Dynamic Models of International Environmental Agreements: A Differential Game Approach

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Abstract

This article provides a survey of dynamic models of international environmental agreements (IEAs). The focus is on environmental problems that are caused by a stock pollutant as are the cases of the acid rain and climate change. For this reason, the survey only reviews the literature that utilizes dynamic state-space games to analyze the formation of international agreements to control pollution. The survey considers both the cooperative approach and the noncooperative approach. In the case of the latter, the survey distinguishes between the models that assume binding agreements and those that assume the contrary. An evaluation of the state of the art is presented in the conclusions along with suggestions for future research.

Keywords: Externalities; public goods; pollution; international environmental agreements; state-space dynamic games; differential games; cooperative and noncooperative games; trigger strategies.

JEL Classification System: C73, D62, H41, Q50

1 Introduction

Pollution is an example of a negative *externality* that is also an important instance of market failure. Externalities imply that the competitive allocation of productive factors is inefficient. The problem is that, if the production or consumption of a good causes a negative externality, market prices do not necessarily reflect the true social costs of the good. In such cases, regulation is justified to recover allocative efficiency. In order to do so, the regulator has a box of tools that has been extensively studied and designed by environmental economists. However, as there are no supranational regulatory agencies, if pollution is transboundary, countries need to collaborate to correct the externality. As regards the geographical impact of pollution, transboundary pollution can be categorized as local, regional and global pollution. Examples of local pollution include tropospheric ozone and eutrophication. The classical example of regional pollution is acid rain and the depletion of stratospheric ozone and climate change are two examples of environmental problems with a global dimension. In all these cases, the countries involved in the externality have to reach an international environmental agreement (IEA) to control pollution.

The aim of this survey is to review the economic literature on IEAs. The focus is on environmental problems that are caused by a *stock pollutant,* as are the cases of acid rain and climate change. In both examples, environmental damages are caused by the deposition of different types of pollutants in the soil or their concentration in the atmosphere. In other words, these environmental problems are associated with the accumulation of emissions and consequently are intrinsically dynamic. For this reason, this paper reviews only the literature that has used dynamic models to investigate the scope and effectiveness of IEAs. Another characteristic of this kind of international environmental problem is that the externality creates a strategic interdependence between the countries. The social welfare of a country depends not only on its emissions, but also on the emissions of the rest of countries as long as the stock of pollution evolves over time according to global emissions. Thus, the dynamic models we are interested in are mathematically represented by a class of dynamic games called *state-space games.* A state-space game contains a set of state variables that describe the main features of a dynamic system at any instant of time.[1] The idea is that the state variables adequately summarize all relevant consequences of the past actions of the players of the game. If time is continuous in the model, the dynamics of the game is given by a set of differential equations and then the game becomes a *differential game.* However, if time is discrete, the dynamics of the game is defined by a set of difference equations and then the game is called a *difference game.* Finally, we would like to point out that another focus of the survey is on theoretical papers. The list of empirical papers that have addressed the issue of this paper is so long that we have decided to concentrate exclusively on theoretical contributions to avoid the paper becoming too long.[2] Nevertheless, there are some references in the text to empirical papers. They have been introduced to enlighten a theoretical debate when this is not conclusive.

There are already some surveys devoted to the issue reviewed in this paper. As far as we know, the literature on the analysis of IEA formation from a game-theoretic approach has been surveyed by Missfeldt (1999), Wagner (2001) and Finus (2008).[3] Missfeldt (1999) reviews the main papers we comment on Section 2 and which were published at the beginning of the nineties. These papers focus on the study of the cooperative and noncooperative solutions of a differential game of international pollution control, but they do not address the issue of IEA stability and effectiveness. Wagner (2001) comments on some papers published during the nineties where this issue is addressed, but using repeated games. The survey in Finus (2008) is excellent, but as in Wagner (2001), he

[1] This approach leaves the papers that use *repeated games* to analyze the scope of the IEAs out of this survey because in a repeated game the distinction between state (stock of pollution) and control (emissions) variables does not apply. In a repeated game, a combination of actions always yields the same "current" payoffs for the players, whereas for a state-space game payoffs depend on the combination of actions and state, and the state evolves over time depending on the players' actions.

[2] Finus (2008) provides a survey that illustrates the game theoretic research on the design of IEAs for the climate change problem using the empirical Stability of Coalitions (STACO) model. Readers interested in empirical models can find a list of the main empirical models used to analyze IEAs in this survey. Jørgensen et al. (2010) also provides a survey of empirical models.

[3] Besides these surveys, there are two books on IEAs that interested readers could look at: Finus (2001) and Barrett (2003).

mainly reviews the papers where repeated games are used to analyze the stability of IEAs in a dynamic framework. More recently, Jørgensen et al. (2010) and Long (2012) published a pair of very complete surveys on topics related to the issue reviewed in this paper. Jørgensen et al. (2010) devote their survey to dynamic games in the economics and management of pollution, and Long (2012) to the applications of dynamic games to global and transboundary issues. In both papers, there is a section on transboundary pollution where the authors comment on the literature regarding IEAs. This survey drinks from the sources of these two papers. However, as we only look at the literature on IEAs, our survey can devote more space to evaluating the different contributions to this literature. In particular, we pay more attention to the role of transfers in promoting participation in a dynamic framework, both from a noncooperative and also a cooperative approach. The first part of the section devoted to the cooperative approach explains different types of transfer schemes in detail. We then present a complete section on IEAs supported by trigger strategies in which we aim to summarize the current state of the issue regarding the possibilities of reaching an agreement with full participation using punishment strategies in the framework of a state-space game.

The paper is organized as follows: Section 2 presents the basic model, a differential game of international pollution control and the cooperative and noncooperative solutions of the model. It also includes the main extensions of the basic model. Section 3 addresses the formation of self-enforcing IEAs with binding agreements. The approach in this section is noncooperative because participation is given by an equilibrium. Section 4 is devoted to the formation of self-enforcing IEAs, when signing an agreement does not guarantee compliance. Section 5 surveys the literature that uses a cooperative approach and, finally, Section 6 presents the conclusions and possible avenues for future research.

2 The Basic Model: A Differential Game of International Pollution Control

At the beginning of the nineties, several papers formulated transnational pollution as a differential game among sovereign governments. The list includes the papers written by van der Ploeg and de Zeeuw (1991, 1992), Hoel (1992, 1993), Long (1992) and Kaitala, Pohjola and Tahvonen (1992). Although the models analyzed by these authors have different features, all of them can be obtained as an extension of the basic model we present below.

Suppose a pollutant is emitted by $N \geq 2$ countries that share a natural resource such as the environment. The concentration level of the pollutant in the environment changes over time according to

$$\dot{P}(t) = \sum_{i=1}^{N} E_i(t) - \delta P(t), \quad P(0) = P_0 \geq 0, \tag{1}$$

where $E_i(t)$ stands for country i' pollutant emissions, $P(t)$ is the pollution stock and $\delta \geq 0$ denotes the depreciation rate of the pollution stock.[4]

As emissions are an inevitable by-product of production and consumption, it is assumed that emissions positively affect social welfare because more emissions imply more production and consumption. However, the stock of pollution is seen as a "public bad" because of its adverse effects on health, quality of life and also production. Thus, the instantaneous social welfare function of country i is written as follows

$$W_i(E_i(t), P(t)) = U_i(E_i(t)) - D_i(P(t)), \tag{2}$$

where $U_i'(E_i)$ may be interpreted as a utility function, and $D_i(P)$ as the "disutility" caused by pollution. Following standard practice, it is assumed that U_i is strictly concave and increasing in E_i and that D_i is convex and increasing in P.

Thus, for transnational pollution, all the countries polluting the environment contribute to the "provision" of a *pure public bad.* Notice, that for this specification of the

[4] For non-constant decay rates, see Forster (1975), Tahvonen and Salo (1996) and, more recently, Kossioris et al. (2008).

social welfare function, all the countries "consume" the same amount of pollution. So, the decentralized or noncooperative provision of the public bad can be represented as a *differential game* in which each country chooses a path of emissions that maximizes the discounted present value of the stream of instantaneous social welfare

$$\max_{\{E_i(t)\}} \int_0^{\infty} e^{-r_i t} \left(U_i(E_i(t)) - D_i(P(t))\right) dt,$$

where $r_i > 0$ is the rate of discount, subject to the dynamic constraint (1).

van der Ploeg and de Zeeuw (1992) show that the *first best* solution of a differential game of international pollution control with *identical* countries has a unique saddle point equilibrium and that the optimal path approaches it asymptotically.[5] For the cooperative solution, initial emissions are greater than steady-state emissions and emissions are *decreasing* along the optimal path, provided that the initial stock of pollution is lower than the steady-state stock of pollution. In this case, the optimal carbon tax (co-state variable) that implements the optimal emissions must be increasing. They also find that the noncooperative open-loop Nash equilibrium has a larger pollution stock and a lower carbon tax in the steady state than the cooperative solution. The reason is that, in the absence of international coordination, each country ignores the adverse effects on the foreign social welfare of an additional unit of emissions and therefore pollutes too much.

However, the main contribution of van der Ploeg and de Zeeuw's (1992) paper is the calculation of the feedback Nash equilibrium or the Markov-perfect Nash equilibrium for a *quadratic* social welfare function as follows

$$W_i(E_i(t), P(t)) = \beta E_i(t) - \frac{1}{2} E_i(t)^2 - \frac{\gamma}{2} P(t)^2.$$

The problem with the open-loop Nash equilibrium solution is that it relies on unrealistic information sets and an infinite period of commitment. Moreover, although the

[5] The first best solution is the most widely used cooperative solution in the literature. For this kind of solution the emissions path is calculated by maximizing a global welfare function defined as the sum of all national welfare functions. Obviously, the maximization of this function yields a Pareto-efficient emissions path. For this solution, all the countries have the same weight in the global welfare function. If the contrary is not written, the reader must understand that when we refer to the cooperative solution, we are referring to the first best solution.

open-loop Nash equilibrium is time-consistent it does not meet the subgame-perfection requirement.[6] They obtain that the open-loop Nash equilibrium *underestimates* the damage of not coordinating environmental policies. The intuition is as follows. An individual country that is considering to emit a marginal amount more causes an increase in the stock of pollution for all countries concerned. In the feedback Nash equilibrium this country knows that the other countries will respond with less pollution. This means that the marginal damage caused to the environment of an additional unit of emissions is less than it would be in the open-loop Nash equilibrium, so that in equilibrium the incentive to have more pollution will be higher in the feedback Nash equilibrium than in the open-loop Nash equilibrium. Clearly, the more appropriate use of the feedback Nash equilibrium concept strengthens the case for international coordination of pollution control. The same result is obtained by Hoel (1993) for a *difference* game of international pollution control with asymmetric countries assuming that no emissions occur after some finite period. He shows that the stock of pollution is higher under the feedback Nash equilibrium than under the open-loop Nash equilibrium and that for the open-loop Nash equilibrium, the stock of pollution is higher than under the cooperative solution. He also shows that the tax implementing the cooperative solution is the same for the open-loop and the feedback equilibrium, in spite of the fact that these two equilibria differ in the absence of an emissions tax. To understand the result it must be taken into account that with the optimal tax, the negative effect of lower future tax reimbursements is exactly equal to the positive environmental effect of other countries reducing their future emissions. Each country therefore chooses its emissions without taking the effect on future emissions from other countries into consideration, just like in the open-loop equilibrium.[7]

Long (1992) focuses on a model with *two* countries and compares the cooperative solution with the open-loop Nash equilibrium and the open-loop Stackelberg equilibrium. For the *symmetric* linear-quadratic case, the steady-state pollution stock for the open-loop

[6] An excellent explanation of the differences between these two types of noncooperative equilibria can be found in Dockner et al. (2000).

[7] The tax scheme proposed by Hoel (1993) consists of the same tax for all countries and reimbursement shares equal to the ratio of national damages over global damages.

Stackelberg equilibrium is greater than the steady-state pollution stock of the open-loop Nash equilibrium. Moreover, the steady state is stable in the sense that convergence can be assured by suitable choices of initial values of the co-state variables. This kind of saddle-point stability is also displayed by the open-loop Nash equilibrium. Both models require the ability of the government to make *credible commitment*. However, if the countries are different, it is possible to find parameter values at which bifurcation takes place for the open-loop Stackelberg equilibrium, so that there exists an optimal path that perpetually orbits around the steady state. This kind of dynamics requires a strong asymmetry in environmental damages and different discount rates.

van der Ploeg and de Zeeuw (1992) also address an interesting extension of the basic model, namely: investment in clean technologies. In order to obtain this extension from the basic model, it is sufficient to consider emissions as an inevitable by-product of production. In that case, $E_i(t)$ can be substituted in (1) by $\alpha Y_i(t)$, where α denotes the emission-output ratio and $Y_i(t)$ stands for the production of country i, and in (2) by the production. In this framework, by investing in the stock of clean technology, say $K(t)$, a country can reduce the emission-output ratio, $\alpha(K)$. Clean technology is assumed to be *public knowledge*, such that all countries benefit from the investment $I_i(t)$ in clean technology of an individual country i as long as the national investment increases the stock of clean technology according to the following differential equation

$$\dot{K}(t) = \sum_{i=1}^{N} I_i(t) - \rho K(t), \quad K(0) = K_0 \geq 0,$$

where $\rho \geq 0$ denotes the rate of depreciation of the common stock of clean technology.

Now, the instantaneous social welfare of country i must be written as follows

$$W_i(Y_i(t), I_i(t), P(t)) = U_i(Y_i(t)) - I_i(t) - A(I_i(t)) - D_i(P(t)),$$

where $A(I_i)$ is a convex adjustment costs function. Assuming that the stock of clean technology does not depreciate, that $\alpha(K) = \alpha_0 K^{-w}$ with $w \leq 1/2$ and quadratic specifications for the utility and damage functions, van der Ploeg and de Zeeuw (1992) obtain that international coordination leads to lower levels of production, clean technology and pollution stock than in the open-loop Nash equilibrium for $w = 1/2$. Thus, even with technical progress, pollution control implies a reduction in the production of good and services.

The Appendix of van der Ploeg and de Zeeuw's (1992) paper also shows that when it is assumed that production at home pollutes the environment more at home than abroad, the steady-state results do not change. In order to develop this analysis, the basic model is extended to allow for separate pollution levels in each country, $P_i(t),\ i = 1, ..., N$. It is assumed that a fraction π of the emissions remains at home, whereas the rest of the emissions spreads to the other countries. Then (1) becomes

$$\dot{P}_i(t) = \pi E_i(t) + (1-\pi) \sum_{j=1, j\neq i}^{N} E_j(t) - \delta_i P_i(t), \quad P_i(0) = P_{i0} \geq 0,\ i = 1, ..., N.$$

The welfare function of government i is now given by

$$\max_{\{E_i(t)\}} \int_0^\infty e^{-r_i t} \left(U_i(E_i(t)) - D_i(P_i(t)) \right) dt.$$

For the symmetric case, it is clear that the steady-state results will not change.

Kaitala, Pohjola and Tahvonen (1992) use empirical estimates of the parameters to solve an asymmetric version of this model. In particular, they analyze an acid rain differential game between Finland and the former USSR. In their model, sulphur emissions are used as the environmental control variables and the acidities of the soils as the state variables. Acidification is consequently considered to be a stock pollutant having long-lasting harmful effects on the environment. The state dynamics consists of two relationships: firstly, a sulphur *transportation model* between regions and, secondly, a model describing how the quality of the soil is affected by sulphur deposition. The countries are assumed to be interested in maximizing the net benefits from pollution control as measured by the impacts on the values of forest growth net of the abatement costs. Cooperative and noncooperative solutions are compared to assess the benefits of bilateral cooperation. The noncooperative solution is given by the open-loop Nash equilibrium. Their results show that cooperation is beneficial to Finland but not to the Soviet Union.

For $N = 2$, the extreme case of asymmetry yields the differential game of *downstream pollution.* For this extreme case, all the pollution of country 2 ends up in country 1, say

$\pi_1 = 1,\ \pi_2 = 0$, which yields

$$\dot{P}_1(t) = E_1(t) + E_2(t) - \delta P_1(t), \quad P_1(0) = P_{10} \geq 0$$

and $P_2(t) = 0$. van der Ploeg and de Zeeuw (1992) also show for the quadratic specification of the social welfare function that the steady-state pollution stock of the open-loop Nash equilibrium is greater than the steady-state pollution stock of the cooperative solution. Nevertheless, implementation of the cooperative solution requires the down-stream country to make side-payments in order to induce the up-stream government to control pollution, since the up-stream country obviously comes off worse in the cooperative solution.[8]

Following this first series of papers, others were published in the nineties about transboundary pollution. Some of them delve deeper into the study of the basic model, while others propose some extensions, although all of them focus on the comparison between the cooperative solution and noncooperative equilibria. First, we comment on the papers that confine their attention to transboundary pollution between two countries. These papers are Dockner and Long (1993), Martin, Patrick and Tolwinski (1993) and Zagonari (1998).

In Martin, Patrick and Tolwinski (1993) a *difference* game of international pollution control between two asymmetric players is used to evaluate the cost of achieving a given target level of CO_2 concentration using a policy based on a tax/subsidy scheme. The authors use *numerical methods* to compute the feedback Nash equilibrium of the game. The asymmetry of the players is reflected in their respective attitudes toward global climate change with one player benefiting from the change and the other losing out, although, overall, the aggregate impact is assumed to be negative. Dockner and Long (1993), using the symmetric linear-quadratic differential game proposed by Long (1992), demonstrate (following Tsutsui and Mino (1990)) that if countries use *non-linear Markov strategies* and have a low discount rate, a Pareto-efficient steady-state pollution stock can be supported as a Markov-perfect Nash equilibrium. Thus, the emergence of cooper-

[8] This is a clear example of the fact that the cooperative solution does not necessarily imply that the agreement is profitable for all countries (individual rationality).

ative outcomes does not require any international agreement but can be brought about through the use of non-linear strategies.[9] Zagonari (1998) investigates the *asymmetric* solution of the linear-quadratic game proposed by Long (1992). He divides countries into "environmental-concerned" countries and "consumption-oriented" countries and shows that if the damages of "consumption-concerned" countries are small enough and their discount rate closes in on the discount rate used to characterize the cooperative solution, then there is a unique globally and asymptotically stable feedback Nash equilibrium in linear strategies that results in a smaller steady-state stock of pollution than the cooperative solution. This result also holds in the extreme case in which "consumption-oriented" countries do not care about environment quality and the countries play non-linear strategies, provided that the discount rate of the "environmental-concerned" countries is not very great. More recently, List and Mason (2001) have shown that if there is a large difference between the utility of emissions for both countries and the initial levels of pollution are sufficiently small, the aggregate payoffs of the feedback Nash equilibrium in linear strategies is larger than the aggregate payoffs corresponding to the cooperative solution. The intuition behind this result is that the cooperative solution applies one shadow price to pollution whereas for the noncooperative equilibrium each player derives its own shadow price. When countries are highly asymmetric, these shadow prices tend to be quite dissimilar. As payoffs become increasingly asymmetric across countries, costs of joint maximization based on one shadow price eventually exceed any benefits from internalizing external effects.[10] Finally, it is worth mentioning a series of papers published by

[9] However, Rubio and Casino (2002) point out that, given the local nature of the non-linear strategies, the possibility of the cooperative pollution stock level being supported as a noncooperative long-run equilibrium depends critically on the value of the initial pollution stock. Moreover, they show that if the initial pollution stock is lower than the cooperative pollution stock, a problem will arise to select the non-linear strategy, since there is always a strategy that gives a better approximation to the cooperative pollution stock. These results limit the scope of the procedure proposed by Tsutsui and Mino (1990) to construct a Markov-perfect equilibrium using non-linear strategies.

[10] Fernandez (2002) analytically solves an asymmetric game of transboundary water pollution with linear benefits and quadratic costs and compares the cooperative and noncooperative solutions using data from the U.S. and Mexico. According to her estimates, cooperation yields a lower steady-state pollution stock. She also finds that trade liberalization provides economic incentives for Mexico to reduce

Yanase (2007, 2009, 2010) where the two countries trade in a polluting good. Pollution is regulated by the government of each country using a tax or an emission quota system, such that finally the author examines dynamic policy games between governments that determine national environmental policy. In the first paper, he assumes a competitive international market, whereas in the second he looks at an international duopoly. In both the focus is on the comparison between the two regimes of regulation. His findings show that the emission tax game produces a more distortionary outcome than the emission quota game; it generates more pollution and lower welfare. In the last paper, the author addresses the effects of trade when the governments use a national tax to control emissions comparing a regime of autarky with free trade. The result is that the effects of trade on global pollution and welfare are ambiguous because policy games can yield multiple equilibria.

Next, we review some papers that analyze the issue of transnational pollution between more than two countries. The list of papers consists of Tahvonen (1994), Xepapadeas (1995a, 1995b) and Dockner and Nishimura (1999). Tahvonen (1994) formulates an integrated assessment model on climate change to obtain a first approximation of the potential gains from cooperation. The model is a linear-state differential game between five geopolitical areas with two state variables: the difference between the present and preindustrial global mean temperature and the carbon concentration above preindustrial level and one control variable, namely: emissions.[11] The game is solved in closed form. Abatement cost parameters are calibrated with a global energy sector model and climate parameters are based on empirical time series. Simulation suggests that an agreement that implements the cooperative solution is beneficial for developing countries compared with the noncooperative Nash equilibrium, but more costly for the industrial world.

Xepapadeas (1995a) proposes a differential game of international pollution control with endogenous technical change. In his model, output is produced using labor and an

transboundary pollution both for the cooperative solution and for the noncooperative equilibrium.

[11] The linear state games are games for which the system dynamics and the utility functions are polynomials of degree one with respect to the state variables and there is no multiplicative interaction at all between the state and the control variables. For this class of differential games, the open-loop strategies are independent of the state and the open-loop Nash equilibria are Markov perfect.

effective resource. The effectiveness of the resource depends on the level of technology that can be changed using labor. The amount of labor is given in each period and the resource can be bought at a constant price by the countries.[12] Emissions are produced by the use of the resource. The level of technology is specific for each country so technology differentials appear among countries, which affect welfare positively. Alternatively, it is assumed that all countries can enter into some international agreement and contribute labor to improve resource saving methods. In this case, the level of technology is common to all countries (it is public knowledge). The results show that if countries devote labor to global R&D on the basis of maximizing individual country's welfare, the outcome will be inferior to the cooperative solution, both in terms of technology and pollution stock. Moreover, the deviation from the cooperative solution increases under the feedback Nash equilibrium in comparison to the open-loop Nash equilibrium. However, if technology differentials generate substantial benefits, then rich countries that can achieve high technology levels individually, may not have incentives to commit to the global R&D agreement, even though doing so would bring about a greater stock of pollution. Finally, it is also discussed how R&D subsidies and emissions taxes can lead to the implementation of the cooperative solution. Xepapadeas (1995b) proposes a model where the stock of pollution adversely affects the growth rate of a renewable resource. In the model, consumption, the resource harvest and the stock of the resource have a positive effect on welfare, whereas the stock of pollution has a negative effect. Output is produced by a polluting factor and is distributed among consumption and cost associated with the use of the factor and resource harvest. Only the produced good is tradable, so if there is no cooperation among countries, assuming international capital markets, production and aggregate uses of output need not be equal in each country in each time period, but should be equal in present value terms. Taking into account this constraint, the open-loop Nash equilibrium and the feedback Nash equilibrium in linear strategies are calculated and compare with the cooperative solution. Assuming that the growth function of the renewable resource is linear in the pollution stock and separable, and that the welfare function is linear and separable in the stock of pollution and stock of the resource, the finding is that

[12] The resource is regarded as a quasi-back stop technology.

the noncooperative equilibrium results in overemissions and resource overexploitation in the steady state and, that, as occurs in the previous paper, the deviation from the cooperative solution increases under the feedback Nash equilibrium when compared to the open-loop Nash equilibrium. The author also shows that applying a tax per unit of polluting factor and a tax per unit of resource harvested, the cooperative solution can be implemented if tax revenues are given back to all countries. However, it might not be possible to implement the scheme through an international agreement because the individual rationality for some countries may not be satisfied or because, even if this condition is satisfied, there might be countries with incentives to defect from the agreement once all other countries have decided to participate.

Dockner and Nishimura (1999) analyze different types of transboundary pollution assuming that the utility function is *linear.* Three cases of transboundary pollution are addressed. One-sided transboundary pollution, global transboundary pollution and global pollution. In the first case, consumers in each country are affected only by the pollution stock of the domestic country and that of one neighbor. In the second case, there is global interaction and each consumer faces costs from all the pollution stocks in the world economy. The last case corresponds to the basic model presented above. The authors show that there exists a unique cooperative solution for the three cases and that in all the cases, the dynamics of the cooperative solution are given by a *most rapid approach* path.[13] They also show the existence of feedback Nash equilibria for the three cases. However, they restrict the analysis of the dynamics of the noncooperative equilibrium to the case of one-sided transboundary pollution with only three countries assuming specific functional forms of the cost functions. Their conclusion is that the lack of coordination may very well result in environmental chaos and complicated dynamics.

More recently, Dutta and Radner (2004 and 2006) have analyzed a global warming *difference* game with technological change and population growth. In the first paper, emissions depend on the use of an energy input according to a coefficient that can be reduced paying a constant marginal cost. The welfare of a country i is given by a concave function of the energy input less the damage due to climate change that is linear

[13] This kind of solution involves approaching the steady-state pollution stock as fast as possible.

in the global stock of greenhouse gases (GHGs) less the cost of changing the emissions coefficient. Given the linearity of the damage function and the adjustment cost function of the emissions coefficient, both for the cooperative and noncooperative (Markov-perfect Nash equilibrium) solutions, the emissions and the emission coefficient for each country are constant after the initial date.[14] The authors show that if the elasticity of the optimal policy for the energy input is lower than unity, the switch from the noncooperative solution of the game to the cooperative solution with the same initial state will decrease every country's emissions in every period. In the second paper, the authors assume that the emissions coefficient is constant but that the population in each country changes exogenously over time. For simplicity, they assume that each population evolves according to a linear first-order difference equation that converges monotonically to a positive steady state. The welfare of country i depends on a function in the emissions and population that for a given population is assumed concave with respect to emissions less the damage due to climate change that is linear in the global GHG stock. However, now the marginal damage is increasing with the population. In this model, although country i' emissions are again independent of the GHG stock, they depend on own-population level. The authors study the population effects on emissions and show again that the emissions of the cooperative solution are below the emissions of the Markov-perfect Nash equilibrium.

Finally, we would like to draw attention to an interesting extension of the basic model proposed by Yang (2006). In this paper, the author distinguishes between local and global stock externalities, taking as an example the case of fossil fuel combustion which generates both CO_2 and SO_2. CO_2 is the most important greenhouse gas whereas SO_2 can cause serious local pollution, but can also alleviate potential global warming because of negative radiative forcing. For this model of negatively correlated local and global stock externalities, Yang (2006) derives the conditions that characterizes the cooperative solution and compares them with the conditions that characterize the open-loop Nash equilibrium of a differential game where the countries internalize the local externality and act strategically to provide the global externality.[15]

[14] The pollution game analyzed by Dutta and Radner (2004) belongs to the class of *linear state games*.

[15] Legras and Zaccour (2011) extend Yang's (2006) model to consider the case of correlated regional and

2.1 Another Version of the Basic Model

In some papers, the differential game of international pollution control has been presented as a problem of minimizing the total costs of reducing pollution. Among these papers, it is worth mentioning those written by Kaitala and Pohjola (1995), Escapa and Gutiérrez (1997) and Mäler and de Zeeuw (1998). Basically, this approach consists of substituting the instantaneous social welfare function (2) by the total cost function

$$TC_i(E_i(t),\ P(t)) = C_i(E_i(t)) + D_i(P(t)),$$

where $C_i(E_i)$ denotes emission abatement costs and $D_i(P(t))$ stands for environmental damages. The abatement cost function is decreasing and convex, and satisfies $C_i(\bar{E}_i) = 0$, where $\bar{E}_i$ is the business-as-usual emissions level.

Kaitala and Pohjola (1995) solve the game of *downstream pollution* for the following *quadratic* specification:[16]

$$TC_1(E_1(t),\ P(t)) = \frac{c_1}{2}(\bar{E}_1 - E_1(t))^2 + \frac{\gamma_1}{2}P(t)^2. \tag{3}$$

They calculate the cooperative solution and the feedback Nash equilibrium in linear strategies. Then, using a numerical example, they investigate the existence and properties of agreeable side-payment programs. An *agreeable* side-payment program has the property that starting at any time τ and at the corresponding point of any feasible state trajectory, the individual cooperative payoff of each country (after side payments) over the remaining time is no less than the Nash equilibrium payoff that the country could obtain if the agreement was discontinued at time t. This is a way of interpreting individual rationality in a dynamic setting. They find that when damage costs are sufficiently high, it is possible to design a *constant* side-payment program that satisfies this property. However, when the damage costs are low, the only possibility to design a side-payment

global stock externalities although their focus is on the use of intertemporal trading rates to implement the cooperative solution.

[16] Really, Kaitala and Pohjola (1995) address the issue of global warming, but they divide the countries in the world into two groups. In group 1 we find the "losers", while group 2 consists of countries that are economically neutral with respect to global warming such that $D_2(P) = 0$.

program is to agree on a time-variable side-payment program in which side-payment flow increases in time.

Escapa and Gutiérrez (1997) look again at the issue addressed by Tahvonen (1994) and quantify how the potential gains derived from cooperation would be distributed among countries for the case of global warming. In the paper, three different cooperative solutions are considered: The *Fist Best* (FB), the *Nash Bargaining* (NB), and the *Kalai-Smorodinsky* (KS). For the FB solution, all the countries have the same weight in the global welfare function, or in other words, all of them have the same bargaining power. In the NB solution, the measure of the bargaining power of each country is determined by the relative welfare at the noncooperative Nash equilibrium. Finally, the KS solution is based on two reference points, the noncooperative Nash equilibrium and the *ideal point* which represents the best outcome available for each country that is consistent with individual rationality for the rest of countries.[17] Escapa and Gutiérrez (1997) rewrite all these definitions in terms of a minimization problem using the total costs of controlling emissions as the objective function. They solve in closed form the open-loop Nash equilibrium of the difference game of international CO_2 emissions control. However, the cooperative solutions are calculated numerically for six blocks of countries. In contrast with the result obtained by Tahvonen (1994), they obtain that cooperation based on the FB solution will not benefit all developing countries. However, cooperation based on the NB or the KS solution will benefit all countries in the world and, besides, the highest gains are for developing countries.

Finally, Mäler and de Zeeuw (1998) solve a dynamic version of the acid rain game proposed by Mäler (1989) for the whole of Europe using specifications for total costs as (3). Cooperative and noncooperative solutions are compared to assess the benefits of multilateral cooperation. They find that although the open-loop Nash equilibrium underestimates the total costs of the feedback Nash equilibrium, for the model studied in the paper, the difference is rather small. In other words, the open-loop Nash equilibrium would be in this case a good approximation of the feedback Nash equilibrium.

[17] Interested readers can consult Kalaï and Smorodinsky (1975) for details.

3 Self-Enforcing IEAs with a Stock Pollutant. Cooperation with Binding Agreements

As has been established by the literature reviewed in the previous section, if countries do not cooperate to control emissions, the noncooperative equilibrium is inefficient. This means that cooperation increases global welfare such that an agreement involving all the countries could be individually rational.[18] However, it is well known that cooperation has at least two problems. One is the cheating problem. Countries may have incentives to deviate from the emissions stipulated in the agreement after it has been signed. Another problem is that countries can decide not to sign the agreement and play as a free-rider. The first problem could be solved using *binding agreements,* but it is not clear whether binding agreements solve the second problem. This issue was addressed by Carraro and Siniscalco (1993) and Barrett (1994), in the framework of a static model where environmental damages depend on global emissions. Carraro and Siniscalco (1993) solved an IEA formation game in two stages to explain how many countries could sign a binding agreement when all the countries are identical *ex-ante.* In the first stage, countries play a simultaneous open membership game and decide on whether to sign or not to sign. In the second stage, countries choose the emission level. In this stage, emissions are defined by a *partial agreement Nash equilibrium with respect to a coalition.*[19] Nonsignatories choose emissions acting noncooperatively, whereas signatories maximize the welfare of the agreement taking the nonsignatories' emissions as given. Participation is given by the Nash equilibrium of the first stage that selects a level of participation such that signatories have no incentives to leave the agreement (internal stability) and nonsignatories have no incentive to join the agreement (external stability). Carraro and Siniscalco (1993) obtain that the maximum number of signatories is three regardless of the importance of

[18] If side payments cannot be implemented to guarantee that all countries improve their welfare when the first best solution is selected, it is always possible to find an efficient solution that satisfies both individual and social or group rationality.

[19] This notion of equilibrium for the emission game was defined formally by Chander and Tulkens (1997).

environmental damages. Barrett (1994) solves the same kind of game but assuming that in the second stage emissions are given by a *partial agreement Stackelberg equilibrium*.[20] The solution is different but it is still pessimistic as regards the participation in an IEA. The number of signatories can be high but only when the gains from cooperation are low. The explanation of this result is given by the fact that when there are more than two countries, the game presents *positive spillovers* for nonsignatories stemming from cooperation. Moreover, the incentives to deviate from the agreement increase quickly with cooperation, so that countries find it more profitable to act as a free-rider of the agreement.

Barrett (1994) and Carraro and Siniscalco (1993) obtain their results within the framework of a symmetric model. More recently, several papers have qualified these pessimistic results assuming heterogenous countries. See, among others, the papers written by Botteon and Carraro (1997), Barrett (2001), Chou and Sylla (2008), Weikard (2009), Fuentes-Albero and Rubio (2010) and Kolstad (2010). Fuentes-Albero and Rubio (2010) establish that asymmetry between countries has no important effect on the scope of cooperation in comparison with the symmetric case if transfers are not used or abatement costs represent the only difference among countries. However, when the difference is in environmental damages, the level of cooperation that can be bought through a self-financed transfer scheme increases with the degree of asymmetry. Fuentes-Albero and Rubio's (2010) analysis highlights that the transfer scheme must be designed to eliminate the individual incentive of a potential signatory to act as a free-rider of the agreement. Eyckmans and Finus (2004) define this kind of transfer scheme as an almost ideal sharing scheme. However, full cooperation cannot be expected since the incentives to deviate from the agreement increase quickly with cooperation.

[20] Barrett (1994) derives his results using numerical simulations. An analytical solution of the game can be found in Rubio and Ulph (2006).

3.1 Dynamic Setting

In all the previous papers, pollution is a *flow* variable. The first papers to analyze the stability of IEAs for a stock pollutant were Rubio and Casino (2005) and Rubio and Ulph (2007). The main difference of the Rubio and Casino (2005) model with respect to the previous literature is that they assume that in the second stage, emissions are given by the Nash equilibrium of the following *linear-quadratic differential game* of international pollution control: each nonsignatory country chooses the level of emissions that maximizes the present value of the stream of net benefits given the emissions path of rival countries including signatories

$$\max_{\{q_j\}} W_j = \int_0^\infty e^{-\delta t} \left(a q_j - \frac{b}{2} q_j^2 - \frac{c}{2} z^2 \right) dt,$$

where z stands for the accumulated emissions.

Signatory countries also take the emissions of nonsignatories as given and commit to a level of emissions that maximizes the discounted present value of the stream of net benefit of the agreement

$$\max_{\{q_i\}} W_i = \int_0^\infty e^{-\delta t} n \left(a q_i - \frac{b}{2} q_i^2 - \frac{c}{2} z^2 \right) dt,$$

where n stands for the number of signatories.

In both cases, countries face the same dynamic constraint

$$\dot{z} = \sum_{i=1}^{n} q_i + \sum_{j=1}^{N-n} q_j - kz,$$

where N is the total number of countries and k a positive rate of natural decay.

In the first stage, the (internal and external) *stability conditions* are defined in terms of the discounted present value of the net benefit. Rubio and Casino (2005) assume that once the countries initially decide to participate (first stage), membership is fixed during the second stage. A numerical simulation shows that a *bilateral* agreement is the unique self-enforcing IEA regardless of the gains from cooperation and the kind of strategies played by the countries (open-loop or feedback strategies). Thus, this dynamic extension of the model analyzed by Carraro and Siniscalco (1993) does not change the nature of the game played by the countries in the first stage. Once again the game presents positive spillovers for nonsignatories stemming from cooperation, such that an agreement with more than two countries is not stable.

Rubio and Ulph (2007) take a step forward assuming that membership is variable. Using a *difference game* with linear benefits from emissions and quadratic environmental damages, they study the membership of an infinite sequence of IEAs, in which, in each period, countries are free to join or to leave the agreement. Thus, in each period, they first solve the two-stage game of the static model for a given stock. Then, given the equilibrium of the game they can compute the stock for the next period. Since they assume that all countries are identical, all they could determine is the number of signatories as a function of the pollutant stock so that to make progress, they assume that in each period there is a *random process* for determining which countries become signatories, such that the probability of any country being a signatory in that period is simply the membership of the stable IEA in that period divided by the total number of countries. So each country has the same *expected* value function, which will depend on the stock of the pollutant at the start of next period. Then, adding the value functions for signatories and nonsignatories weighted by the probability of being a signatory or a nonsignatory, they obtain an equation which implicitly defines the expected value function. Unfortunately, there does not exist a quadratic value function that satisfies the implicit equation obtained in the paper. However, they devise an *algorithm* that allows them to approximate the value function by a quadratic function of the stock and to derive some *numerical* results. They show that there is a steady-state pollution stock with corresponding steady-state IEA membership and that as the stock rises towards the steady state, IEA membership falls. Moreover, they find that the greater the environmental damages, and hence the greater the potential gains from cooperation, the smaller the membership of a self-enforcing IEA. Thus, assuming that membership is variable yields different results as regards participation in an IEA, but they remain rather pessimistic about the scope of cooperation.

The previous models assume that all the countries are identical so that transfers cannot play any role in stabilizing the agreement. Bosello et al. (2003) and Carraro et al. (2006) used integrated assessment simulation models of climate change to analyze which could be the effects of the use of transfers over the participation in an IEA. In both papers, stability conditions are analyzed in terms of the discounted present value of social welfare, as in Rubio and Casino (2005). Bosello et al. (2003) check whether the conjecture that a more equitable sharing of the costs of controlling emissions would induce developing countries to sign a global climate treaty is supported by empirical evidence. Their results show that while equity increases the profitability of a climate agreement, it does not offset the incentives to free-ride. A similar analysis is performed by Carraro et al. (2006). They test the effects of different transfer schemes on stability. The transfer schemes are the Shapley Value, the Nash Bargaining solution, the Chander and Tulkens (1997) transfer scheme and the almost ideal transfer schemes defined by Eyckmans and Finus (2004).[21] The results show that the latter promote more cooperation although, full cooperation is not achieved in any case. Nevertheless, we should not be very optimistic, because the results obtained by these authors indicate that there is a conflict between equity and stability that is the same as saying that we face a conflict between equity and efficiency. On the one hand, if the focus is on equity, the analysis shows that the transfer schemes that promote equity do not promote participation, i.e. they do not belong to the family of almost ideal transfer schemes. On the other hand, if the focus is on participation, the almost ideal transfer schemes can require developing countries that suffer large environmental damages to have to buy the cooperation of developed countries that suffer lower damages to stabilize an agreement with a high level of participation.

Another paper that warrants some comments is de Zeeuw (2008). In this paper, de Zeeuw uses the concept of *farsightedness,* introduced in the literature by Chwe (1994) and Ray and Vohra (2001) and applied to IEAs by Eyckmans (2001) and Diamantoudi and Sartzetakis (2002) to evaluate the participation in an IEA in a dynamic context. For de Zeeuw (2008), the stability conditions are defined assuming that countries are *myopic,* since they take their decision on participation in an IEA assuming that the other countries are not going to change their decision, a typical feature of the Nash equilibrium concept. As an alternative, the concept of farsightedness implies that countries realize

[21] The Chander and Tulkens' transfer scheme and the Shapley Value are addressed in detail in Section 5.

that a deviation may trigger further deviations, but they do not necessarily assume a full breakdown. The idea is that such a sequence of deviations ends when a new stable situation is reached. If a nonsignatory in that new situation is worse off than a signatory in the initial situation, deviations are deterred. Diamantoudi and Sartzetakis (2002) find, in the framework of a static model with identical countries, that there exists always a unique set of farsighted stable IEAs. Farsighted IEAs can be much larger than those supported by the myopic stability concept, but are not always Pareto efficient. Similar results are obtained by Eyckmans (2001) using the CLIMNEG dynamic integrated assessment model. The simulations calculated by Eyckmans (2001) working with discounted present values show that the Kyoto coalition is more stable than suggested by the myopic stability concept, but that the stability analysis is very sensitive to the coalitional surplus sharing rule, i.e. to the transfer scheme used by the agreement. de Zeeuw (2008) extends this analysis to a dynamic framework. His paper investigates how interaction between the behavioral reaction pattern that the concept of farsightedness implies and the adjustment process of the emissions affects the results on the stability of coalitions. He proposes a simple abatement model with identical countries and exogenous growth of global emissions where the level of emissions is the state variable and the abatement level the control variable. The paper uses numerical examples to show that if it takes time to detect deviations, trigger mechanisms may not work. The reason is that abatement occurs during that time and therefore the level of emissions decreases before detection. It follows that costs will have decreased, and therefore the threat of triggering a smaller coalition may not be sufficient to deter defections anymore. This leads to the conclusion that large coalitions can only be stable if damage costs are very small in comparison to abatement costs.[22] This result reproduces in a dynamic context the result derived by Barrett (1994) in a static context: participation can be high, but only when the gains from cooperation are low.

[22]Biancardi (2010) has shown that the result changes if damage costs are linear. Biancardi (2010) solves a *linear state game* with a stock pollutant where damage costs depend linearly on the stock and finds a positive relationship between environmental damages and the size of coalitions when the concept of farsightedness is used.

More recently, Breton et al. (2010) presented an analysis of the stability of IEAs with a flavour of evolutionary games. In the paper, they solve a *difference game* with quadratic utility and linear environmental damages where, as part of the agreement, each signatory has to punish nonsignatories. This behavior originates a *non-environmental cost* supported by signatories which creates an asymmetry between signatories and nonsignatories that are identical *ex-ante*. They solve the game in three stages assuming variable membership as in Rubio and Ulph (2007). First, they calculate optimal emissions and value functions for a given number of signatories. Using the value functions, they apply the standard stability conditions to determine initial participation, as in Rubio and Casino (2005), but then they assume that the proportion of signatories changes over time following discrete-time *replicator dynamics*[23]

$$s_{t+1} = s_t \frac{V^S(s_t, P_t)}{s_t V^S(s_t, P_t) + (1 - s_t) V^D(s_t - \frac{1}{N}, P_t)} \text{ if } s_t \in [1/N, 1],$$

where V^S and V^D are the discounted present welfare of a signatory and a nonsignatory respectively, P_t is the pollution stock, N the total number of countries and s_t is the fraction of countries that sign the agreement. Replicator dynamics captures the notion that a strategy yielding welfare that is above (below) average increases (decreases) the relative share of the population using that strategy and that the "speed" of change depends on relative welfare inequality.

The numerical simulations of the game yield that the steady-state equilibrium in which no country joins the IEA is always possible, but provided that sanctions are strong enough and/or that the cost of punishing is not too high, this equilibrium coexists with either a *partial-cooperation* solution or with *full cooperation*. When two equilibria coexist, initial conditions are decisive: if the initial coalition is not large enough for a given initial level of pollution stock, the equilibrium is full defection, which can be interpreted as a minimum participation clause. Finally, they find that the number of signatories in a stable IEA is inversely related to environmental damages or, equivalently, to the gains

[23] Replicator dynamics has been used in common-pool resource games to describe the evolution of a population of agents, where two behaviors can be adopted. See for instance Sethi and Somanathan (1996), Noailly et al. (2007) and Osés-Eraso and Viladrich-Grau (2007).

coming from cooperation. The same result was obtained by Barrett (1994) and de Zeuuw (2008).

4 IEAs Supported by Trigger Strategies. Cooperation without Binding Agreements

Binding agreements cannot be implemented in all circumstances. In fact, in the international arena, the agreements signed by sovereign countries are rarely completely binding. This leads the analysis of international cooperation on environmental problems to a different framework to that that used in the previous sections. In this framework, the issue of the scope of international cooperation on pollution control becomes more complicated given the dynamic nature of the problem. Thus, although a lot of work has been done on the issue of cooperation in a dynamic setting using *repeated games*, the same cannot be said for *differential games*. In order to understand this difference, it should be taken into account that the dynamics of repeated games is simpler than the dynamics of differential games. In a repeated game, a combination of actions always yields the same "current" payoffs for the players, whereas for differential games this is not the case, as payoffs depend on the combination of actions and state and the state evolves over time depending on the players' actions. Differential games address richer dynamics than that addressed by repeated games. For this reason, it is not trivial to translate the results obtained in the framework of this literature to the literature on differential games. Maybe, this could explain why the literature on IEA without binding agreements is scarce. Thus, we consider it appropriate to begin this section by commenting some of the results regarding the joint exploitation of a productive asset, a model that shares many similarities with the dynamic pollution game addressed in this paper.[24] The first papers that study the stability of cooperation in the joint exploitation of a productive asset were published in the eighties by Hämäläinen et al. (1984, 1985), Cave (1987) and Kaitala and Pohjola (1988).

[24]The main difference is that the dynamics of these types of models are more complex than the dynamics of the basic model presented in Section 2, because they include a stock growth function that is not usually linear in the differential equation that describes the evolution of the system.

Hämäläinen et al. (1984, 1985) use numerical examples of different types of fisheries to show that the use of retaliation threats can be *effective* to support a cooperative solution as an equilibrium. They study a differential game with two countries and use the Kalai-Smorodinski solution to calculate the cooperative solution. The authors assume that if a country deviates from the agreement, it takes a time τ before it is detected. Then, once cheating is detected, the other country will switch immediately to a punishment strategy for a period h after which a new bargaining problem will be solved for the resumption of cooperative behavior.[25] The numerical examples developed by Hämäläinen et al. (1984, 1985) show that there exist values for τ, h and a constant punishment harvest rate that from the initial state eliminate the incentive to cheat. However, they do not check the credibility of this kind of trigger strategy.

Cave (1987) analyzes whether an agreement could be stable in the model proposed by Levhari and Mirman (1980) to study the joint exploitation of a renewable resource by two countries. This model is defined in discrete time. The payoffs depend only on consumption (extraction rate) and the stock evolves according to a concave function that depends on previous stock less total extraction. Using a logarithm function for the payoffs and an exponential production function, Levhari and Mirman show that there exists a unique Markov-perfect Nash equilibrium in linear strategies such that players consume a constant fraction of the stock in each period.[26] Using this result as a basis Cave (1987) concludes that cooperative extraction rates can be supported by the simple and credible threat that greets any defection with an immediate and irrevocable return to the Markov-perfect Nash equilibrium. As the author recognizes, this approach is suited

[25] As in differential games time is continuous, punishment begins at the same time defection has been detected.

[26] Dutta and Sundaram (1993a) deliver a complete characterization of the set of Markov-perfect Nash Equilibria (MPNE) of dynamic common-property resource games *à la* Levhari and Mirman (1980). They use an example to show that MPNE could lead to the reverse phenomenon of underexploitation of the resource, although the MPNE are always inefficient. A similar result was obtained by Dockner and Sorger (1996) for a continuous-time version of Levhari and Mirman's (1980) model. Finally, Dutta and Sundaram (1993b) study the equilibria of these kinds of games assuming that the resource can have a positive effect on player utility.

to situations where the players can communicate but cannot make binding commitments. Cave also shows that cooperation can be supported by punishments that can be Pareto superior to the reversion to the extraction rates corresponding to the Markov-perfect Nash equilibrium. Kaitala and Pohjola (1988) present a model of joint exploitation of a renewable resource in continuous time in the line of the previous works by Hämäläinen et al. (1984, 1985) with efficient memory equilibria. In their model, the harvest is given by the multiplication of the fishing effort and the stock and the net revenue of the countries is linear with respect to the fishing effort which cannot be larger than a given upper bound. As in Cave (1987), if one of the countries deviates from the agreement, then both countries continue extracting the resource in a noncooperative way for the rest of the game. The problem is that in continuous time it is not easy to incorporate memory into the strategies of the players. The approach followed by Kaitala and Pohjola (1988) to overcome this difficulty was introduced by Tolwinski et al. (1986). Their approach utilizes the concept of $\tau-$strategies first proposed by Friedman (1971). According to this approach, the players divide the time horizon into intervals of an arbitrary length τ in order to sample the resource system at the time points $t_j = j\tau,\ j = 0, 1, 2, ...$ Sample information is used to make decisions about harvesting during the following time interval $[t_j, t_{j+1})$. Then, the resource is monitored at regular intervals, the length of which is τ. However, a pair of $\tau-$strategies can fail in providing an equilibrium if the time interval τ and the discount rate are large. In order to guarantee that a pair of $\tau-$strategies can be utilized to sustain cooperation, the players define their strategies as an infinite sequence of $\tau-$strategies, where τ tends to zero. When these kinds of strategies are used, cheating will be detected without delay. Hence, the only actual choices the countries need to make are between cooperation and noncooperation and the trigger strategies produce a subgame perfect equilibrium.

Benhabib and Radner (1992) and Rustichini (1992) extend the analysis of trigger-strategy equilibria to a model similar to Levhari and Mirman's (1980) model, but in continuous time. Benhabib and Radner (1992) assume that the utility is *linear* in consumption and independent of the stock and that consumption is constrained by an upper bound that is defined by fast consumption strategies. The authors show that these extreme strategies are a Markov-Nash equilibrium for some values of the initial stock, so that for these values extreme strategies can be used to sustain cooperation.[27] In both papers, the trigger strategy implies that after a player detects that a defection has occurred, the country consumes the asset as fast as possible so that in a finite period of time the stock is exhausted. Thus, players seeing the imminent demise of the asset would face strong pressure to reconsider their deviation. They assume that each player can observe the stock of the asset with a fixed delay, i.e., at time t each player can observe the *history* of the state variable up through time $(t-\tau)$, where the delay τ is a fixed, positive parameter of the model. In the same line as the papers in continuous time, we have just reviewed, once the deviation is detected, the other country will switch immediately to a punishment strategy. Thus, Benhabib and Radner (1992) show that the existence of a trigger-strategy equilibrium depends not only on the discount rate and detection technology, but also on the initial level of the state variable. The analysis of the trigger-strategy equilibria for this class of dynamic games is extended by Dutta (1995) to infinite horizon stochastic games with perfect monitoring in discrete time.[28] He shows that the folk theorem of repeated games also applies for stochastic games under certain conditions. First, he imposes asymptotic state independence and uses one of the following two assumptions on the set of feasible long-run average payoffs: payoff asymmetry or full dimensionality. This last assumption requires the dimension of the set of feasible payoffs to be the same as the number of players.

The first analysis of international cooperation for pollution control based on the use of trigger strategies was presented by Dockner et al. (1996) for a model of two countries in discrete time. They assume a *linear* utility function for emissions and a strictly convex damage function. Given the linearity of payoffs with respect to the control variable, the *most rapid approach path* to the cooperative steady-state value of the stock is optimal. They show that the game admits at least two Markov-perfect Nash equilibria. One equilibrium that generates fast convergence to a steady-state pollution stock as occurs with the cooperative solution and another equilibrium that can lead to very complicated

[27] Rustichini (1992) obtains a similar conclusion for a larger class of utility functions.

[28] A dynamic game can be seen as a stochastic game where the law of motion is deterministic.

dynamics and has the particular feature that each player is indifferent about all of the possible choices. The authors call such an equilibrium a make-the-opponent-indifferent (MTOI) equilibrium. This kind of strategy constitutes a Nash equilibrium for the pollution control game under some linear constraints on the damage functions of the two countries and can be used, under some conditions, as a trigger strategy to sustain the cooperative solution. One of these conditions is that the discount rate must not be too large.[29] Another interesting paper where international cooperation between two countries aimed at controlling pollution emissions is addressed is Jørgensen and Zaccour (2001a). These authors use the model in Section 2 with investment in clean technologies, but without discounting and for a finite temporal horizon to show that the cooperative solution can be achieved as an *incentive equilibrium* in which each country uses an emissions strategy that is linear in the other country's emission level. An incentive equilibrium has the property that when one player implements the strategy, the other player can do no better than to act in accordance with the agreement. Moreover, the incentive strategies are credible.[30] The authors compute linear incentive strategies and find that the slopes of these strategies are given by the ratios of marginal damage costs. These ratios are positive and constant over time due to the assumption that the damage costs are linear with respect to the pollution stock. The authors also study the bargaining problem of allocating joint welfare between the two countries, where the status quo is given by an open-loop Nash equilibrium. They adopt the *egalitarian principle* which gives an equal division of the surplus of cooperation. This approach ensures that the *global individual rationality* condition is satisfied. This condition establishes that for the entire duration of the agreement, in the cooperative solution each country receives a payoff which, after side payments, is no less than the disagreement payoff of the country. Moreover, they suggest a decomposition over time of the total net welfares such that *instantaneous individual rationality* is assured. This means that at any time the net instantaneous welfare

[29] Yanese (2005) extends the Dockner at al. (1996) analysis to the case of a linear utility function for emissions with flow externalities, i.e. to the case where the utility of one country depends on its own emissions and also on the emissions of the other country.

[30] This concept of equilibrium has been used in resource exploitation games by Ehtamo and Hämäläinen (1993).

obtained by each player dominates his net instantaneous noncooperative welfare. The decomposition over time proposed by these authors recommends allocating players their instantaneous equilibrium welfare plus the cooperation dividend at each moment in time. The cooperation dividend is defined as the difference between a player's total net cooperative welfare (after side payments) and total noncooperative welfare, divided by the duration of the game.

More recently, Dutta and Radner (2009, 2010) and Mason et al. (2011) have again taken up the analysis of international cooperation for pollution control without binding agreements. Dutta and Radner (2009) use a simpler version of the difference pollution game presented in Dutta and Radner (2004). Given the linearity of the game with respect to the state, they obtain that both efficient emissions and noncooperative emissions are constant. They show that for the *best equilibrium* that can be supported by trigger strategies, the emissions are also constant, albeit lower than noncooperative emissions.[31] Trigger strategies that utilize the *worst equilibrium* for each player, are asymmetric and have a two-stage structure. In the first stage, and for exactly one period, all countries other than the deviant emit a greater amount than noncooperative emissions. This reaction punishes all countries. However, in the second stage, the sanctioning countries select an equilibrium that maximizes a weighted sum of equilibrium payoffs, with zero weight on the sanctioned country. In such an equilibrium, the country with zero weight typically has to choose a very low level of emissions. This is therefore the long-term punishment that a country suffers for deviating from an agreement. Its emissions are permanently reduced in incentive-compatible fashion. Dutta and Radner (2010) present an extension of Dutta and Radner (2009) to allow for exogenous capital accumulation. Their analysis shows that even with low discount factors, the threat of reverting to the noncooperative equilibrium is not sufficient to deter the growth in emissions of the fastest growing economies. However, these countries can be encouraged to cut emissions if the slower growth economies are willing to make transfers to them.

Mason et al. (2011) claim that as the trigger strategies used in the previous papers imply that once a country deviates from the agreement, punishment begins and continues

[31] Second-best emissions coincide with efficient emissions provided the discount rate is not too large.

forever, they are not robust against renegotiation because the countries can do far better by restarting an agreement. In order to avoid this criticism, the authors propose a *two-part punishment strategy* that ensures punishment is sufficiently severe to deter cheating and that all countries have an incentive to carry out the punishment if called upon to do so.[32] The authors propose a difference game where utility and damages are non-linear and identify conditions under which a two-part punishment strategy can support the first-best outcome as a subgame perfect equilibrium. Using a simulation model, they find that whether or not the two-part punishment strategies lead to a self-enforcing agreement depends non-monotonically on the discount factor. They also find non-monotonicity regarding the marginal utility and damages: the two-phase agreement does not support cooperation when the slope of the marginal utility is too great or too small relative to the slope of marginal damages. Finally, their numerical simulations demonstrate that the agreement may be self-enforcing as the pollution stock becomes sufficiently large while that is not the case for lower stocks.

5 Cooperative IEAs Sustained by Transfers

A classical distinction between cooperative and noncooperative games is that the cooperative approach allows *binding agreements* while noncooperative games do not. However, this distinction is difficult to apply to the literature on IEAs. In the games analyzed by Barrett and others, which were commented on in Section 3, the countries sign binding agreements, but the approach is noncooperative. The reason is that the countries decide to participate in a strategic way, i.e. participation is given by the Nash equilibrium of the first stage. In the literature reviewed in this section, the approach is different, as the authors avoid dealing with individual decisions and tend to focus on the set of

[32] This kind of two-part punishment strategy has been analyzed by Polasky et al. (2006) and Tarui et al. (2008) in the framework of a common-property renewable resource game. Though extraction from a common-property resource shares many similarities with the dynamic pollution game surveyed in this paper, one important difference is that environmental damages are potentially unbounded, whereas in a resource model the worst payoff a player can receive is zero.

possible outcomes of the negotiations and the conditions that might be "reasonable" or "appealing" or "fair" to impose on an acceptable outcome. The first papers to apply this approach to the study of international cooperation for controlling pollution emissions were published by Chander and Tulkens (1995, 1997). In these papers, the *core* of an IEA formation game with transferable utility is studied.[33] Usually, these games are described in *coalition form*, $\Gamma = (N, w)$, where N stands for the set of players and w for the *characteristic function*. The characteristic function associates to each coalition $S \subset N$ a unique real number $w(S)$. Chander and Tulkens propose a characteristic function, called the γ-*characteristic function,* which associates to each coalition the maximum aggregate payoff that the coalition can guarantee to itself assuming that players outside the coalition behave as singletons and act strategically to maximize their payoffs taking as given the emissions of the other players including those forming the coalition. Thus, the γ-characteristic function $w^{\gamma}(S)$ associates to the coalition the payoff corresponding to a *partial agreement Nash equilibrium with respect to the coalition.* Once the characteristic function is defined, an *imputation* is a payoff vector that gives each country at least as much as the country can obtain in the fully noncooperative equilibrium (individual rationality) and gives all countries together $w^{\gamma}(N)$ (group rationality). Thus, an imputation is a way of sharing the benefits of cooperation that satisfies *individual* and *group rationality* so that the set of imputations contains all reasonable outcomes for a cooperative game. From this set, the *core* of the game, denoted $C(N, w^{\gamma})$, selects all the imputations that are not dominated.[34] In Chander and Tulkens (1995) the following imputation is proposed[35]

$$y_i^{CT} = TC_i^* + T_i = C_i(E_i^*) + D_i(E^*) + T_i,$$

[33] Transferable utility means that each coalition of players can achieve a certain total amount of utility that it can freely divide among its members in any mutually agreeable fashion. Then, transferable utility exists in a game where all outcomes are measured in money and any amount of money that is achievable by a coalition can be divided arbitrarily among the coalition members.

[34] An imputation x is dominated by y via the coalition K if y gives more to the members of K than x and y^K is achievable by K, i.e. $\sum_{i \in K} y_i \leq w^{\gamma}(K)$.

[35] Chander and Tulkens (1995) develop their analysis in terms of the total costs of controlling emissions, see the model presented in Section 2.1, whereas Chander and Tulkens (1997) use a social welfare function.

where the transfer T_i is given by

$$T_i^{CT} = -\left[C_i(E_i^*) - C_i(\bar{E}_i)\right] + \frac{D_i'}{D_N'}\left[\sum_{i\in N} C_i(E_i^*) - \sum_{i\in N} C_i(\bar{E}_i)\right].$$

In this expression $D_N' = \sum_{i\in N} D_i'$ and $\bar{E}_i$ and E_i^* stands for the fully noncooperative equilibrium emissions and the emissions that minimize joint global costs respectively. Thus, each individual transfer consists of two parts: a payment to each country which covers its increase in abatement costs between the fully noncooperative equilibrium and the (fully) cooperative solution (first squared bracket), and a payment by each country of a proportion D_i'/D_N' of the total of these differences across all countries (second squared bracket). It is easy to show that if the damages are linear, the imputation proposed by Chander and Tulkens (1995) implies a distribution of the surplus of cooperation in the proportion D_i'/D_N'

$$y_i^{CT} = T\bar{C}_i + \frac{D_i'}{D_N'}\left[\sum_{i\in N} TC_i^* - \sum_{i\in N} T\bar{C}_i\right]$$

which guarantees the individual rationality of the imputation. Chander and Tulkens (1995) show that their imputation belongs to the core. However, their result is not fully general as they obtain it only under two alternative assumptions: either linearity of the damage cost function D_i, or identical abatement cost functions C_i for all countries.[36] Then if y^{CT} is the solution proposed, no coalition S can improve their payoffs by coming to an arrangement of its own. It is the threat of breaking up into singletons of those players not in S that prevents this free-riding behavior for coalition S, and it is also what induces full cooperation[37].

Unfortunately, the behavior assumption made for players outside the coalition is not entirely compulsory. Why should they stay singletons? Note that when players in S break the grand coalition N, players in $N\backslash S$ will be better off if they make a joint minimization

[36] Helm (2001) shows that the core of the game (N, w^γ) is non-empty even when the imputation y^{CT} fails to belong to the γ-core. The proof relies only on standard convexity assumptions and, therefore, substantially generalizes the results obtained by Chander and Tulkens.

[37] A further discussion on the γ-characteristic function in the setting of infinitely repeated games is given in Chander (2007).

against S than if they remain as singletons. Moreover, with positive spillovers the coalition S will receive an overall greater payoff. Hence we can suspect that coalitions have more free-riding incentives as precluded by the γ-characteristic function. For example, Uzawa (2003) shows that the core of a global warming game that does not assume that countries in $N \backslash S$ dissolve into singletons may be empty.

Next, we would like to refer to one of the most prominent solutions used in cooperative games that has also been applied in the analysis of IEAs: the Shapley (1953) Value. The Shapley Value can be calculated for any game in coalition form having a finite number of players, and it has the further advantage of giving a unique outcome that satisfies both individual rationality and group rationality, although its main appeal is that it selects an imputation that satisfies a fairness criterion. The payoff to each player is a weighted average of the contributions that the player makes to each of the coalitions to which its belongs, with the weights depending on the number of players, n, and the number of members in each coalition, s.

$$\phi_i(w) = \sum_{S \subseteq N:\ i \epsilon S} \frac{(n-s)!\,(s-1)!}{n!}\left(w(S) - w(S \backslash i)\right).$$

Nevertheless, the applicability of the Shapley Value for the study of IEAs is limited by two problems. Firstly, there are no guaranties that the Shapley Value belongs to the core of a game. Sufficient conditions (such as the convexity of the characteristic function w) are not given for the global warming games. Secondly, the number of coalitions for which we need to compute $w(S)$ is 2^{n-1}. This number increases exponentially with the size of the grand coalition making the computation of the Shapley Value extremely costly, at least for practical purposes.

5.1 Dynamic Setting

One of the requirements for implementing a cooperative agreement is that the agreement be individually rational. Individual rationality is easy to define in a static context, but in a dynamic setting it can have different interpretations. Consequently, there are several notions of individual rationality that have been used in the literature. Kaitala and Pohjola (1995) use the notion of agreeability (see Section 2.1 for an explanation of this idea of dynamic individual rationality). Jørgensen et al. (2003, 2005) use another notion of dynamic individual rationality, namely: time consistency. This condition is weaker than the agreeability condition since it requires the same as the agreeability condition but only along the cooperative state trajectory. Jørgensen at al. (2003) identify conditions under which time consistency and agreeability can be verified in linear-state differential games with and without side payments, and illustrate their results using a linear-state differential game of international pollution control. They find that any allocation of the surplus of cooperation defined in terms of the discounted present value of the stream of instantaneous welfare at each point of time satisfies time consistency and agreeability. The authors suggest different allocation rules. One of them is to allocate the surplus in proportion to the ratio of a country's noncooperative emissions to cooperative emissions. Given the structure of the game, this ratio and the side payments are constant. In Jørgensen et al. (2005), the authors extend the analysis to the case of linear-quadratic differential games. They show that the cooperative solution with side payments is agreeable and therefore time-consistent, if the egalitarian principle is used to allocate the surplus of cooperation between the different countries, although in this case the transfers are not constant.

Other authors such Jørgensen and Zaccour (2001b), Petrosjan and Zaccour (2003), and more recently Fanokoa et al. (2011) focus on the intertemporal decomposition of the discounted present value of the stream of instantaneous welfare after side-payments have been made at the initial point of time. Petrosjan and Zaccour (2003) analyze an infinite-horizon cooperative game of pollution control in continuos time $(N, w(P(t)))$, $t \in [0, \infty)$, where each country minimizes the total cost of emissions abatement.[38] The characteristic function of the pollution game is given by the minimum total cost of the coalition calculated assuming that the countries that are not in the coalition select the level of emissions corresponding to the feedback Nash equilibrium.[39] Using this characteristic

[38] Jørgensen and Zaccour (2001b) address the intertemporal decomposition of the initial side-payments in a differential game of downstream pollution.

[39] The rationale behind this characteristic function is that the fully noncooperative game is seen as a business-as-usual (BAU) scenario. Moreover, the authors claim that this approach simplifies enormously the computations. Zaccour (2003) shows that this characteristic function coincides with the

function, the allocation of the total cooperative cost among the countries is based on the Shapley Value.[40] Once transfers have been made at the initial point of time to give to each country its Shapley Value, the authors propose an intertemporal decomposition scheme or *imputation distribution procedure* of the initial Shapley Value of each country that is time-consistent. In order to satisfy this property the imputation distribution procedure must allocate the following amount to country i at time t,

$$\beta_i(t) = r\phi_i(w(P^*(t)) - \frac{d}{dt}\phi_i(w(P^*(t)).$$

This formula allocates a cost corresponding to the interest payment (interest rate times its discounted present value of total costs under cooperation given by its Shapley Value) minus the variation over time of this discounted present value of total costs at time t to country i .[41] The authors illustrate the procedure to calculate the intertemporal decomposition of the Shapley Value using a simplified linear-state differential game of international pollution control with three identical countries. They find that the allocation obtained belongs to the core, although they do not present general results for inclusion in the core.

A first application of the Chander and Tulkens' transfer scheme in a dynamic setting can be found in Germain et al. (1998, 2003). The authors analyze a dynamic cooperative game of pollution control in discrete time with a finite planning horizon $(N, w^{\gamma}(P_t))$, $t = 1, ..., T$ where P_t stands for the pollution stock. The main difference with respect to the static approach is that the fully noncooperative Nash equilibrium is not considered as a

γ-charateristic function if the differential game is of the linear-state variety.

[40] A first application of the Shapley Value in a dynamic setting can be found in Filar and Gaertner (1997). In this paper, the Shapley Value is used to allocate the total emissions among four regions in a global warming game. Trade flows between regions are used to measure the strength of all possible coalitions and to define their characteristic function values. In their approach, the characteristic function is given exogenously and then the problem of fixing the behavior of players outside each coalition is avoided.

[41] As remarked in Zaccour (2008), the procedure to obtain a time-consistent imputation distribution procedure given by this formula is completely general and can be used for any solution concept, other than the Shapley Value. For instance, in Fanokoa et al. (2011), instead of the Shapley Value the authors use the egalitarian principle to allocate the surplus of cooperation between the two players of the game.

reference in order to compute the transfers. Instead of that the authors use the *fallback noncooperative equilibrium*. The idea behind this concept is the following: in each period t countries know that later on, thanks to the cooperative transfers to which they will have access, they will be better off than at the noncooperative equilibrium. Hence, the reference point at time t is noncooperation at time t, followed by cooperation afterwards.[42] In other words, the authors assume that players have *rational expectations*. In this way, the γ-characteristic function of the game can also be computed for each period t. Then, under certain conditions the following transfer scheme induces γ-core imputations at each t

$$\tilde{T}_i^{CT}(P) = -\left[C_i(E_i^*) - C_i(E_i^V)\right] + \tilde{\mu}_i(P^*)\left[\sum_{i\in N} C_i(E_i^*) - \sum_{i\in N} C_i(E_i^V)\right],$$

where

$$\tilde{\mu}_i(P^*) = \frac{F_i'(P^*)}{\sum_{j\in N} F_j'(S^*)}$$

with $F_i(S^*) = D_i(S^*) + r\tilde{y}_i^{CT}(S^*)$ where r is the discount factor, $\tilde{y}_i^{CT}(S^*)$ is the imputation or value function of the next period and E_i^V stands for the emissions corresponding to the fallback noncooperative equilibrium. The paper ends with the description of a numerical algorithm that calculates the value functions and the transfers when the cost functions are convex. Germain et al. (2010) extend these results to a two-dimensional setting of pollutant emissions and investment in capital goods for the linear damage case.

Finally, to end this section we would like to comment the papers published by Yeung (2007) and Yeung and Petrosyan (2008). Yeung (2007) extends the analysis of time consistency to a differential game of transboundary industrial pollution with linear damages. A noted feature of the game is that the industrial sectors remain competitive among themselves, while the governments cooperate in pollution abatement. The imputation proposed in the paper give to each country at each point of time a share of the global welfare corresponding to cooperative solution proportional to the countries' relative sizes of noncooperative payoffs. The authors formulate a payment distribution scheme that

[42] Germain et al. (1998) focus on the linear damage case and use the noncooperative open-loop Nash equilibrium to calculate transfers and define the characteristic function, instead of the fallback noncooperative equilibrium used in Germain et al. (2003).

implements the imputation and guarantees time-consistency. In the last part of the paper the analysis is extended to the case where the dynamics of pollution accumulation is governed by a stochastic differential equation. In Yeung and Petrosyan (2008) regional environmental damages are incorporated into the stochastic version of the game.

6 Conclusions

The aim of this survey has been to review the economic literature on dynamic models of IEAs. The focus has been on international environmental problems that are caused by a *stock pollutant,* as are the cases of acid rain and climate change, which has led us to select only the papers that follow a differential game approach for the survey. From the review of the literature, the following conclusions can be drawn. In regard to the basic model, it is clear that while the interdependence in the dynamic model is richer than in the static model, the stylized results of the latter are robust, except for some particular cases presented by Zaganori (1998) and List and Mason (2001) and can also be found in a dynamic framework. Thus, the steady-state pollution stock of the noncooperative equilibria is usually larger than the steady-state pollution stock of the cooperative solution and the noncooperative equilibria are inefficient. Moreover, the feedback Nash equilibrium yields a larger stock of pollution than the open-loop Nash equilibrium. If we look at the scope and effectiveness of international cooperation, results depend on the approach used in the analysis. A first obvious distinction is between the noncooperative and cooperative approach and within the noncooperative framework, between the models that assume binding agreements and those that assume the contrary.

The analysis of cooperation with binding agreement from a noncooperative approach has proved particularly difficult when countries are free, in each period, to join or to leave the agreement. The main conclusion that can be obtained from the review of this part of the literature is that in the case of binding agreements transfers must be applied not only to guarantee individual rationality, but also to eliminate the incentives of some countries to act as free-riders of the agreement. However, the design of transfer schemes that promote cooperation in a dynamic framework are still to be developed. The main contribution to date is Carraro et al. (2006), but their analysis of the role of transfers is based on the assumption that the decision to participate in the agreement is taken at the initial moment and is based on discounted payoffs net of transfers, i.e. transfers only apply at the initial moment. However, in a dynamic context profitability (individual rationality) and stability conditions should be checked throughout the temporal horizon. Thus, we think that this is a line of research that has clearly not yet been exhausted. Another avenue for future research under a noncooperative approach would be to continue with the path opened by Breton et al. (2010). Practically all the literature based on binding agreements uses the Nash equilibrium concept or, in other words, the stability conditions to select the level of participation in an IEA. However, Breton at al. (2010) deviate from this approach to adopt an evolutionary perspective where the group (signatories versus nonsignatories) that performs better is joined by a fraction of new agents. Surely, it is time to investigate the scope and effectiveness of IEAs using equilibrium concepts other than the Nash equilibrium. The literature that has followed a noncooperative approach, but without assuming that the agreements are binding, has advanced more in the dynamic analysis of IEAs than the literature that assumes binding agreements, but at the cost of making particular assumptions. For instance, Dockner at al. (1996) show that trigger strategies can be used to sustain the cooperative solution but for a *linear* utility function. Furthermore, Dutta and Radner (2009) obtain the same results, but for a *linear* damage function. In both cases, the dynamics of model is simpler than that associated with the standard model where the utility function is concave and the damage function is convex. Mason et al. (2011) have studied the standard model in discrete time, but their main findings are based on numerical examples.

As regards the literature that has adopted a cooperative approach, it seems that the research has yielded more complete models than those elaborated under a noncooperative approach. The analysis presented by Germain et al. (2003) which proposes a transfer scheme that induces imputations which belong to the core in each period of time has no match in the literature based on a noncooperative approach. The problem with the cooperative perspective is that it yields very "optimistic" predictions with respect to participation in an IEA, which usually are not supported by the empirical evidence.

Finally, we would like to point out an extension of the basic model that could be very promising. We are talking about the model proposed by Xepapadeas (1995a): a differential game of international pollution control with endogenous technical change. In his model, incorporation into an agreement is seen as club membership, whereby all the members benefit from the investment efforts of each member, i.e. the level of technology is common to all signatories. In these circumstances, becoming a nonsignatory has a cost in terms of the level of technology level the country enjoys, which could compensate the benefits associated to the increase in emissions the nonsignatory can implement when it is not under the discipline of the agreement. The result is that cooperation could be stabilized at a high level of participation.

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