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Benchekroun, H.; Ray Chaudhuri, A.

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Discussion paper

**CLEANER TECHNOLOGIES AND THE STABILITY OF
INTERNATIONAL ENVIRONMENTAL AGREEMENTS**

BY

**HASSAN BENCHEKROUN,
AMRITA RAY CHAUDHURI**

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Cleaner technologies and the stability of international environmental agreements

Hassan Benchekroun^a and Amrita Ray Chaudhuri^b

Abstract:

This paper shows that, if countries are farsighted when deciding whether to defect from a coalition, then the implementation of cleaner technologies may jeopardize the chances of reaching an international environmental agreement. The grand coalition may be destabilized by the implementation of cleaner technologies, ultimately resulting in higher global emissions and lower global welfare. We further show that the higher the stock of pollution at the instant when the cleaner technology is implemented, the more likely that the above mechanism unfolds. We examine a reduction in the emission per output ratio as well as measures that enhance the natural rate of decay of stock pollutants.

JEL classifications: Q20, Q54, Q55, Q58, C73.

Keywords: transboundary pollution, renewable resource, clean technologies, coalition formation, differential games.

^aDepartment of Economics, McGill University, and CIREQ, Canada; E-mail: hassan.benchekroun@mcgill.ca

^bDepartment of Economics, University of Winnipeg, Canada, and Center, TILEC, Tilburg University, The Netherlands, E-mail: a.raychaudhuri@uwinnipeg.ca

1 Introduction

This paper examines the stability of international agreements on emission reductions of a transboundary pollutant when the countries involved implement "cleaner" technologies that reduce emission-output ratios. We also show that measures to increase the natural rate of absorption of stock pollutants have qualitatively similar effects on the stability of international agreements on emission reductions.

This topic gains importance in light of the large expenditures that have been made in recent years for creating cleaner technologies. In February, 2002, the US announced a policy for climate change that would rely on domestic, voluntary actions to reduce the "greenhouse gas intensity" (ratio of emissions to economic output) of the U.S. economy by 18% over the next 10 years. Since then other major polluters such as China and India have also committed to emission per output targets and investment in clean technologies worldwide has consistently risen. In 2007 alone, new investment in clean energy rose by 60% above the 2006 level globally (UNEP Report, 2008).¹

We focus on those cases of transboundary pollution that affect a small number

¹The G8 summit held in July 2009 included a commitment by the members to double public investment in the research and development of climate-friendly technologies by 2015. The agreement at the COP16 meeting held in Cancun in December 2010 includes a "Green Climate Fund," proposed to be worth \$100 billion a year by 2020, to assist poorer countries in mitigating emissions, partially by financing investments in clean technologies (UNFCCC Press Release, 11 December 2010).

Countries that have channelled their government spending to this end include the US (e.g. the introduction of the Investing to Modernize the Production of American Clean Energy and Technology (IMPACT) Act of 2012 to provide incentives for clean energy and to repeal fossil fuel subsidies for big oil companies). The EU has also, in 2009, declared that €105 billion will be invested in the "green economy" through the EU Cohesion Policy (more than 30% of the regional policy budget for 2007-2013). Over the last five years, China has also increased its renewable energy generation to 8.8% of total primary energy consumption, making it one of the world's leading producers.

of countries or blocks of countries. This is an important scenario to consider since certain types of transboundary pollutants, in reality, damage a few neighbouring countries/regions. For example, consider the pollution of lakes that are surrounded by a few countries each with their independent emission strategies (see, for example, Bayramoglu (2006) which studies the pollution of the Black Sea which affects Romania and Ukraine), or consider the pollution of the Great Lakes by Canada and the US which eventually led to the Great Lakes Water Quality Act and Clean Water Act in the 1970s).² Another scenario where this setting gains relevance lies within the context of climate change. In recent international negotiations over climate change (for example, at the UNFCCC COP Meetings at Copenhagen, 2009, and Cancun, 2010), only a small number of large countries or blocks of countries (e.g. US, China, and EU) dominated discussions and played a decisive role in determining the outcomes.

When the negotiations over emissions of transboundary pollutants involve a small number of countries, each country internalizes the effect of its own decisions on the outcome in terms of the stability of the coalition in question and in terms of emission and welfare levels. In order to model the behaviour of countries within such a context in line with reality, we must allow each country to behave strategically in relation to others when deciding whether to participate in or defect from coalitions and when deciding how much to emit. For this reason, we use a game theoretic approach to modeling transboundary pollution where all countries first decide whether to be a signatory to an IEA and then simultaneously choose their individual emission strate-

²Note that in this paper, for simplicity, we abstract away from the extreme case where the eutrophication of the lake causes irreversible damage, referred to in the literature as the "shallow lake" problem.

gies. Moreover, the fact that we focus on a small number of countries/regions affects our choice of stability criteria for the possible coalitions that may arise amongst them, as follows.

Much of the IEA literature uses the internal and external stability criteria as described by d'Aspremont et al (1983) and applied to the context of IEAs by Barrett (1994), Carraro and Siniscalco (1993), Diamantoudi and Sartzetakis (2006), Hoel and Schneider (1997) and others. These criteria rely on the restrictive assumption that if one country defects from a given coalition, the rest of the members of the coalition continue to participate in the IEA. The general conclusion of much of the IEA literature is that only small coalitions (of size 2 or 3) can be stable (see for example, Barrett, 1994 and 2003; Diamantoudi and Sartzetakis, 2006; Finus, 2003). However if only small coalitions form, the assumption that a player does not take into account the impact of its decision to leave a coalition on the decision of the other coalition members to remain in the coalition is more difficult to justify. Therefore, we use an alternative set of stability criteria referred to in the literature as "farsightedness" under which when a country contemplates leaving an IEA, it takes into account the repercussions on other countries' adherence to the IEA.³ See Diamantoudi and Sartzetakis (2002) and Eyckmans (2003) for the application of the farsightedness concept in IEAs in a static framework and de Zeeuw (2008) in a dynamic framework.⁴ When

³Farsightedness is a stability concept that lies in the middle of two extremes that have been used in the previous literature on IEAs. On the one hand, internal and external stability assumes that when one country defects, the rest of the coalition remains intact. On the other extreme, the gamma-core stability concept of cooperative game theory assumes that when one country defects, the rest of the coalition completely disintegrates. See Ray and Vohra (2001) and Chwe (1994) for a detailed discussion of farsightedness in coalition formation games.

⁴De Zeeuw (2008) takes into account the dynamics of emissions adjustments and shows that large and small coalitions occur only if the cost of emissions is relatively small compared to the cost

a small group of large players are involved, it seems that countries are indeed farsighted when making their decisions. For example, when the US refused to ratify the Kyoto protocol, its stated reason was that other countries (especially the large developing countries like China and India) would not behave cooperatively if the US committed to reducing its emissions. Effectively, the US chose not to join the IEA because it anticipated other countries to defect if it joined, which is an application of the concept of farsightedness.⁵

We show that if countries use the farsighted criterion for deciding whether to defect from a coalition, the grand coalition, which is farsighted stable in the presence of a sufficiently dirty technology, may be destabilized by the implementation of a cleaner technology that reduces the emissions per output ratio, ultimately resulting in higher global emissions and lower global welfare.

We first derive this result within a static model, and then generalize it to a dynamic model which allows the pollutant to accumulate over time. This is an important step in the analysis since several transboundary pollutants are also accumulative such as greenhouse gases in the atmosphere and phosphorus in lakes. The dynamic framework allows us to examine the impact of a change in the natural rate of decay of the stock pollutants on the stability of an IEA. Also, it is an interesting extension from a theoretical perspective since Benckroun and Ray Chaudhuri (2011) and van der Ploeg and de Zeeuw (1992) show that countries' free riding in-

of abatement.

⁵The United States signed the Protocol on November 12, 1998. However, the Clinton Administration did not submit the Protocol to the Senate, since one of the conditions passed in mid-1997, meaningful participation by developing countries in binding commitments limiting greenhouse gases, had not been met. (see the Encyclopedea of Earth for further details: http://www.eoearth.org/article/Kyoto_Protocol_and_the_United_States)

centives are exacerbated when their emission decisions are functions of the stock of pollution. Benchekroun and Ray Chaudhuri (2011), using a similar setting to this paper, show that in the dynamic case it is more likely that countries may respond to a cleaner technology by increasing their equilibrium emissions to an extent such that the stock of pollution increases and welfare decreases. A priori, it is unclear whether the free-riding incentives of countries regarding IEAs as derived in the static case carry over to the dynamic case.

For the dynamic setting, we use the seminal transboundary pollution game model in Dockner and Long (1993) and van der Ploeg and de Zeeuw (1992). In contrast with van der Ploeg and de Zeeuw (1992) and Jorgensen and Zaccour (2001), we have taken the ratio of emissions to output as exogenously given. Van der Ploeg and de Zeeuw (1992) (section 8) and Jorgensen and Zaccour (2001) consider the case where the ratio of emissions to output is endogenous and is a decreasing function of the level of the stock of clean technology. While van der Ploeg and de Zeeuw (1992) assume that the stock of clean technology is public knowledge, Jorgensen and Zaccour (2001) consider the case where the stock of clean technology, also referred to as the stock of abatement capital, is country specific. Each country can invest in the abatement capital in addition to its control of emissions.⁶

Rubio and Casino (2005) study the stability of IEAs using a differential game setting similar to ours. They use the internal and external stability criteria and

⁶Van der Ploeg and de Zeeuw (1992) compare the outcome under international policy coordination and the open loop equilibrium when there is no coordination. They show that the level of production and the stock of clean technology are both higher under the non-cooperative equilibrium.

Jorgensen and Zaccour (2001) consider an asymmetric game where there exist two regions facing a pure downstream problem. They design a transfer scheme that induces the cooperative levels of abatement and satisfies overall individual rationality for both regions.

show that the two country coalition is the unique stable coalition. Rubio and Ulph (2007) also study IEAs in the presence of stock pollutants. They allow countries to decide each period whether they wish to participate in the IEA and investigate whether a large coalition can be stable in the steady state. Breton, Sbragia and Zaccour (2010) also model IEAs in a dynamic setting. They consider the formation of an IEA in an international pollution game where signatory countries are assumed to be able to punish the non-signatories at a cost. They propose an evolutionary process through which countries may gradually reach a stable agreement. They adopt a replicator dynamics, under which evolutionary pressures are put in favor of the group (signatories versus non-signatories) obtaining the highest payoff. None of these papers analyze the impact of technology changes and the role of the stock of pollution on the stability of IEAs.

We start our analysis within a standard static model of a transboundary pollution game and then show that our main results carry over to the dynamic context. We further use the dynamic framework to show that the higher the stock of pollution, the more likely that the implementation of clean technologies destabilizes the grand coalition, thus reducing (and possibly reversing) the benefits of implementing cleaner technologies. Also, within the dynamic context, there arises an alternate type of measure that countries may engage in to counter pollution: one that increases the rate of natural absorption of the stock of pollution such as reforestation. This type of measure is shown to have a similar impact on the stability of IEAs as reducing the emission per output ratio.

Section 2 presents the basic model. Section 3 presents the analysis for the static

scenario where pollution damage depends on the current emission levels. Section 4 presents the analysis for the dynamic scenario where the pollution damage depends on the stock of pollution. Section 5 presents the concluding remarks.

2 The Model

Consider n countries indexed by $i = 1, \dots, n$. Each country produces a single consumption good, ϕ_i . Production generates pollution emissions. Let ε_i denote country i 's emissions of pollution. We have:

$$\varepsilon_i = \theta \phi_i \tag{1}$$

where θ is an exogenous parameter that represents each country's ratio of emissions to output. The implementation of a cleaner technology is represented by a fall in θ .

The instantaneous net benefits of country $i = 1, \dots, n$ are given by

$$b_i(\phi_i) = U_i(\phi_i) - D_i(\cdot) \tag{2}$$

where $D_i(\cdot)$ represents the pollution damage that is a by-product of the production process, and

$$U_i(\phi_i) = A\phi_i - \frac{B}{2}\phi_i^2, \quad A > 0$$

We consider two scenarios. In the first, the pollution damage faced by each country, $D_i(\cdot)$, is a function of total emissions of all the countries. This is the static version of the model, as presented in the following section. We then analyze the

scenario where emissions are allowed to accumulate into a stock of pollution over time and the pollution damage faced by each country, $D_i(\cdot)$, is a function of this pollution stock. This is the dynamic version of the model, as presented in Section 4.

3 The Static Model

The pollution damage faced by country i is given by:

$$D_i(\sum_{i=1}^n \varepsilon_i) = \frac{s}{2} (\sum_{i=1}^n \varepsilon_i)^2, \quad s > 0. \quad (3)$$

We begin by studying the equilibria under non-cooperation and full cooperation.

We then analyze coalition formation in the following subsection.

The non-cooperative equilibrium

The objective of country i 's government is to choose a production strategy, q_i (or equivalently a pollution control strategy), that maximizes $b_i(q_i)$. That is,

$$\max_{q_i} Aq_i - \frac{B}{2}q_i^2 - \frac{s}{2} (\sum_{i=1}^n \theta q_i)^2 \quad (4)$$

The best response function of country i is given by:

$$q_i^{nc} = \frac{A - s\theta (\sum_{j \neq i}^n \theta q_j)}{(B + s\theta^2)}$$

By symmetry, we have

$$q_i^{nc} = \frac{A}{B + ns\theta^2}, \quad i \in \{1, \dots, n\}$$

Full Cooperation

The objective of country i 's government is to choose a production strategy, q_i (or equivalently a pollution control strategy), that maximizes the joint net benefits from consumption across all countries:

$$\max_{q_i} \sum_{i=1}^n b_i(q_i) = \max_{q_i} \sum_{i=1}^n \left(Aq_i - \frac{B}{2}q_i^2 \right) - n\frac{s}{2} (\sum_{i=1}^n \theta q_i)^2$$

The output of each country is given by:

$$q_i^c = \frac{A}{B + n^2s\theta^2}$$

3.1 Coalition Formation

Consider the scenario where the countries decide to form an international environmental agreement. More specifically, let $M \subset N$ countries sign an agreement while $N \setminus M$ do not. We denote the size of coalition M by m and the total output produced by the coalition by $Q_m = mq_m$, where q_m is the output of a representative signatory. Similarly, $Q_{nm} = (n - m)q_{nm}$ is the total output produced by the complement of the coalition with q_{nm} being the output produced by a representative non-signatory. The sum of the output of the signatory and non-signatory countries, that is global

output, is given by $Q = Q_m + Q_{nm}$.

We assume that the nonsignatories behave noncooperatively and the signatories maximize the joint welfare of the members of the coalition. The coalition and the nonsignatories are assumed to choose their emission strategies simultaneously.

The nonsignatories' maximization problem is given by:

$$\max_{q_i} Aq_i - \frac{B}{2}q_i^2 - \frac{s}{2}\theta^2 (\Sigma_i^{n-m}q_i + \Sigma_j^mq_j)^2, \quad i \in N \setminus M, \quad j \in M \quad (5)$$

The signatories' maximization problem is given by:

$$\max_{q_j} \Sigma_j^m \left(Aq_j - \frac{B}{2}q_j^2 \right) - m\frac{s}{2}\theta^2 (\Sigma_i^{n-m}q_i + \Sigma_j^mq_j)^2, \quad i \in N \setminus M, \quad j \in M$$

This results in the following best response function of the nonsignatories:

$$A - Bq_i - s\theta^2 (\Sigma_i^{n-m}q_i + \Sigma_j^mq_j) = 0$$

By symmetry, we have

$$A - Bq_{nm} - s\theta^2 ((n - m)q_{nm} + mq_m) = 0 \quad (6)$$

The best response function of the signatories is given by:

$$A - Bq_j - ms\theta^2 (\Sigma_i^{n-m}q_i + \Sigma_j^mq_j) = 0$$

By symmetry, we have:

$$A - Bq_m - ms\theta^2 ((n - m)q_{nm} + mq_m) = 0 \quad (7)$$

Solving (6) and (7) simultaneously, we get

$$\begin{aligned} q_m^* &= \frac{A(B + s\theta^2(1 - m)(n - m))}{B(B + s\theta^2(-m + n + m^2))} \\ q_{nm}^* &= \frac{A(B + s\theta^2m(m - 1))}{B(B + s\theta^2(-m + n + m^2))} \end{aligned}$$

We note that $q_m^* > 0$ iff

$$\theta < \bar{\theta} \equiv \sqrt{\frac{B}{s(m - 1)(n - m)}}$$

We also note that if $m = 0$, we have $q_{nm}^* = q_i^{nc}$, and if $m = n$, we have $q_m^* = q_i^c$. Let the total output be given by $Q^* \equiv mq_m^* + (n - m)q_{nm}^*$.

The welfare of each signatory country, at the equilibrium, is given by:

$$w_m^* \equiv Aq_m^* - \frac{B}{2}(q_m^*)^2 - \frac{s}{2}\theta^2(Q^*)^2 \quad (8)$$

The welfare of each non-signatory country, at the equilibrium, is given by:

$$w_{nm}^* \equiv Aq_{nm}^* - \frac{B}{2}(q_{nm}^*)^2 - \frac{s}{2}\theta^2(Q^*)^2 \quad (9)$$

Global welfare under a coalition of size m , given a total of n countries is denoted by

$W_{m,n}^*$.

$$W_{m,n}^* = mw_m^* + (n - m)w_{nm}^*$$

Much of the IEA literature uses the internal and external stability criteria as described by d'Aspremont et al (1983) which assumes that if one country defects from a given coalition, the rest of the members of the coalition continue to participate in the IEA. Under such stability criteria the general conclusion of much of the IEA literature is that only small coalitions (of size 2 or 3) can be stable (see for example, Barrett, 1994 and 2003; Diamantoudi and Sartzetakis, 2006). Moreover, small coalitions achieve sizable gains in welfare compared to non-cooperation only when the number of players is small. However for small coalitions and number of players, the assumption that a player does not take into account the impact of its decision to leave a coalition on the decision of the other coalition members to remain in the coalition is more difficult to justify. Therefore, we use an alternative set of stability criteria referred to in the literature as "farsightedness" under which when a country considers leaving an IEA, it takes into account the implications on other countries' adherence to the IEA. We analyze the stability of coalitions using the farsighted stability concept as used by Eyckmans (2003), Diamantoudi and Sartzetakis (2006), Osmani and Tol (2009) and de Zeeuw (2008) in the context of environmental agreements. In this paper, we shall focus on the case of a small number of players because we believe that it is in those situations where the assumption of farsightedness seems most realistic. Henceforth, for simplicity, we focus on the case where $n = 3$, and analyze how the stability of the grand coalition (made of three players) is affected by technology changes. The paper highlights certain possible results and therefore,

we consider the simplest case where the possible outcomes of interest arise.

We proceed in two steps: first, we analyze the stability of the two country sub-coalition and then we proceed to analyze the stability of the grand coalition. For the purpose of our analysis, it is useful to define the stability function, which is represented by the following:

$$\Phi_i(m) = w_m^*(m) - w_{nm}^*(m-1). \quad (10)$$

Two country coalition

When $\Phi_i(2) \geq 0$ neither coalition member has an incentive to leave the coalition (assuming the third country does not join the coalition). Moreover, when $\Phi_i(3) < 0$, the third country does not have an incentive to join the coalition (assuming the other two coalition members remain in the coalition).

Remark: Note that for the case of 3 countries, the farsighted stability criterion is closely related to the internal and external stability criteria as presented by d'Aspremont et al (1983). The grand coalition of size 3 is farsighted stable if and only if a coalition of size 2 is internally unstable.

Proposition 1: *There exists $\bar{\theta}_{ms} \equiv \sqrt{\left(\frac{2}{11}\sqrt{3} + \frac{1}{11}\right) \frac{B}{s}} \simeq 0.637 \sqrt{\frac{B}{s}}$ such that the coalition of size two is farsighted stable if $\theta \leq \bar{\theta}_{ms}$.*

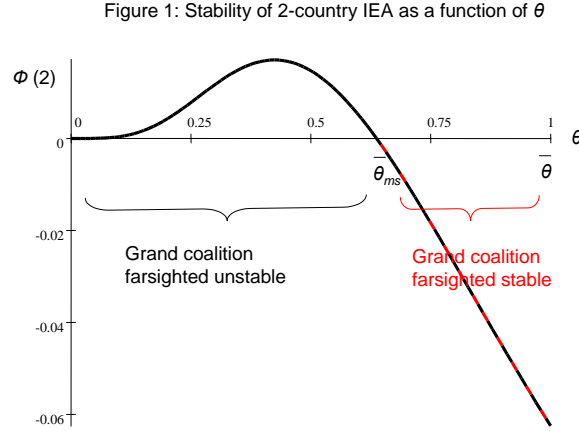
Proposition 1 follows from the fact that $\Phi(3) = -72 \frac{A^2}{B} s^3 \frac{\theta^6}{(5s\theta^2+B)^2(9s\theta^2+B)} < 0$. Also, it can be shown that

$$\Phi(2) = -\frac{9}{2} \frac{A^2}{B} s^2 \frac{\theta^4 (11s\theta^2 + B (2\sqrt{3} - 1))}{(3s\theta^2 + B)^2 (5s\theta^2 + B)^2} \left(s\theta^2 - \frac{(1 + 2\sqrt{3})}{11} B \right)$$

and, therefore, $\Phi(2) \geq 0$ iff $s\theta^2 \leq \left(\frac{2}{11}\sqrt{3} + \frac{1}{11}\right) B \simeq 0.405B$.

Proposition 1 implies that we have internal stability for $s\theta^2 < \left(\frac{2}{11}\sqrt{3} + \frac{1}{11}\right) B$, that is, for values of θ that are sufficiently low. Thus, implementing a cleaner technology may stabilize the IEA of size 2.

Figure 1 shows $\Phi(2)$ as a function of θ for $A = B = s = 1$.



In this simple model the coalition structure is dependent on the level of the technology parameter θ and we have that for $\theta \leq \bar{\theta}_{ms} \equiv \sqrt{\left(\frac{2}{11}\sqrt{3} + \frac{1}{11}\right) \frac{B}{s}}$ the coalition of size 2 is stable.

We have $\frac{\partial q_m^*}{\partial \theta} = \frac{-2\theta snmA}{(B - ms\theta^2 + ns\theta^2 + m^2s\theta^2)^2} < 0$ and $\frac{\partial q_{nm}^*}{\partial \theta} = \frac{-2\theta snA}{(B - ms\theta^2 + ns\theta^2 + m^2s\theta^2)^2} < 0$. That is, as θ decreases, q_m^* and q_{nm}^* both increase. This is because the implementation of the cleaner technology reduces the damage from production at the margin, giving each country an incentive to increase its output. The rate of increase in emissions of each signatory country in response to cleaner technology is higher than that of the non-signatory. Thus, as the cleaner technologies are implemented, it becomes less costly to stay inside the coalition of size two in terms of sacrificed production.

Grand coalition

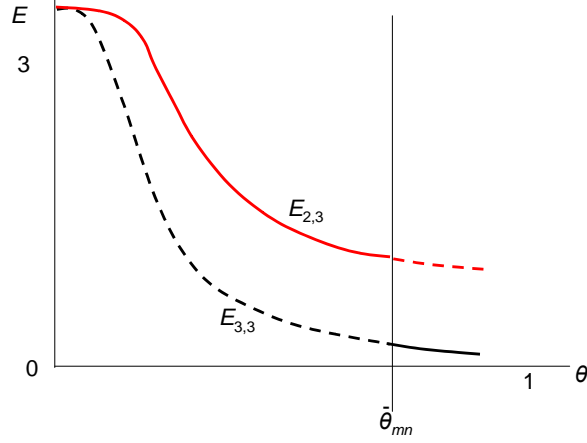
In the case of 3 countries, when say country 1 contemplates leaving the grand coalition, it compares its payoff under the grand coalition to its payoff if countries 2 and 3 form a coalition or to its payoff when countries 2 and 3 break up as well, depending on country 2 and 3's incentives to continue forming a coalition. Since the decision of country 2 and 3 to form a coalition depends on the level of technology, as per Proposition 1, we have the following.

Proposition 2: *The grand coalition is farsighted stable for $\theta > \bar{\theta}_{ms}$.*

When θ is above $\bar{\theta}_{ms}$, if say country 1 contemplates leaving the grand coalition it will compare its payoff under the grand coalition to the payoff under the non-cooperative outcome since for $\theta > \bar{\theta}_{ms}$ the coalition that contains country 2 and 3 only is (internally) unstable. Therefore, for θ above $\bar{\theta}_{ms}$, country 1 will opt to remain in the grand coalition. The same reasoning applies to countries 2 and 3. When θ is below $\bar{\theta}_{ms}$, if say country 1 contemplates leaving the grand coalition it will compare its payoff under the grand coalition to the payoff under the outcome where countries 2 and 3 continue to form a coalition since for $\theta < \bar{\theta}_{ms}$ the coalition that contains countries 2 and 3 is stable.

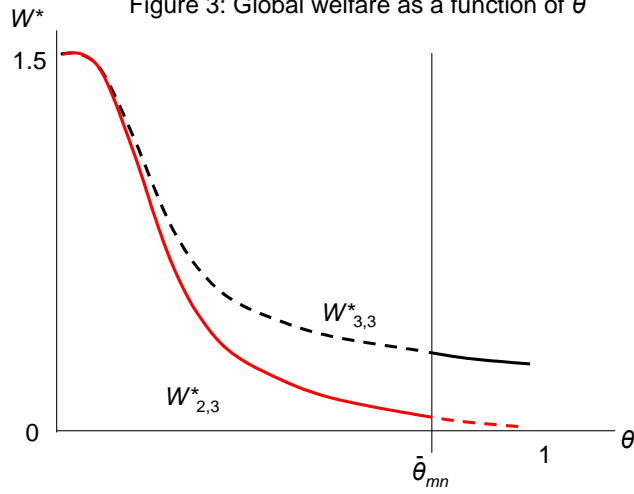
In this case, the equilibrium level of total emissions under a (farsighted) stable coalition will exhibit a discontinuity with a downward jump at $\theta = \bar{\theta}_{ms}$. See Figure 2.

Figure 2: Global emissions as a function of θ



We have an upward discontinuity of the level of welfare under a (farsighted) stable coalition, at $\theta = \bar{\theta}_{ms}$. See Figure 3.

Figure 3: Global welfare as a function of θ



An important implication of this analysis is that, under the farsighted stable coalition criterion, a decrease in the emissions per output ratio from $\theta' > \bar{\theta}_{ms}$ to $\theta'' < \bar{\theta}_{ms}$ can have a negative impact on world welfare since it breaks down the sustainability of the grand coalition (which is stable under θ' and unstable under

θ''). In Figure 3, for example, the global welfare drops by more than 45% by going from the grand coalition to the coalition with two members.

4 The Dynamic Model

In this section, we extend our analysis to the dynamic case where the emissions are allowed to accumulate into a stock over time and pollution damage is a function of this stock.

Emissions of pollution accumulate into a stock, $P(t)$, according to the following transition equation:

$$\dot{P}(t) = \sum_{i=1}^n \varepsilon_i(t) - kP(t) \quad (11)$$

with

$$P(0) = P_0 \quad (12)$$

where $k > 0$ represents the rate at which the stock of pollution decays naturally.⁷

For notational convenience, the time argument, t , is generally omitted throughout the paper although it is understood that all variables may be time dependent.

The damage function of country $i = 1, \dots, n$ is given by:

$$D_i(P) = \frac{s}{2}P^2, \quad s > 0. \quad (13)$$

We begin by studying the equilibria under non-cooperation and full cooperation.

We then analyze coalition formation in the following subsection.

⁷For $n = 2$ and $\theta_1 = \theta_2 = 1$, our model is equivalent to Dockner and Long (1993).

4.1 The Markov perfect equilibrium

The objective of country i 's government is to choose a production strategy, $q_i(t)$ (or equivalently a pollution control strategy), that maximizes the discounted stream of net benefits from consumption, denoted by $\phi_i(t)$:

$$w_i(\phi_i(t), P(t)) \equiv \max_{q_i} \int_0^{\infty} e^{-rt} b_i(\phi_i(t), P(t)) dt \quad (14)$$

subject to the accumulation equation (11) and the initial condition (12). The discount rate, r , is assumed to be constant and identical for all countries. We define below a subgame perfect Nash equilibrium of this n -player differential game.

Countries use Markovian strategies: $\phi_i(\cdot) = q_i(P, \cdot)$ with $i = 1, \dots, n$. The n -tuple (q_1^*, \dots, q_n^*) is a Markov Perfect Nash equilibrium, MPNE, if for each $i \in \{1, \dots, n\}$, $\{\phi_i(t)\} = \{q_i^*(P(t), t)\}$ is an optimal control path of the problem (14) given that $\phi_j(\cdot) = q_j^*(P, \cdot)$ for $j \in \{1, \dots, n\}$, $j \neq i$.

In the following section, we analyze the case where countries are identical, that is $\theta_1 = \dots = \theta_n = \theta$. In this case, such a game admits a unique linear equilibrium and a continuum of equilibria with non-linear strategies (Dockner and Long (1993)). The linear equilibrium is globally defined and, therefore, qualifies as a Markov perfect equilibrium. The non-linear equilibria are typically locally defined, i.e. over a subset of the state space. We focus in this analysis on the linear strategies equilibrium. Since our contribution is to highlight an a priori unexpected outcome from the adoption of a “cleaner” technology, we wish to make sure that our result is not driven by the fact that countries are using highly “sophisticated” strategies.

Proposition 3: *The vector (q, \dots, q)*

$$q_i^*(P) = q(P) \equiv \frac{1}{B}(A - \beta\theta - \alpha\theta P), \quad i = 1, \dots, n \quad (15)$$

constitutes a Markov perfect linear equilibrium and discounted net welfare is given by

$$W_i(P) = -\frac{1}{2}\alpha P^2 - \beta P - \mu, \quad i = 1, 2 \quad (16)$$

where

$$\alpha = \frac{\sqrt{B(B(2k+r)^2 + (2n-1)4s\theta^2) - (2k+r)B}}{2(2n-1)\theta^2}$$

$$\beta = \frac{An\alpha\theta}{B(k+r) + (2n-1)\alpha\theta^2}$$

$$\mu = -\frac{(A - \beta\theta)(A - (2n-1)\beta\theta)}{2Br}$$

The steady state level of pollution

$$P_{SS}(\theta) = \frac{n\theta(A - \theta\beta)}{Bk + n\alpha\theta^2} > 0 \quad (17)$$

is globally asymptotically stable.

Proof: We use the undetermined coefficient technique (see Dockner et al (2000) Chapter 4) to derive the linear Markov perfect equilibrium. The details are omitted. (See Proposition 1 of Dockner and Long (1993) for the case where $\theta = 1$). ■

We note that $q_i > 0$ iff $P < \bar{P}(\theta) \equiv \frac{1}{\alpha}(A - \theta\beta)$. It is straightforward to show that $\bar{P}(\theta) > P_{SS}(\theta)$ for all $\theta \geq 0$.

4.2 Full Cooperation

The objective of country i 's government is to choose a production strategy, $q_i(t)$ (or equivalently a pollution control strategy), that maximizes the joint discounted stream of net benefits from consumption across all countries:

$$\max_{q_i} \sum_{i=1}^n w_i(\phi_i(t), P(t))$$

subject to the accumulation equation (11) and the initial condition (12).

Proposition 4: *The vector (q_c, \dots, q_c)*

$$q_i^c(P) = q_c(P) \equiv \frac{1}{B}(A - \beta_c \theta - \alpha_c \theta P), \quad i = 1, \dots, n \quad (18)$$

constitutes the fully cooperative equilibrium and joint discounted welfare of all countries is given by

$$W_i^c(P) = -\frac{1}{2}\alpha_c P^2 - \beta_c P - \mu_c, \quad i = 1, 2 \quad (19)$$

where

$$\alpha_c = \frac{1}{n\theta^2} \left(-Bk - \frac{1}{2}Br + \frac{1}{2}\sqrt{4B^2kr + 4B^2k^2 + B^2r^2 + 4Bn^2s\theta^2} \right)$$

$$\beta_c = \frac{A}{B}n\theta \frac{\alpha_c}{k + r + \frac{1}{B}n\theta^2\alpha_c}$$

$$\mu_c = \frac{-n(A - \theta\beta_c)^2}{2Br}$$

The steady state level of pollution

$$P_{SS}^c(\theta) = \frac{(k+r)\theta nA}{(Bkr + Bk^2 + n^2s\theta^2)} > 0 \quad (20)$$

is globally asymptotically stable.

Proof: We use the undetermined coefficient technique (see Dockner et al (2000) Chapter 4) to derive the fully cooperative equilibrium. The details are omitted. (See Proposition 1 of Dockner and Long (1993) for the case where $n = 2$ and $\theta = 1$). ■

4.3 Coalition Formation

The coalition formation game remains the same as in the static model in the previous section.

The nonsignatories' maximization problem is given by (4) subject to the accumulation equation (11) and the initial condition (12) and the signatories maximization problem is given by:

$$\max_{q_i} W_m(P) = \sum_{i=1}^m w_i(\phi_i(t), P(t)), \quad i \in M$$

subject to the accumulation equation (11) and the initial condition (12).

Let signatories' joint value function be

$$W_m(P) = -\frac{1}{2}\alpha_m P^2 - \beta_m P - \mu_m \quad (21)$$

Let each nonsignatory's value function be

$$W_{nm}(P) = -\frac{1}{2}\alpha_{nm}P^2 - \beta_{nm}P - \mu_{nm} \quad (22)$$

In (21) and (22), α_m , β_m , μ_m , α_{nm} , β_{nm} and μ_{nm} are functions of the parameters of the model. They are derived using the same methodology as used to derive Propositions 3-4, using (23) and (24) as given below.

The signatories' production strategies satisfy the Hamilton-Jacobi-Bellman equation as given by:

$$rW_m(P) = \max_{q_1, \dots, q_m} \left\{ A(\sum_{i=1}^m q_i) - \frac{B}{2}(\sum_{i=1}^m q_i^2) - m\frac{s}{2}P^2 + W'_m(P)[\theta\sum_{i=1}^n q_i - kP] \right\} \quad (23)$$

Each non-signatory's production strategies satisfies the Hamilton-Jacobi-Bellman equation as given by:

$$rW_{nm}(P) = \max_{q_i} \left\{ Aq_i - \frac{B}{2}(q_i^2) - \frac{s}{2}P^2 + W'_{nm}(P)[\theta\sum_{i=1}^n q_i - kP] \right\} \quad (24)$$

Due to the asymmetric nature of the game between the signatories and non-signatories, the expression for the stability function is cumbersome. Therefore, we proceed with a numerical example that illustrates the main results. To construct the numerical example we use parameter values as used by List and Mason (2001) to illustrate the case of greenhouse gas emissions by US states. We set $r = 4\%^8$,

⁸This value of the discount rate is in line with that used by Nordhaus in his climate change models.

$k = 0.01$, $B = \theta^2 = 1$ and $s \in \{0.003063, 0.15315, 0.000613\}$. For these parameter values, the example is identical to the benchmark case of List and Mason (2001). We then vary θ and k to study the impact of cleaner technologies.

4.4 The effect of clean technologies on IEAs

We first show that results qualitatively similar to those reported by Proposition 1 for the static case carry over to the dynamic context.

As in the static case, the grand coalition is internally unstable in this example, as illustrated by Figure 4, which also implies that the two-country coalition is externally stable.

Figure 4: Internal stability of grand coalition as a function of θ at $P = 0$

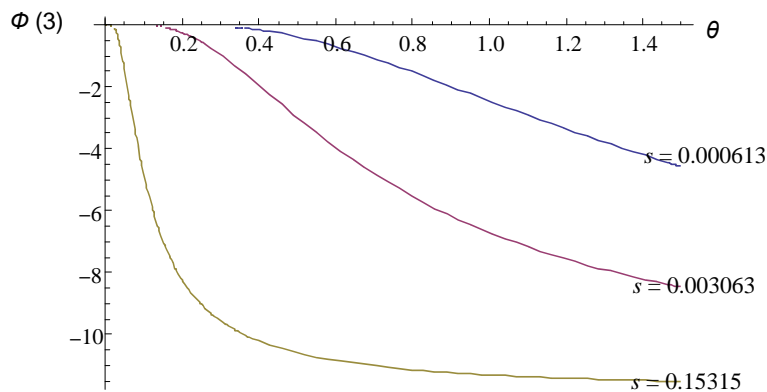
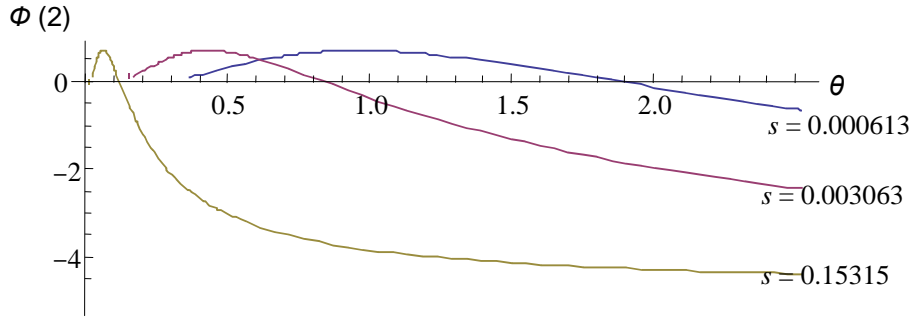


Figure 5 is similar to Figure 1 and illustrates a result similar to Proposition 1. Ceteris paribus, if θ decreases to a level below a certain threshold due to the implementation of a cleaner technology, a two-country coalition becomes stable. The intuition behind this result is also similar to the static case: each coalition member's output is more elastic with respect to θ than the non-member's output at a given P .

Figure 5: Internal stability of 2-country IEA as a function of θ at $P = 0$



This is illustrated by examining the emission strategies as functions of P .

Figure 5 further illustrates that the threshold in terms of θ is decreasing in s . That is, the higher the damage parameter, the lower the range of θ such that the two-country coalition is stable.

Figures 6-7 show that the cleaner technology reduces the gap between the emission strategies of the members and non-members. This reduces the cost of remaining in the two-country coalition and explains why the two country coalition becomes internally stable with the implementation of the cleaner technology.

Figure 6: Emission strategies at $\theta = 0.3$ as P varies

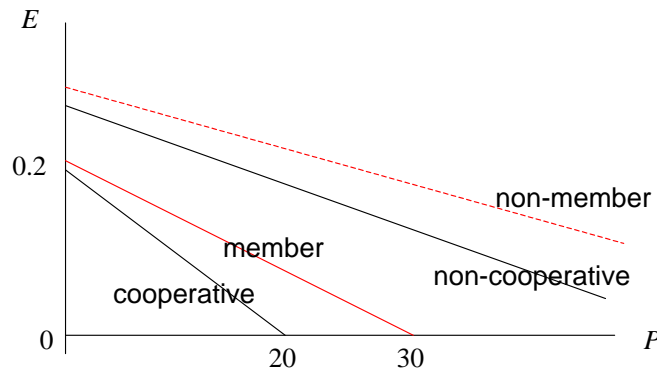
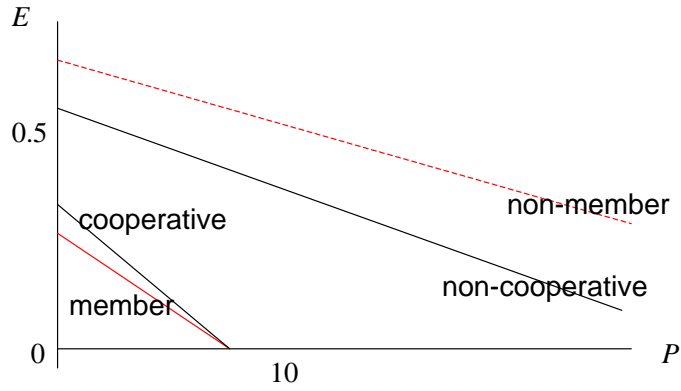
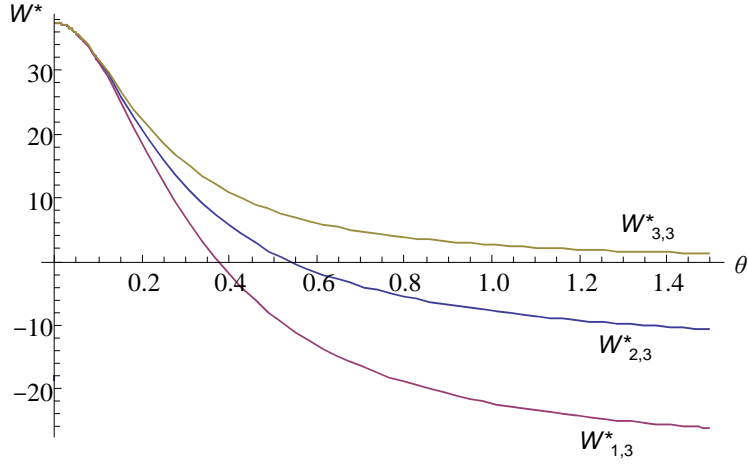


Figure 7: Emission strategies at $\theta = 1$ as P varies



As in the static case, as long as the two-country coalition is stable, the grand coalition is unstable by the farsightedness criterion. This has an optimistic implication: the higher the damage parameter, the greater the range of θ for which the grand coalition is stable by the farsightedness criterion at a given P . That is, the grand coalition is more likely to be stable by the farsightedness criterion when the gains from cooperating on emission reduction are high, given dirtier the technologies and more damaging pollutants. It follows that the disintegration of the grand coalition can be costly. Figure 5 illustrates the global welfare as a function of θ under the grand coalition, the two-country coalition and the non-cooperative equilibrium for $s = 0.003063$. As per Figure 4, the two-country coalition becomes stable at the threshold value of θ given by $\theta = 0.874$. As Figure 8 illustrates, at $\theta = 0.874$, going from the grand coalition to the two-country coalition decreases global welfare by around 295%.

Figure 8: Global welfare as a function of θ at $s = 0.003063$, $P = 0$



Within a dynamic context, one of the factors that influences the stability of coalitions is the stock of pollution at the instant when the decision about whether to join or leave the coalition is made. Figure 9 shows that the higher the stock, the more likely that the two-country coalition is stable, and consequently, the less likely that the grand coalition is stable.

Figure 9: Internal stability of 2-country IEA as a function of θ at $s = 0.003063$

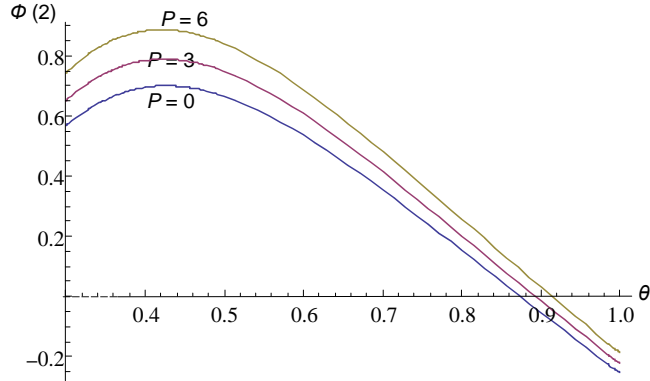
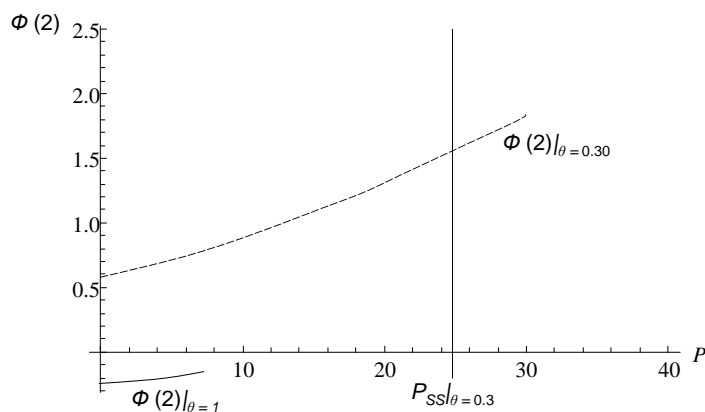


Figure 10 shows $\Phi(2)$ as a function of P at $\theta = 1$ and $\theta = 0.3$. Starting at $P = 0$, suppose θ falls from 1 to 0.3 due to the implementation of a clean technology. At

$\theta = 1$, the two-country coalition is internally unstable. However, the reduction in θ makes this coalition stable. Moreover, as shown by Figure 10, as the stock rises in transition to the new steady state, the stability function increases. The higher the stock, the greater the incentive of the two members to remain in the coalition. Thus, once the grand coalition disintegrates, it remains disintegrated forever after.

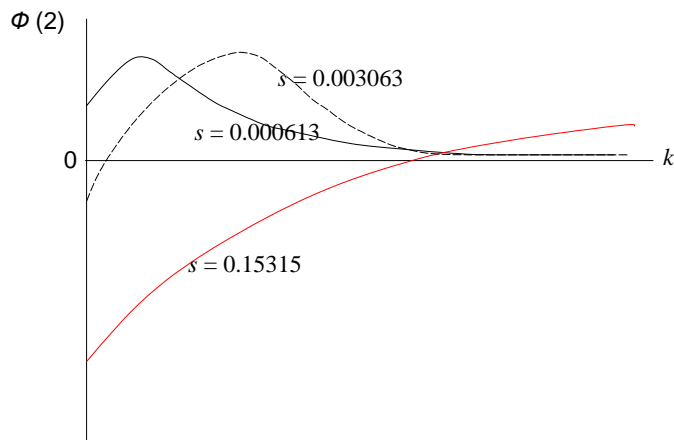
Figure 10: Internal stability of 2-country IEA as a function of P at $s = 0.003063$



Next, we examine how a change in k , the natural rate of absorption, affects the stability of coalitions. One example of actively increasing k is reforestation. According to Canadell and Raupach (2008), terrestrial ecosystems remove nearly 3 billion tons of anthropogenic carbon every year, absorbing about 30% of all CO₂ emissions from fossil fuel burning and net deforestation. China has used 24 Mha of new forest plantations and natural forest regrowth to offset 21% of Chinese fossil fuel emissions in 2000. Another example of increasing k is ocean nourishment which is a type of geoengineering based on introducing nutrients to the upper ocean to increase marine food production (phytoplankton) and to sequester carbon dioxide from the atmosphere.

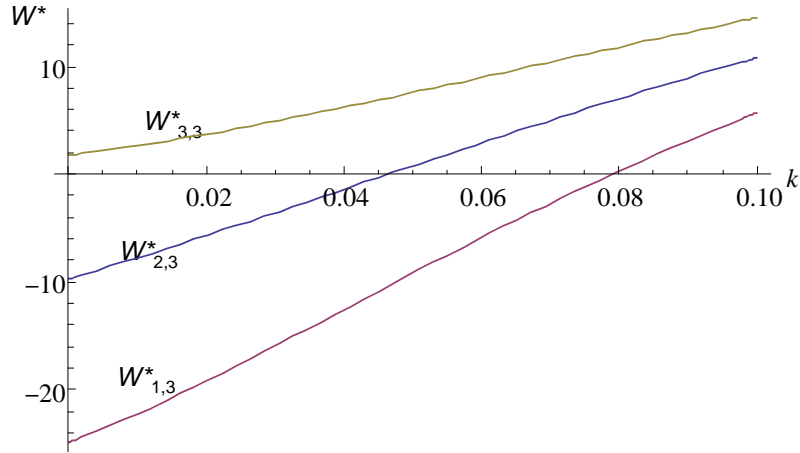
The grand coalition is not internally stable for the range of k shown in Figure 11, implying that the two country coalition is externally stable. As shown by Figure 11, an increase in k beyond a threshold, renders the two-country coalition internally stable. This also implies that investing in technologies that increase k may destabilize the grand coalition. The higher the damage parameter, the higher the threshold of k beyond which the grand coalition is destabilized.

Figure 11: Internal stability of 2-country IEA as a function of k at $P = 0$



As Figure 12 illustrates, going from the grand coalition to the two-country coalition decreases global welfare by around 305%.

Figure 12: Global welfare as a function of k at $s = 0.003063$, $P = 0$



5 Concluding Remarks

This paper shows that, if countries are farsighted when deciding whether to defect from a coalition, then the implementation of cleaner technologies may jeopardize the chances of reaching an international environmental agreement. We showed, both analytically within a static framework and using a numerical example within a dynamic framework, that implementing clean technologies may destabilize an otherwise stable grand coalition when countries are farsighted. We considered a reduction the emission per output ratio as well as measures that enhance the natural rate of decay of stock pollutants. We showed that the higher the stock of pollution, the more likely that the above mechanism unfolds. We would like to note that this analysis highlights a possibility result and should not be taken as a general wisdom. While it contains a rather pessimistic message, it should be viewed more as a warning against the perception that technology improvement is the panacea to all the major transbound-

ary pollution problems than a recommendation to discourage the implementation of cleaner technologies.

The main policy recommendation that can be drawn from this analysis is that, greener production processes or measures to enhance nature's capacity to clean the environment do not necessarily eliminate the need to agree on environmental policies with appropriate transfers across regions to reach self-sustainable and successful environmental agreements (see e.g., Germain et al. (2003) or Petrosjan and Zaccour (2003) for the case of the design of transfers in dynamic transboundary pollution games). For each particular transboundary pollution problem, a specific analysis taking into account the number, size and behavior of players (farsighted or myopic) when contemplating the ratification of an agreement is necessary before one can determine what role cleaner technologies may play in reaching an agreement.

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