NC}$ is typically negative, therefore the feedback effect reduces the future marginal damage from pollution and boosts the incentive of each country to increase its current emissions compared to a situation where this channel is absent (e.g., if countries choose emission paths instead of emission policies).

3 Anticipated IEAs

Having provided the benchmark case, we now examine the impact of a fully anticipated IEA that would implement an emission strategy in period 2 (denoted by $E_{2,C}(P)$) that is more environmentally friendly than the BAU policy in period 2. We separately consider four types of IEAs: (i) $E_{2,C}(P) = \bar{E}$, (ii) $E_{2,C}(P) = (1-\varepsilon)E_{2,NC}(P)$, (iii) $E_{2,C}(P) = E_{2,NC}(P) - \eta$ and (iv) $E_{2,C}(P) = E_{2,Coop}(P)$.

An IEA of type (i) prescribes a specific target of the level of emissions in period 2. Under this type of IEA, countries are assumed to be able to commit to a level of emissions in period 2, even if the stock of pollution in period 2 turns out to be different from the level anticipated. This arrangement is similar to the commitment assumed in open-loop games and results in equilibria that may not be subgame perfect.

IEAs of type (ii) and (iii) correspond to a cut, percentage in case of (ii) and uniform in case of (iii), with respect to the BAU policy. Note that they represent a cut with respect to an emission *policy* and not a level of emissions (as in case (i)). Using emission policies for period 2 yields a more robust IEA than an IEA of type 1, since the agreement is stock dependent. If the stock of pollution in period 2 differs from what was originally anticipated, the principle of the agreement is still valid. This robustness is similar to that of a subgame perfect equilibrium in a non-cooperative framework[15]. The IEAs of type (ii) and (iii) are inspired from a negotiation process where the benchmark is the BAU

[15] see Dockner et al. (2000) Ch 4.

scenario, and where parties try to find improvements over the BAU policies. The size of the departure, captured by either ε or η, reflects the limitations of policy makers to impose changes with respect to a BAU scenario because of political pressure and lobbying from different groups in the economy. The influence of interest groups, whether environmental groups or groups representing industrial interests, on environmental policy is well established (See e.g., Oates and Portney (2003) or Wangler et al. (2011) for a survey).

The IEA of type (iv) is provided as a benchmark. It represents the 'ideal' agreement that can be reached in period 2. Under an IEA of type (iv) policy makers are assumed free of any domestic political constraints, and can choose freely the welfare maximizing policy of the country they represent. While it is a useful benchmark, in particular in the assessment of the potential gains from an IEA, or the absence of an IEA, it has proven to be too difficult to reach in practice. Most of the IEAs take the form of a reduction with respect to a BAU scenario.

3.1 IEA Type 1: Setting an emission target

We examine the case where

$$E_{2,C}\left(P\right) = \bar{E} \text{ where } 0 < \bar{E} < E_{2,NC}\left(P_{2,NC}\right)$$

and where $P_{2,NC}$ is the equilibrium stock of pollution at the beginning of period 2 in the non-cooperative scenario. Thus $E_{2,NC}\left(P_{2,NC}\right)$ represents the equilibrium emissions in period 2 in the absence of an IEA in period 2. Since $\bar{E} < E_{2,NC}\left(P_{2,NC}\right)$, setting emissions in period 2 at $\bar{E}$, represents indeed a more environmentally friendly policy than the BAU policy.

The problem of country i is

$$\max_{E}\left(u\left(E\right) - D\left(P_1 + E + \sum_{k\in I\setminus\{i\}} E_{1,k}\right) + \beta\left(u\left(\bar{E}\right) - D\left(P_2 + n\bar{E}\right)\right)\right)$$

where

$$P_2 = \left(P_1 + E + \sum_{k\in I\setminus\{i\}} E_{1,k}\right)\left(1-\delta\right).$$

Assuming a symmetric equilibrium, the first order condition of the problem above implies an emission strategy $E_{1,C}\left(P\right)$ that solves

$$u'\left(E_{1,C}\right) - D'\left(P_1 + nE_{1,C}\right) - \beta\left(1-\delta\right)D'\left(\left(P_1 + nE_{1,C}\right)\left(1-\delta\right) + n\bar{E}\right) = 0$$

Lemma 1. *Suppose that an IEA in period is anticipated to implement a predetermined level of emissions where $\bar{E} < E_{2,NC}\left(P_{2,NC}\right)$, a decrease in the threshold $\bar{E}$ unambiguously results in an increase in current emissions.*

Proof: See Appendix A.

We should note, however, that setting $\bar{E} = E_{2,NC}(P_{2,NC})$ does not yield $E_{1,C} = E_{1,NC}$. Indeed, when $\bar{E} = E_{2,NC}(P_{2,NC})$, we have $E_{1,C} < E_{1,NC}$, a result proven in the lemma below. This is due to the feedback effect that is present in the non-cooperative case (i.e., $E'_{2,NC}(P_2) < 0$).[16]

Lemma 2. *Suppose that an IEA in period 2 is anticipated to implement a predetermined level of emissions $\bar{E} = E_{2,NC}(P_{2,NC})$. This unambiguously results in a decrease in current emissions.*

Proof: See Appendix B.

We can infer from Lemmas 1 and 2 that the overall impact of setting emissions in period 2 to a level $\bar{E} < E_{2,NC}(P_{2,NC})$ on current emissions is ambiguous. It clearly results in a decrease of current emissions if $\bar{E}$ is sufficiently close to $E_{2,NC}(P_{2,NC})$, whereas setting $\bar{E}$ at level close to zero may result in an increase of current emissions.[17] This result is summarized in the following proposition:

Proposition 1. *Suppose that a fully anticipated IEA in period 2 implements a predetermined level of emissions $\bar{E} \leq E_{2,NC}(P_{2,NC})$. The impact of such an IEA on the equilibrium emissions in period 1 is ambiguous.*

3.2 IEA Type 2: A percentage cut in emissions

Suppose now, that in period 1 countries anticipate an IEA of the following type:

$$E_{2,C}(P) = (1-\varepsilon) E_{2,NC}(P) \text{ where } \varepsilon \in [0,1].$$

When $\varepsilon < 1$, the policy $E_{2,C}(P)$ is indeed a more environmentally friendly policy than the BAU policy since we have

$$E_{2,C}(P) < E_{2,NC}(P) \text{ for all } P.$$

In period 1, the problem of country i is now:

$$\max_E \left(u(E) - D\left(P_1 + E + \sum_{k \in I \backslash \{i\}} E_{1,k}\right) + \beta\left(u\left((1-\varepsilon) E_{2,NC}(P_2)\right) - D\left(P_2 + n(1-\varepsilon) E_{2,NC}(P_2)\right)\right)\right)$$

with

$$P_2 = \left(P_1 + E + \sum_{k \in I \backslash \{i\}} E_{1,k}\right)(1-\delta)$$

Assuming a symmetric equilibrium, the emission strategy in period 1, denoted by $E_{1,C}(P)$, solves the following first order condition of the above problem:

[16] The feedback effect of production constraints has been highlighted in Dockner and Haug (1990, 1991) in the context of dynamic import quotas.

[17] See appendix C for a proof in the case where the damage from pollution is such that $D'(0) = 0$.

$$u'\left(E_{1,C}\left(P_1\right)\right) - D'\left(P_1 + nE_{1,C}\left(P_1\right)\right) = R\left(\varepsilon\right)$$

where

$$R\left(\varepsilon\right) \equiv -\beta\left(1-\delta\right)\Lambda$$

with

$$\Lambda \equiv u'\left(\left(1-\varepsilon\right)E_{2,NC}\left(P_2\right)\right)\left(1-\varepsilon\right)E'_{2,NC}\left(P_2\right) - \left(\left(1+n\left(1-\varepsilon\right)E'_{2,NC}\left(P_2\right)\right)\right)D'\left(P_2 + n\left(1-\varepsilon\right)E_{2,NC}\left(P_2\right)\right).$$

Lemma 3. *We have*

$$E_{1,NC}\left(P_1\right) > E_{1,C}\left(P_1\right) \text{ for all } P_1$$

if and only if

$$R\left(0\right) < R\left(\varepsilon\right).$$

Proof: This follows from the facts that (i)

$$u'\left(E_{1,C}\left(P_1\right)\right) - D'\left(P_1 + nE_{1,C}\left(P_1\right)\right) = R\left(\varepsilon\right)$$
$$u'\left(E_{1,NC}\left(P_1\right)\right) - D'\left(P_1 + nE_{1,NC}\left(P_1\right)\right) = R\left(0\right)$$

and, (ii) $u'\left(X\right) - D'\left(P_1 + nX\right)$ is a strictly decreasing function of X.■

To establish the sign of $R\left(0\right) - R\left(\varepsilon\right)$, we examine the impact of a change in ε on $R\left(.\right)$. For tractability reasons, we examine the impact of a marginal proportional reduction of emissions with respect to the BAU scenario, i.e., marginal change in ε in the neighborhood of $\varepsilon = 0$.

Proposition 2. *A marginal proportional reduction of future emissions results in a decrease (an increase) of current emissions if and only if* $\sigma \equiv -\frac{E_{2,NC}(P_2)u''(E_{2,NC}(P_2))}{u'(E_{2,NC}(P_2))} < 1$

$$E_{1,NC}\left(P_1\right) > E_{1,C}\left(P_1\right) \text{ iff } \sigma < 1.$$

Proof: See Appendix D.

From Proposition 2, it is immediate that in the case where utility has a constant elasticity of marginal utility, i.e.,

$$u\left(E\right) = \frac{E^{1-\sigma}}{1-\sigma}$$

we have $R'\left(0\right) > 0$ or $E_{1,NC}\left(P_1\right) > E_{1,C}\left(P_1\right)$ iff $\sigma < 1$.

Along with the specification in which the utility exhibits constant elasticity, another widely used framework is the linear-quadratic (LQ) model, where utility is a quadratic function of emissions, and the damage function is a quadratic function of the stock of pollution. We show below that the sign of $R'\left(0\right)$ is ambiguous even in the LQ case:

$$u\left(E\right) = E\left(A - \frac{B}{2}\right)E$$

and

$$D(P) = \frac{1}{2}\gamma P^2.$$

For the rest of the exposition, we impose $A = 1$ and $B = 1$ without loss of generality. It can be shown, at a symmetric equilibrium, that the emissions strategies satisfy

$$E_{2,NC}(P) = \begin{cases} \frac{1-\gamma P}{1+n\gamma} & \text{for } 1-\gamma P \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

$$E_{1,C}(P) = \max\left\{0, \frac{\Gamma + \Phi P}{\Delta}\right\}$$

where

$$\begin{aligned} \Delta &= 1 + (3+\beta(1-\delta)^2)n\gamma + (3n + \beta(1-\delta)^2(1+\varepsilon^2+2\varepsilon(n-1)))n\gamma^2 + (1+\beta(1-\delta)^2\varepsilon^2)n^3\gamma^3 \\ &> 0 \end{aligned}$$

$$\Gamma = 1 + \gamma(2n - \beta(\delta-1)(-1+\varepsilon)(\varepsilon+n)) + \gamma^2 n(n - \beta(\delta-1)(\varepsilon-1)(1+n\varepsilon))$$

$$\Phi = -\gamma\left(1 + \beta(1-\delta)^2 + \left(1+\beta(1-\delta)^2\varepsilon^2\right)\gamma^2 n^2 + \gamma\left(\beta(1-\delta)^2\left(1+\varepsilon^2+2\varepsilon(n-1)\right) + 2n\right)\right)$$

In the special case where $\varepsilon = 0$, we have $E_{1,C}(P) = E_{1,NC}(P)$. Moreover, substitution of u'' and u' gives

$$\sigma = \frac{(E_{2,NC}(P_2))^2}{1 - E_{2,NC}(P_2)}$$

The sign of $\sigma - 1$ is difficult to determine, since the expression of P_2 is non-trivial. We can however state that in the limit case where γ tends to zero, one would expect $E_{2,NC}(P_2)$ to be close to 1, and therefore σ tends to infinity, implying that a marginal proportional reduction of future emissions results in an increase of current emissions. In another limit case where γ becomes arbitrarily large, one could expect $E_{2,NC}(P_2)$ to tend to zero and therefore σ would tend to zero, implying that a marginal proportional reduction of future emissions results in a decrease of current emissions. We provide more precise statements for analysis of the sign of $\frac{dE_{1,C}(P)}{d\varepsilon}$ below. For ease of exposition, we examine the cases $P = 0$ and $P > 0$ separately.

The case $P = 0$:

It can be shown that

$$\left.\frac{dE_{1,C}(0)}{d\varepsilon}\right|_{\varepsilon=0} = \frac{\beta(1-\delta)\gamma(n-1)(1+n\gamma)\Omega}{\Delta^2}$$

where

$$\Omega = 1 + \left(-1 + \beta\,(1-\delta)^2 + 2\delta\right)\gamma n - n^3\gamma^3 + \gamma^2 n\left(\beta\,(1-\delta)^2 + n\,(2\delta - 3)\right).$$

Therefore the sign of $\left.\frac{dE_{1,C}(0)}{d\varepsilon}\right|_{\varepsilon=0}$ is the same as that of Ω.

The term Ω is a cubic function of γ. Its graph in a (γ, Ω) space has an inverted N shape and there exist γ_1 and $\gamma_2 > \gamma_1$ where Ω reaches a local minimum and maximum respectively. The function is an increasing function of γ over (γ_1, γ_2) and decreasing elsewhere.

Lemma 4. *There exists a unique $\bar{\gamma} > 0$ such that $\Omega < 0$ for $\gamma > \bar{\gamma}$ and $\Omega > 0$ for $0 < \gamma < \bar{\gamma}$.*

Proof: See Appendix E.

We now summarize our main result for this case in the proposition below.

Proposition 3. *There exists a unique $\bar{\gamma} > 0$ such that for $\gamma < (>)\bar{\gamma}$ the adoption of a marginally more environmental friendly emission policy $E_{2,C}(P) = (1-\varepsilon)\,E_{2,NC}(P)$ by all players results in an increase (decrease) in equilibrium emissions in period 1 in the neighborhood of $P = 0$.*

Proof: This follows from the fact that the sign of $\left.\frac{dE_{1,C}(0)}{d\varepsilon}\right|_{\varepsilon=0}$ is given by the sign of Ω and from Lemma 4.■

The case $P > 0$ **:**

Recall that

$$E_{1,C}(P) = \frac{\Gamma + \Phi P}{\Delta}$$

Let $F(\varepsilon) = \frac{\Phi}{\Delta}$. After substitution and derivation with respect to ε we obtain

$$F(\varepsilon) = -\frac{\gamma\left(1 + \beta\,(1-\delta)^2 + \left(1 + \beta\,(1-\delta)^2\,\varepsilon^2\right)\gamma^2 n^2 + \gamma\left(\beta\,(1-\delta)^2\left(1 + \varepsilon^2 + 2\varepsilon\,(n-1)\right) + 2n\right)\right)}{1 + (3 + \beta(1-\delta)^2)n\gamma + (3n + \beta(1-\delta)^2(1 + \varepsilon^2 + 2\varepsilon\,(n-1)))n\gamma^2 + (1 + \beta(1-\delta)^2\varepsilon^2)n^3\gamma^3}$$

for which it can be shown that

$$F'(0) = -\frac{2\,(n-1)\,\beta\gamma^2\,(\delta-1)^2\,(n\gamma+1)^2}{\left(3n^2\gamma^2 + n^3\gamma^3 + 3n\gamma + n\beta\gamma + n\beta\gamma^2 + n\beta\gamma\delta^2 - 2n\beta\gamma^2\delta + n\beta\gamma^2\delta^2 - 2n\beta\gamma\delta + 1\right)^2} < 0$$

An increase in ε results in a decrease of the slope, a steeper emission strategy. From the expressions above, we can conclude that

Proposition 4. *There exists a unique $\bar{\gamma} > 0$ such that for $\gamma > \bar{\gamma}$ the adoption of a marginally more environmental friendly emission policy $E_{2,C}(P) = (1-\varepsilon)\,E_{2,NC}(P)$ by all players results in an decrease in equilibrium emissions in period 1, for all $P \geq 0$.*

For $\gamma < \bar{\gamma}$ the impact of the adoption of a marginally more environmental friendly emission policy $E_{2,C}(P) = (1-\varepsilon)\,E_{2,NC}(P)$ by all players on the equilibrium emissions in period 1 depends on P : There exists $\bar{P} > 0$ such that $E_{1,C}(P) > E_{1,NC}(P)$ if and only if $P < \bar{P}$.

3.3 IEA Type 3: A constant cut in emissions

In this section, we examine the case where countries anticipate an IEA in period 2 that features a constant cut in emissions:

$$E_{2,C}(P) = E_{2,NC}(P) - \eta \text{ where } \eta \in [0, E_{2,NC}(P_{2,NC})]$$

The problem of country i is

$$\max_E \left(u(E) - D\left(P_1 + E + \sum_{k \in I \setminus \{i\}} E_{1,k}\right) + \beta\left(u\left(E_{2,NC}(P_2) - \eta\right) - D\left(P_2 + nE_{2,NC}(P_2) - n\eta\right)\right)\right)$$

where

$$P_2 = \left(P_1 + E + \sum_{k \in I \setminus \{i\}} E_{1,k}\right)(1 - \delta)$$

The first order condition for the problem above characterizes the symmetric equilibrium strategy $E_{1,C}(P)$.

$$u'(E_{1,C}(P_1)) - D'(P_1 + nE_{1,C}(P_1)) = Q(\eta)$$

where

$$Q(\eta) \equiv -\beta(1-\delta)\left(u'\left(E_{2,NC}(P) - \eta\right)E'_{2,NC}(P) - \left(1 + nE'_{2,NC}(P)\right)D'\left(P + nE_{2,NC}(P) - n\eta\right)\right)$$

Comparing $E_{1,C}(P)$ with $E_{1,NC}(P)$ amounts to comparing $Q(\eta)$ and $Q(0)$. Since $u''(E_{1,NC}(P_1)) - D''(P_1 + nE_{1,NC}(P_1)) < 0$, we have $E_{1,C}(P) < E_{1,NC}(P)$ if and only if $Q(\eta) > Q(0)$. The sign of $Q(\eta) - Q(0)$ is difficult to determine with a general specification. As in the case of a proportional emission reduction, we evaluate the sign of $Q(\eta) - Q(0)$ in the case of a marginal decrease of emissions with respect to the BAU policy.

Proposition 5. *The adoption of a marginally more environmental friendly emission policy $E_{2,C}(P) = E_{2,NC}(P) - \eta$ by all players results in an increase of current emissions.*

Proof: See Appendix F.

In the LQ model, it can be shown that the result of proposition 5 extends to the case of non-marginal constant cut of emissions.

3.4 IEA Type 4: Ex-post first-best emissions

We examine the case where countries anticipate that there will be full cooperation in period 2: The chosen vector of emission strategies will be the one that maximizes the joint welfare of all the countries in period 2. We call this agreement, the ex-post first-best IEA, and denote the corresponding emission strategy $E_{2,Coop}(P_2)$. In period 1, each country acts non-cooperatively, choosing its emission strategy that maximizes its private welfare.

At a symmetric equilibrium, period 1 strategy, denoted by $E_{1,C}(P)$ solves

$$\begin{aligned} & u'(E_{1,C}(P_1)) - D'(P_1 + nE_{1,C}(P_1)) \\ & +\beta(1-\delta)\left(u'(E_{2,Coop}(P_2))E'_{2,Coop}(P_2) - \left(\left(1+nE'_{2,Coop}(P_2)\right)\right)D'(P_2+nE_{2,Coop}(P_2))\right) \\ = \ & 0 \end{aligned}$$

In section 2, we have shown that under full cooperation in period 2 we have $u'(E_{2,Coop}(P_2)) - nD'(P_2 + nE_{2,Coop}(P_2)) = 0$, and therefore the expression can be simplified further to

$$u'(E_{1,C}(P_1)) - D'(P_1 + nE_{1,C}(P_1)) - \beta(1-\delta)D'(P_2 + nE_{2,Coop}(P_2)) = 0.$$

In the following proposition, we provide a necessary condition for this particular IEA to result in a decrease of current emissions.

Proposition 6. *If an IEA in period 2 that implements the first-best emissions strategies results in a decrease of current emissions then we must have*

$$\frac{u'(E_{2,Coop}(P_{2,Coop}))}{u'(E_{2,NC}(P_{2,NC}))} - n\left(1+(n-1)E'_{2,NC}(P_{2,NC})\right) > 0. \tag{6}$$

Proof: See Appendix G.

We argue below that the necessary condition for $E_{1,NC}(P_1) > E_{1,C}(P_1)$ given in the above proposition is never satisfied in the linear-quadratic (LQ) framework and the case where utility function is logarithmic.

First of all, if $E_{1,NC}(P_1) > E_{1,C}(P_1)$ were satisfied, then we have $P_{2,NC} > P_{2,Coop}$. Ignoring the possibility of optimal zero emissions, since cooperative emissions strategy is downward sloping, we have

$$E_{2,Coop}(P_{2,NC}) < E_{2,Coop}(P_{2,Coop})$$

or

$$u'(E_{2,Coop}(P_{2,NC})) > u'(E_{2,Coop}(P_{2,Coop}))$$

This implies

$$\frac{u'(E_{2,Coop}(P_{2,Coop}))}{u'(E_{2,NC}(P_{2,NC}))} - n\left(1+(n-1)E'_{2,NC}(P_{2,NC})\right) < \frac{u'(E_{2,Coop}(P_{2,NC}))}{u'(E_{2,NC}(P_{2,NC}))} - n\left(1+(n-1)E'_{2,NC}(P_{2,NC})\right)$$

However, we show below in the LQ and Log cases that

$$\frac{u'(E_{2,Coop}(P))}{u'(E_{2,NC}(P))} - n\left(1+(n-1)E'_{2,NC}(P)\right) < 0 \text{ for all } P,$$

and in particular

$$\frac{u'(E_{2,Coop}(P_{2,NC}))}{u'(E_{2,NC}(P_{2,NC}))} - n\left(1+(n-1)E'_{2,NC}(P_{2,NC})\right) < 0.$$

Therefore, the necessary condition for $E_{1,NC}(P_1) > E_{1,C}(P_1)$ in proposition 6 is never satisfied. It must then be the case that $E_{1,NC}(P_1) \leq E_{1,C}(P_1)$.

Linear-Quadratic Case: Let $u(x) = x\left(A - \frac{1}{2}x\right)$ and $D(P) = \frac{1}{2}\gamma P^2$, after substitution of the optimal strategies, it can be shown that

$$\frac{u'(E_{2,Coop}(P_2))}{u'(E_{2,NC}(P_2))} - n\left(1 + (n-1)E'_{2,NC}\right) = -\frac{\gamma n(n-1)^2}{(1+\gamma^2 n^3 + \gamma n(1+n))} < 0$$

Logarithmic Utility Case: Let $u(x) = \ln(x)$ and $D(P) = \frac{1}{2}\gamma P^2$. It is straightforward to show that the equilibrium strategies satisfy

$$E_{2,NC}(P) = \frac{\frac{\sqrt{4n+\gamma P^2}}{\sqrt{\gamma}} - P}{2n}$$

$$E_{2,Coop}(P) = \frac{\frac{\sqrt{4+\gamma P^2}}{\sqrt{\gamma}} - P}{2n}$$

Condition (6) becomes

$$G(P,n) \equiv \frac{-\sqrt{\gamma}P + \sqrt{4n+\gamma P^2}}{-\sqrt{\gamma}P + \sqrt{4+\gamma P^2}} - \frac{(n+1) + \frac{(n-1)\sqrt{\gamma}P}{\sqrt{4n+\gamma P^2}}}{2} > 0 \tag{7}$$

In the limit case where P tends to zero it is straightforward to see that we have

$$G(0,n) \equiv \sqrt{n} - \frac{n+1}{2} < 0 \text{ for } n > 1. \tag{8}$$

In Appendix H we prove that (7) is violated in general, for $P > 0$.

We therefore conclude that for both the LQ and log-utility specifications, an IEA in period 2 that implements the first-best emissions strategies results in an increase of current emissions.

4 Optimal Cooperative Announcement

Up to this point, our results concentrated on how the announcement of various cooperative agreements to be implemented in the future influenced emissions in period 1, relative to BAU. We illustrated that, this relationship is ambiguous in general, and for specific environments in which it is not, the characterization is a challenging task. The announced cooperative agreements for period 2 were exogenously given and we analyzed their implications on period 1 emissions.

In this section, we ask a different question: What is the optimal cooperative agreement to announce, taking into account the countries' response in anticipation? We focus exclusively on the case where commitment to an emission level is feasible. A constant emissions target for period 2 is chosen optimally, prior to noncooperative emissions decisions in period 1.[18]

We consider cooperative emissions of the form $\bar{E}(P_2) = \theta$, where $\theta \geq 0$ is chosen prior to period 1 emissions decisions. The next result relates optimal choice of θ to the fully cooperative emissions level.

[18] The discussion of the case where countries cannot commit to a pollution level is postponed until Remark 1.

Proposition 7. *Let* $P_2 = (1-\delta)[P+nE_1(P;\theta)]$ *denote the pollution level in period 2 that prevails under the ex ante optimal choice of* θ*. The target emissions always exceeds the fully cooperative emissions that would occur under* P_2*, i.e.* $\bar{E} = \theta > E_{2,coop}(P_2)$*.*

Proof:

Fix some P. The value of following θ in period 2 is

$$V_2(P_2;\theta) = u(\bar{E}) - D(P_2 + n\bar{E}) = u(\theta) - D(P_2 + n\theta)$$

This implies

$$\frac{\partial V_2}{\partial \theta} = u'(\bar{E}) - nD'(P_2 + n\bar{E})$$
$$\frac{\partial V_2}{\partial P_2} = -D'(P_2 + n\bar{E})$$

These results can be used to show that the symmetric non-cooperative emissions strategy in period 1 solves

$$u'(E_1(.)) - D'(P + nE_1(.)) - \beta(1-\delta)D'(P_2 + n\theta) = 0 \tag{9}$$

where $P_2 = (1-\delta)(P + nE_1(.))$. This equality holds for any value of θ, differentiating it with respect to θ yields

$$\left[u''(E_1(.)) - nD''(P + nE_1(.)) - n\beta(1-\delta)^2 D''(P_2 + n\theta)\right]\frac{\partial E_1}{\partial \theta} - n\beta(1-\delta)D''(P_2 + n\theta) = 0$$

Since $u'' < 0$, and $D'' > 0$ by assumption, we have

$$\frac{dE_1}{d\theta} < 0 \text{ for all } \theta \geq 0. \tag{10}$$

The social planner's problem is

$$\max_{\theta \geq 0} u(E_1(\theta)) - D(P + nE_1(\theta)) + \beta V_2(P_2;\theta)$$

The first-order condition with respect to θ, at an interior solution, is

$$\left[u'(E_1(.)) - nD'(P + nE_1(.)) - n\beta(1-\delta)D'(P_2 + n\theta)\right]\frac{dE_1}{d\theta} + \beta[u'(\theta) - nD'(P_2 + n\theta)] = 0$$

Using (9), this expression simplifies to

$$(1-n)u'(E_1(.))\frac{dE_1}{d\theta} + \beta[u'(\theta) - nD'(P_2 + n\theta)] = 0$$

Since inequality (10) holds, $[u'(\theta) - nD'(P_2 + n\theta)] < 0$ must hold at an optimal choice of θ. Using the fact that fully cooperative emissions strategy satisfies $u'(E_{2,coop}(P_2)) - nD'(P_2 + nE_{2,coop}(P_2)) = 0$ and the objective is strictly concave in the choice of emissions, $\theta > E_{2,coop}(P_2)$ must be satisfied.■

If the IEA could revisit its emission level for period 2 it would set it at a lower level than the one announced. The reason for the apparent lax announced level by the IEA is to reduce the extent of free riding taking place in period 1; larger emissions in period 2 implies a higher damage caused by the emissions in period 1 thereby inducing each country to curb its period 1 emissions.

Remark 1: Suppose countries are not able to commit to an emission level in period 2, and instead choose an emission policy to announce for period 2. Using an emission policy assumes that emissions are adjustable in period 2. One can expect that, if in period 2 countries can adjust their emission levels, countries will choose the level that maximizes the global welfare in period 2 given the stock that will be observed at the beginning of period 2, i.e., countries will then choose the emission level $E_{2,coop}(P_2)$. Any alternate emission policy for period 2, that is announced in the beginning of the game, would not be credible[19].

5 Discussion and concluding remarks:

The contribution of this paper is twofold. First, we have shown that strategic behavior can potentially exacerbate the tragedy of the commons in the pre-cooperation phase when there are delays in the agreement. Second, we have identified types of IEA that can result in the attenuation of the tragedy of the commons problem in the pre-cooperation phase. In terms of policy recommendation, as far as the emission levels are concerned, an IEA that sets a target emission level or a percent cut in emission policy (in case the elasticity of marginal utility is smaller than unity) perform better than an IEA the implements a constant cut with respect to the BAU emission policy.

The incentive to emit more pollution in period 1, in anticipation of a future IEA can be reduced (or eliminated) by decreasing (or removing) the sensitivity of the emissions to the stock of pollution in period 2. Under an emission policy in period 2 that is downward sloping, each player has an extra benefit from emissions in period 1. Since an increase in private emissions results in an increase in the future stock of pollution, and in turn in a decrease of the other players' emissions. The strength of this feedback depends on how steep the emission policy is. IEAs of type 1 and 2 in affect not only reduce the level of emissions, but also the slope of the emission policy. In contrast, an IEA of type 4, in the LQ and log-utility framework, implements a steeper emission policy. Not surprisingly, the feedback is exacerbated and each country responds by increasing its own current emissions.

In our framework, the damage incurred in period 2 is the result of the stock of pollution, after emissions in period 2 take place, $P_2 + nE_{2,NC}(P_2)$. One possible target that can be set by negotiators is to achieve a percentage cut in the *stock* of pollution, for instance, $(1-\varepsilon)(P_2 + nE_{2,NC}(P_2))$. Such an objective is equivalent to choosing an emission policy $E_{2,C}(P) = (1-\varepsilon) E_{2,NC}(P) - \frac{\varepsilon}{n} P$. The equivalent change in emission policy would imply a steeper environmental policy, a stronger feedback effect, and ultimately larger emissions in period 1 than under a percent cut in the BAU emission policy. Similarly,

[19] Note that the cases of $E_{2,C}(P) = (1-\varepsilon) E_{2,NC}(P)$ or $E_{2,C}(P) = E_{2,NC}(P) - \eta$ studied above were motivated by the fact that $E_{2,coop}(P)$ is not feasible (e.g., due to political economy constraints) and only (small) departures from the non-cooperative policy are possible. In this section, $E_{2,Coop}(.)$ is feasible.

an IEA that aims to achieve a constant cut in the stock of pollution of the form $(P_2 + nE_{2,NC}(P_2)) - \eta$ is equivalent to adopting an emission policy $E_{2,C}(P) = E_{2,NC}(P) - \frac{\eta}{n}$, and would therefore have qualitatively the same effect as a constant cut with respect to the BAU emission policy, i.e., an increase in emissions in period 1 with respect to the BAU scenario. It is straightforward to establish this result as well as Propositions 2 and 5 within an infinite time horizon model where cooperation takes place from period 2 onwards.[20]

We have treated the case where an agreement is delayed, but is implemented with certainty at a future date. Our qualitative results extend to the case where there is uncertainty about the success or actual implementation of an agreement at a future date. Players then maximize the expected discounted sum of their payoffs. The case analyzed in this paper corresponds to the limit case where the probability of success or implementation of an agreement in the future tends to one. Allowing for a probability of a successful agreement smaller than one would not change our results qualitatively.

We believe that the lessons learned from this analysis extend to dynamic stock public good games in general (see e.g., Fershtman and Nitzan (1991)). Anticipating a future agreement that will increase the provision of a public good with a respect to a business-as-usual policy may result in an increase or a decrease of current contributions of the public good. The optimistic message of this paper is that it is possible to have agreements over contribution policies for the future than can alleviate the tragedy of the commons in the present. To this end, a careful examination of the slopes of the contribution policy and the BAU policy is required.

[20]The steps are similar to the steps followed in the 2 period model. They are omitted, but are available from the authors upon request.

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Appendices

Appendix A

Lemma 1. *Suppose that an IEA in period is anticipated to implement a predetermined level of emissions where $\bar{E} < E_{2,NC}(P_{2,NC})$, a decrease in the threshold $\bar{E}$ unambiguously results in an increase in current emissions.*

Proof: Total differentiation with respect to $\bar{E}$ gives

$$u''(E_{1,C})\frac{dE_{1,C}}{d\bar{E}} - D''(P_1 + nE_{1,C})\,n\frac{dE_{1,C}}{d\bar{E}} - \beta(1-\delta)D''\left((P_1 + nE_{1,C})(1-\delta) + n\bar{E}\right)\left(n(1-\delta)\frac{dE_{1,C}}{d\bar{E}} + n\right) = 0$$

or

$$\begin{aligned} & \frac{dE_{1,C}}{d\bar{E}}\left(u''(E_{1,C}) - D''(P_1 + nE_{1,C})\,n\frac{dE_{1,C}}{d\bar{E}} - \beta(1-\delta)D''\left((P_1 + nE_{1,C})(1-\delta) + n\bar{E}\right)n(1-\delta)\right) \\ = \; & \beta(1-\delta)D''\left((P_1 + nE_{1,C})(1-\delta) + n\bar{E}\right)n \end{aligned}$$

that is

$$\frac{dE_{1,C}}{d\bar{E}} = \frac{\beta(1-\delta)D''\left((P_1 + nE_{1,C})(1-\delta) + n\bar{E}\right)n}{\left(u''(E_{1,C}) - D''(P_1 + nE_{1,C})\,n\frac{dE_{1,C}}{d\bar{E}} - \beta(1-\delta)D''\left((P_1 + nE_{1,C})(1-\delta) + n\bar{E}\right)n(1-\delta)\right)} < 0$$

Therefore a decrease in $\bar{E}$ unambiguously results in an increase of $E_{1,C}$.■

Appendix B

Lemma 2. *Suppose that an IEA in period 2 is anticipated to implement a predetermined level of emissions $\bar{E} = E_{2,NC}(P_{2,NC})$. This unambiguously results in a decrease in current emissions.*

Proof: When $\bar{E} = E_{2,NC}(P_{2,NC})$, we have

$$u'(E_{1,C}) - D'(P_1 + nE_{1,C}) - \beta(1-\delta)D'((P_1 + nE_{1,C})(1-\delta) + nE_{2,NC}(P_{2,NC})) = 0$$

with

$$(u'(E_{2,NC}(P_2)) - nD'(P_2 + nE_{2,NC}(P_2)))\,E'_{2,NC}(P_2) > 0$$

whereas in the non-cooperative scenario

$$\begin{aligned} & u'(E_{1,NC}) - D'(P_1 + nE_{1,NC}) = \\ & -\beta(1-\delta)(u'(E_{2,NC}(P_2)) - nD'(P_2 + nE_{2,NC}(P_2)))\,E'_{2,NC}(P_2) \\ & +\beta(1-\delta)D'(P_2 + nE_{2,NC}(P_2)) \\ = \; & 0 \end{aligned}$$

Let

$$h(E) = u'(E) - D'(P_1 + nE) - \beta(1-\delta)D'\left((P_1 + nE)(1-\delta) + n\bar{E}\right)$$

we have $h' < 0$ and

$$h\left(E_{1,C}\right) = 0$$

and at $\bar{E} = E_{2,NC}\left(P_{2,NC}\right)$ we have

$$h\left(E_{1,NC}\right) = -\beta\left(1-\delta\right)\left(u'\left(E_{2,NC}\left(P_2\right)\right) - nD'\left(P_2 + nE_{2,NC}\left(P_2\right)\right)\right)E'_{2,NC}\left(P_2\right) < 0$$

and therefore

$$E_{1,C} < E_{1,NC}.\blacksquare$$

Appendix C

The non-cooperative equilibrium emission $E_{1,NC}$ is solution to

$$\begin{aligned} u'\left(E_{1,NC}\right) - D'\left(P_1 + nE_{1,NC}\right) &= \beta\left(1-\delta\right)D'\left(P_{2NC} + nE_{2,NC}\left(P_{2NC}\right)\right) \\ &-\beta\left(1-\delta\right)\left(u'\left(E_{2,NC}\left(P_{2NC}\right)\right) - nD'\left(P_{2NC} + nE_{2,NC}\left(P_{2NC}\right)\right)\right)E'_{2,NC}\left(P_{2NC}\right) \end{aligned} \tag{11}$$

where $P_{2NC} = \left(P_1 + nE_{1,NC}\right)\left(1-\delta\right)$. We know that in period 2 we have

$$u'\left(E_{2,NC}\left(P_2\right)\right) - D'\left(P_2 + nE_{2,NC}\left(P_2\right)\right) = 0$$

so

$$u'\left(E_{1,NC}\right) - D'\left(P_1 + nE_{1,NC}\right) = \beta\left(1-\delta\right)D'\left(P_{2NC} + nE_{2,NC}\left(P_{2NC}\right)\right)\left(1 + \left(n-1\right)E'_{2,NC}\left(P_{2NC}\right)\right) \tag{12}$$

Under an IEA that sets a target emissions level, the equilibrium emission level in period 1, $E_{1,C}$, is solution to

$$u'\left(E_{1,C}\right) - D'\left(P_1 + nE_{1,C}\right) = \beta\left(1-\delta\right)D'\left(P_{2,C} + n\bar{E}\right) \tag{13}$$

where $P_{2C} = \left(P_1 + nE_{1,C}\right)\left(1-\delta\right)$.

First we note that that for $\beta = 0$ we have $E_{1,C} = E_{1,NC}$ and $P_{2C} = P_{2NC}$. Moreover total differentiation of (12) with respect β gives

$$\begin{aligned} & \left(u''\left(E_{1,NC}\right) - D''\left(P_1 + nE_{1,NC}\right)\right)n\frac{dE_{1,NC}}{d\beta} \\ = \; & \left(1-\delta\right)D'\left(P_{2NC} + nE_{2,NC}\left(P_{2NC}\right)\right)\left(1 + \left(n-1\right)E'_{2,NC}\left(P_{2NC}\right)\right) \\ & +\beta\left(1-\delta\right)\frac{d\left(D'\left(P_{2NC} + nE_{2,NC}\left(P_{2NC}\right)\right)\left(1 + \left(n-1\right)E'_{2,NC}\left(P_{2NC}\right)\right)\right)}{dP_2}\frac{dP_{2NC}}{dE_{1,NC}}\frac{dE_{1,NC}}{d\beta} \end{aligned}$$

which, when $\beta = 0$, simplifies into

$$\left(u''\left(E_{1,NC}\right) - D''\left(P_1 + nE_{1,NC}\right)\right)n\left.\frac{dE_{1,NC}}{d\beta}\right|_{\beta=0} = \left(1-\delta\right)D'\left(P_{2NC} + nE_{2,NC}\left(P_{2NC}\right)\right)\left(1 + \left(n-1\right)E'_{2,NC}\left(P_{2NC}\right)\right).$$

Similarly, total differentiation of (13) with respect β gives

$$\left(u''\left(E_{1,C}\right) - D''\left(P_1 + nE_{1,C}\right)\right) n\frac{dE_{1,C}}{d\beta} = (1-\delta) D'\left(P_{2C} + n\bar{E}\right) + \beta (1-\delta) \frac{dD'\left(P_{2C} + \bar{E}\right)}{dE_{1,NC}} \frac{dE_{1,C}}{d\beta}$$

which, when $\beta = 0$, yields

$$\left(u''\left(E_{1,C}\right) - D''\left(P_1 + nE_{1,C}\right)\right) n \left.\frac{dE_{1,C}}{d\beta}\right|_{\beta=0} = (1-\delta) D'\left(P_{2C} + n\bar{E}\right)$$

So

$$\begin{aligned} & \left(u''\left(E_{1,NC}\right) - D''\left(P_1 + nE_{1,NC}\right)\right) n \left(\left.\frac{dE_{1,C}}{d\beta}\right|_{\beta=0} - \left.\frac{dE_{1,NC}}{d\beta}\right|_{\beta=0}\right) \\ = \quad & (1-\delta)\left(D'\left(P_{2C} + n\bar{E}\right) - D'\left(P_{2NC} + nE_{2,NC}\left(P_{2NC}\right)\right)\left(1 + (n-1) E'_{2,NC}\left(P_{2NC}\right)\right)\right) \end{aligned}$$

or

$$\left(u''\left(E_{1,NC}\right) - D''\left(P_1 + nE_{1,NC}\right)\right) n \left(\left.\frac{dE_{1,C}}{d\beta}\right|_{\beta=0} - \left.\frac{dE_{1,NC}}{d\beta}\right|_{\beta=0}\right) = (1-\delta)\left(D'\left(P_{2C} + n\bar{E}\right) - D'\left(P_{2NC} + nE_{2,NC}\left(P_{2NC}\right)\right)\right.$$

for $\bar{E} = 0$, since $u'' - D'' < 0$, we have

$$\begin{aligned} & sign\left(\lim_{\delta \to 1^-}\left(\left.\frac{dE_{1,C}}{d\beta}\right|_{\beta=0} - \left.\frac{dE_{1,NC}}{d\beta}\right|_{\beta=0}\right)\right) \\ = \quad & -sign\left(\lim_{\delta \to 1^-}\left(\left(D'\left(P_{2C}\right) - D'\left(P_{2NC} + nE_{2,NC}\left(P_{2NC}\right)\right)\left(1 + (n-1) E'_{2,NC}\left(P_{2NC}\right)\right)\right)\right)\right) \end{aligned}$$

We know that

$$1 + nE'_{2,NC}\left(P_2\right) > 0$$

and therefore, for $E'_{2,NC}\left(P_2\right) < 0$, we have

$$1 + (n-1) E'_{2,NC}\left(P_2\right) > 0.$$

Moreover in the limit case where $\delta \to 1^-$ we have full depreciation of the stock ofpollution and therefore $P_2 \to 0$. We have

$$\begin{aligned} & \lim_{\delta \to 1^-}\left(\left(D'\left(P_{2C}\right) - D'\left(P_{2NC} + nE_{2,NC}\left(P_{2NC}\right)\right)\left(1 + (n-1) E'_{2,NC}\left(P_{2NC}\right)\right)\right)\right) \\ = \quad & \lim_{\delta \to 1^-}\left(\left(D'(0) - D'\left(nE_{2,NC}(0)\right)\left(1 + (n-1) E'_{2,NC}(0)\right)\right)\right) \end{aligned}$$

Since $E_{2,NC}(0) > 0$ and $\left(1 + (n-1) E'_{2,NC}(0)\right) > 0$, when $D'(0) = 0$ we have

$$\lim_{\delta \to 1^-}\left(\left(D'\left(P_{2C}\right) - D'\left(P_{2NC} + nE_{2,NC}\left(P_{2NC}\right)\right)\left(1 + (n-1) E'_{2,NC}\left(P_{2NC}\right)\right)\right)\right) < 0$$

and thus

$$\lim_{\delta \to 1^-}\left(\left.\frac{dE_{1,C}}{d\beta}\right|_{\beta=0} - \left.\frac{dE_{1,NC}}{d\beta}\right|_{\beta=0}\right) > 0.$$

Recall that $E_{1,C} = E_{1,NC}$ when $\beta = 0$. We can therefore conclude that, when $D'(0) = 0$, for $\bar{E} = 0$, there exists $\bar{\beta} > 0, \bar{\delta} \in (0,1)$ such that

$$E_{1,C} - E_{1,NC} > 0 \text{ for } 0 < \beta < \bar{\beta} \text{ and } 1 > \delta > \bar{\delta}. \blacksquare$$

Appendix D

Proposition 2. *A marginal proportional reduction of future emissions results in a decrease (an increase) of current emissions if and only if* $\sigma \equiv -\frac{E_{2,NC}(P_2)u''(E_{2,NC}(P_2))}{u'(E_{2,NC}(P_2))} < 1$

$$E_{1,NC}(P_1) > E_{1,C}(P_1) \text{ iff } \sigma < 1.$$

Proof:

We have

$$\begin{aligned}\frac{R'(\varepsilon)}{-\beta(1-\delta)} &= -u'((1-\varepsilon)E_{2,NC}(P_2))E'_{2,NC}(P_2) - E_{2,NC}(P_2)u''((1-\varepsilon)E_{2,NC}(P_2))(1-\varepsilon)E'_{2,NC}(P_2) \\ &\quad -\left(-nE'_{2,NC}(P_2)\right)D'(P_2 + n(1-\varepsilon)E_{2,NC}(P_2)) \\ &\quad -\left(\left(1 + n(1-\varepsilon)E'_{2,NC}(P_2)\right)\right)(-nE_{2,NC}(P_2))D''(P_2 + n(1-\varepsilon)E_{2,NC}(P_2))\end{aligned}$$

The impact of a marginal change in ε in the neighborhood of $\varepsilon = 0$ is given by

$$\begin{aligned}\frac{R'(0)}{\beta(1-\delta)} &= (u'(E_{2,NC}(P_2)) - nD'(P_2 + nE_{2,NC}(P_2)))E'_{2,NC}(P_2) \\ &\quad + E_{2,NC}(P_2)u''(E_{2,NC}(P_2))E'_{2,NC}(P_2) \\ &\quad - n\left(1 + nE'_{2,NC}(P_2)\right)E_{2,NC}(P_2)D''(P_2 + nE_{2,NC}(P_2))\end{aligned}$$

Using expression (2) gives

$$\begin{aligned}\frac{R'(0)}{\beta(1-\delta)} &= (u'(E_{2,NC}(P_2)) - nD'(P_2 + nE_{2,NC}(P_2)))E'_{2,NC}(P_2) \\ &\quad + E_{2,NC}(P_2)\left(u''(E_{2,NC}(P_2))E'_{2,NC}(P_2) - nu''(E_{2,NC}(P_2))E'_{2,NC}(P_2)\right)\end{aligned}$$

or

$$\begin{aligned}\frac{R'(0)}{\beta(1-\delta)} &= (u'(E_{2,NC}(P_2)) - nD'(P_2 + nE_{2,NC}(P_2)))E'_{2,NC}(P_2) \\ &\quad + E_{2,NC}(P_2)(1-n)u''(E_{2,NC}(P_2))E'_{2,NC}(P_2)\end{aligned}$$

that is

$$\frac{R'(0)}{\beta(1-\delta)E'_{2,NC}(P_2)} = \underbrace{u'(E_{2,NC}(P_2)) - nD'(P_2 + nE_{2,NC}(P_2))}_{<0} + \underbrace{E_{2,NC}(P_2)(1-n)u''(E_{2,NC}(P_2))}_{>0} \tag{14}$$

Note that $u'(E_{2,NC}(P_2)) - nD'(P_2 + nE_{2,NC}(P_2)) < 0$ from $E_{2,NC}(P_2)$ larger than first-best emissions which solve $u'(E) - nD'(P_2 + nE) = 0$.

The sign of $R'(0)$ is therefore undetermined.

The condition (14) may be rewritten as

$$\frac{R'(0)}{\beta(1-\delta)} = -(n-1)E'_{2,NC}(P_2)\,u'(E_{2,NC}(P_2))(1-\sigma)$$

where

$$\sigma \equiv -\frac{E_{2,NC}(P_2)\,u''(E_{2,NC}(P_2))}{u'(E_{2,NC}(P_2))}$$

The sign of $R'(0)$ depends on the elasticity of marginal utility. It is positive iff $\sigma < 1$.■

Appendix E

Lemma 4. *There exists a unique $\bar{\gamma} > 0$ such that $\Omega < 0$ for $\gamma > \bar{\gamma}$ and $\Omega > 0$ for $0 < \gamma < \bar{\gamma}$.*

Proof: We first establish existence of $\bar{\gamma}$ such that $\Omega = 0$. This follows from the fact that $\Omega(\gamma = 0) = 1 > 0$, $\lim_{\gamma -> \infty} \Omega = -\infty$ and that Ω is continuous.

We now establish uniqueness of $\bar{\gamma}$. The function Ω can have at most three roots. From $\Omega(\gamma = 0) = 1 > 0$ we can infer that Ω cannot have two positive roots only. Suppose Ω has three positive roots then one of the following two statements must hold Ω is strictly decreasing strictly convex in the neighborhood of $\gamma = 0$

$$\frac{d\Omega}{d\gamma} = \left(-1 + \beta(1-\delta)^2 + 2\delta\right)n - 3n^3\gamma^2 + 2n\gamma\left(\beta(1-\delta)^2 + n(2\delta - 3)\right)$$

$$\frac{d^2\Omega}{d\gamma^2} = -6n^3\gamma + 2n\left(\beta(1-\delta)^2 + n(2\delta - 3)\right)$$

At $\gamma = 0$, $\left.\frac{d\Omega}{d\gamma}\right|_{\gamma=0} = \left(\beta(1-\delta)^2 + 2\delta - 1\right)n < 0$

$$\left.\frac{d^2\Omega}{d\gamma^2}\right|_{\gamma=0} = 2n\left(\beta(1-\delta)^2 + n(2\delta - 3)\right) > 0$$

$$\left.\frac{d^2\Omega}{d\gamma^2}\right|_{\gamma=0} = 2n\left(\frac{1}{n}\left.\frac{d\Omega}{d\gamma}\right|_{\gamma=0} + (n-1)2\delta - 3n + 1\right)$$

The term $(n-1)2\delta - 3n + 1$ is a strictly increasing function of δ for $n > 1$ therefore, since $\delta \in [0,1]$ is no larger than $(n-1)2 - 3n + 1 = -n - 1 < 0$. Therefore if $\left.\frac{d\Omega}{d\gamma}\right|_{\gamma=0} \leq 0$ we must have $\left.\frac{d^2\Omega}{d\gamma^2}\right|_{\gamma=0} < 0$, i.e. Ω is strictly concave in the neighborhood of $\gamma = 0$. This rules out the existence of three positive roots of Ω. This completes the proof.■

Appendix F

Proposition 5. *The adoption of a marginally more environmental friendly emission policy $E_{2,C}(P) = E_{2,NC}(P) - \eta$ by all the players results in an increase of current emissions.*

Proof:

We have

$$\frac{Q'(\eta)}{-\beta(1-\delta)} = -u''(E_{2,NC}(P)-\eta)\,E'_{2,NC}(P) + n\left(1+nE'_{2,NC}(P)\right)D''(P+nE_{2,NC}(P)-n\eta)$$

and thus

$$\frac{Q'(0)}{-\beta(1-\delta)} = -u''(E_{2,NC}(P))\,E'_{2,NC}(P) + n\left(1+nE'_{2,NC}(P)\right)D''(P+nE_{2,NC}(P))$$

From (2)

$$u''(E_{2,NC})\,E'_{2,NC} - \left(1+nE'_{2,NC}\right)D''(P_2+nE_{2,NC}) = 0 \tag{15}$$

so

$$\frac{Q'(0)}{-\beta(1-\delta)} = (n-1)\,u''(E_{2,NC}(P))\,E'_{2,NC}(P) > 0$$

or

$$Q'(0) < 0$$

and therefore in the neighborhood of $\eta = 0$ we have

$$Q(\eta) < Q(0) \text{ for } \eta > 0$$

and thus

$$E_{1,C}(P_1) > E_{1,NC}(P_1) \text{ for all } P_1.\blacksquare$$

Appendix G

Proposition 6. *If an IEA in period 2 that implements the first-best emissions strategies results in a decrease of current emissions then we must have*

$$\frac{u'(E_{2,Coop}(P_{2,Coop}))}{u'(E_{2,NC}(P_{2,NC}))} - n\left(1+(n-1)\,E'_{2,NC}(P_{2,NC})\right) > 0.$$

Proof: Using equation (4) we have

$$u'(E_{1,C}(P_1)) - D'(P_1+nE_{1,C}(P_1)) - \beta(1-\delta)\frac{u'(E_{2,Coop}(P_2))}{n} = 0$$

Recall that for the non-cooperative equilibrium we have

$$u'(E_{1,NC}(P_1)) - D'(P_1+nE_{1,NC}(P_1)) - \beta(1-\delta)\left(1+(n-1)\,E'_{2,NC}\right)u'(E_{2,NC}(P_2)) = 0$$

If $E_{1,NC}(P_1) > E_{1,C}(P_1)$ then, since $u''-D''<0$,

$$u'(E_{1,NC}(P_1)) - D'(P_1+nE_{1,NC}(P_1)) < u'(E_{1,C}(P_1)) - D'(P_1+nE_{1,C}(P_1))$$

that is

$$\beta(1-\delta)\left(1+(n-1)\,E'_{2,NC}\right)u'(E_{2,NC}(P_2)) < \beta(1-\delta)\frac{u'(E_{2,Coop}(P_2))}{n}$$

or

$$\frac{u'\left(E_{2,Coop}\left(P_{2,Coop}\right)\right)}{u'\left(E_{2,NC}\left(P_{2,NC}\right)\right)} - n\left(1+(n-1)\,E'_{2,NC}\left(P_{2,NC}\right)\right) > 0. \tag{16}$$

where

$$P_{2,NC} = P_1 + nE_{1,NC}\left(P_1\right)$$

and

$$P_{2,Coop} = P_1 + nE_{1,C}\left(P_1\right)$$

The above condition (16) is a necessary condition for $E_{1,NC}\left(P_1\right) > E_{1,C}\left(P_1\right)$.■

Appendix H

We show in this appendix that, for $P \geq 0$, condition (6) is never satisfied, i.e., $G\left(P,n\right) < 0$. Without loss of generality we set $\gamma = 1$. We have

$$G\left(P,n\right) = \frac{-P+\sqrt{4n+P^2}}{-P+\sqrt{4+P^2}} - \frac{n+1+\frac{(n-1)P}{\sqrt{4n+P^2}}}{2} \tag{17}$$

we rewrite

$$\frac{-P+\sqrt{4n+P^2}}{-P+\sqrt{4+P^2}} = 1 + \frac{-\sqrt{4+P^2}+\sqrt{4n+P^2}}{-P+\sqrt{4+P^2}}$$

or

$$\frac{-P+\sqrt{4n+P^2}}{-P+\sqrt{4+P^2}} = 1 + \frac{4n-4}{\left(-P+\sqrt{4+P^2}\right)\left(\sqrt{4+P^2}+\sqrt{4n+P^2}\right)}$$

We can therefore write that

$$\begin{aligned} & \left(-P+\sqrt{4+P^2}\right)\left(\sqrt{4+P^2}+\sqrt{4n+P^2}\right) \\ = \;& 4+P^2-P\sqrt{4+P^2}+\sqrt{4+P^2}\sqrt{4n+P^2} > 4+2\sqrt{4n+P^2} \end{aligned}$$

because we have $P^2 - P\sqrt{4+P^2} < 0$ and $\sqrt{4+P^2} > 2$.

We thus have

$$\frac{-P+\sqrt{4n+P^2}}{-P+\sqrt{4+P^2}} < 1 + \frac{4n-4}{4+2\sqrt{4n+P^2}}$$

which implies that

$$G\left(P,n\right) < 1 + \frac{4n-4}{4+2\sqrt{4n+P^2}} - \frac{n+1+\frac{(n-1)P}{\sqrt{4n+P^2}}}{2} \tag{18}$$

or

$$G\left(P,n\right) < 1 - \frac{n+1}{2} + \frac{4n-4}{4+2\sqrt{4n+P^2}} - \frac{(n-1)\,P}{2\sqrt{4n+P^2}} \tag{19}$$

We can rewrite this inequality as

$$G\left(P,n\right) < (n-1)\left(-\frac{1}{2} - \frac{P}{2\sqrt{4n+P^2}} + \frac{4}{4+2\sqrt{4n+P^2}}\right) \tag{20}$$

or

$$G\left(P,n\right) < -\frac{(n-1)}{2\sqrt{P^2+4n}\left(P^2+4n-4\right)}\left(\left(P^2+4+4n\right)\sqrt{P^2+4n} - 16n - 4P + 4Pn - 4P^2 + P^3\right). \tag{21}$$

where $A \equiv \left(P^2+4+4n\right)\sqrt{P^2+4n}-16n-4P+4Pn-4P^2+P^3$.

We now show that the expression A is positive. Indeed, we have

$$A > \bar{A} \equiv -\left(P^2+4+4n\right)\sqrt{P^2+4n}-16n-4P+4Pn-4P^2+P^3$$

moreover the product $A\bar{A}$ gives

$$A\bar{A} = -8P^5-4P^4n-64P^3n+32P^3-32P^2n^2+32P^2n-128Pn^2+128Pn-64n^3+128n^2-64n$$

or

$$A\bar{A} = -8P^5-4P^4n-32P^3\left(2n-1\right)-32P^2n\left(n-1\right)-128Pn\left(n-1\right)-64n\left(n-1\right)^2 < 0$$

Since $A\bar{A} < 0$ and $A > \bar{A}$ this implies that $A > 0$ and therefore from equation (21), we have that $G\left(P,n\right) < 0$.■