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MODELLING TRANSBOUNDARY POLLUTION: a review of the literature

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GAME-THEORETIC MODELLING OF TRANSBOUNDARY POLLUTION:

A REVIEW OF THE LITERATURE

by

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ABSTRACT

The purpose of this paper is to give an overview of the economic literature on transboundary pollution. In particular the focus is on the most recent literature which incorporates behavioural assumptions with the help of game theory. In the first section the general context is introduced, and particular problems pointed out. Next, the various game solution concepts which have been evaluated in the transboundary pollution context are depicted. In the last part, the issue of free riding concerning transboundary pollution abatement is analysed.

INTRODUCTION

Environmental externalities have always existed, but it was not until the second half of this century that they assumed a global scope. In the 1970s international concern about the depletion of the ozone layer and the greenhouse effect grew. At the United Nations Conference on the Human Environment in 1972, held in Stockholm, all the nations present agreed for the first time that responsibility had to be taken with respect to transboundary pollution. In particular it was stated that

> "States have in accordance with the charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other states or of areas beyond the limits of national jurisdiction."[1]

In addition, the Conference adopted the Polluter Pays Principle (PPP) which makes the polluter responsible for the costs of pollution abatement. However, merely stating this principle without any enforcement mechanism did not deter states from polluting other states without compensating them.

Currently a wide range of pollutants attract the attention of the international community. The safeguarding of international commons such as the atmosphere, the

[1]in: Principle 21 of 'The Declaration of the Human Environment' adopted by the OECD countries at the Stockholm Conference.

oceans, the tropical forest, the Antarctic and biodiversity necessitates the control of global pollutants. Examples of global pollutants are chlorofluorocarbons (CFC) and Halons which contribute to the depletion of the ozone layer, and carbon dioxide (CO_2) and methane which add to global warming. Sulphur dioxide, as a regional pollutant, leads to acid rain. Other types of transboundary pollution (TP) affect only a limited number of countries like the pollution of the river Rhine which mainly affects Germany and Holland.[2]

The notion of TP refers to pollution which is released in one country but which causes damage in at least one other country. While internalising pollution involving two parties at the national level is difficult, the problem is amplified if more than one country is involved; if within the borders of a country one party profits from pollution emissions, and another party is damaged, the national authorities could enforce sanctions against the polluters to benefit the pollutees. This is impossible at the country level because, under the rules of international law, private citizens of one country do not have the right to sue private citizens of another country. States can appeal to the International Court of Justice, but the convicted state can always refuse to comply with the Court's decision. The past twenty years have shown that, despite the theoretical acceptance of the PPP, it might become necessary to 'bribe' countries in order to give them an incentive for pollution abatement; this has been named the

[2] In this paper I will focus on global warming games and on acid rain games. However, there are also games in other areas, such as biodiversity (Barrett, 1994/b), ozone depletion (Heister, 1993) and international water resources (Kaitala and Pohjola (1988), Barrett, 1994/a).

Victim Pays Principle (VPP). This principle has been applied in practice for example when China was made concessions in order to comply with the Montreal Protocol.

The matter is further complicated when pollution affects more than two countries, and all of these countries are at the same time emitters. In the case of one-sided pollution the problem can be reduced to the question of 'who pays?'[3], but in the multi-party case the situation is more complex. A crucial question for instance is how to get individual countries to forgo attempts to free ride on the control efforts of others.

When analysing global pollution, most economists have focused on evaluating the aggregate costs and benefits of implementing international taxes or systems of tradable permits. However, in the past five years efforts have been made to incorporate behavioural assumptions in the analysis. It was recognised that a situation of environmental and economic conflict with several actors (countries) called for the application of game theory methods in order to analyse the problem, or even to give policy advice. While axiomatic game theory can reveal what potential gains are to be made from cooperation, and hence is able to deliver a further incentive for cooperation, non-cooperative game theory focuses on how strategies work and whether they are likely to have a positive impact on the final outcome.

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[3]The 'Coase theorem' for example shows that if it is possible to clearly define who has the property right over the use of an environmental asset, and subsequently allow bargaining among the owners and prospective users, an efficient level of environmental quality will be reached. This result, however, depends on the free availability of information.

One of the first thorough analyses in this area was done by Kuhl (1987) who examined static as well as dynamic aspects of international negotiations on transboundary pollution. In particular he identifies two types of ecological-economic interdependencies among countries. On the one hand there are indirect impacts related to decisions with respect to environmental allocation at the national level, and on the other hand there are direct impacts which stem from the fact that countries are connected 'ecologically' (i.e. transboundary pollution). The indirect impacts were discussed widely during the 70s and 80s. They concern the impact of national environmental policy regarding questions of balanced foreign trade and repercussions on international competitiveness via changes of relative prices. However, this type of (pecuniary) externality is internalised through adjustment processes on the world markets[4]. Thus, regarding allocation, there is no need for international coordination. This is different for the direct impacts due to transboundary pollution. As long as countries use environmental resources, such as air and water, in an uncoordinated way, there prevails the danger that one country over utilises this resource at the expense of other countries. Kuhl's analysis is purely theoretical.

One of the first attempts to estimate actual spillovers from transboundary pollution was undertaken by Mäler (1989) for the case of acid rain in Europe. Such estimation involves high degrees of uncertainty, not only because of the uncertainty relating to the magnitude and deposition of emission transport, but also because of the difficulties of evaluating the emissions-damage relationship. However, it is essential to evaluate the magnitude of transboundary spillovers if countries aim at coordinating their

[4]See for example Siebert, Eichinger et al (1980) or Gronych (1980).

environmental policy in the long-run. Some aspects regarding uncertainties with this type of analysis will be discussed below. Mäler's publication appears to have generated a wide range of analyses in this area of game theoretic applications to TP.

DIFFERENT TYPES OF TRANSBOUNDARY POLLUTION

Different types of TP demand different ways of modelling, and different specifications of damage and benefit functions. Appropriate modelling of these is essential for further game theoretic analysis. Before looking at the specification of functional forms we will discuss some more general aspects relating to the nature of pollution. Monitoring the transport of pollution is particularly important when TP involves substantial asymmetries. In the case of acid rain it is now possible with the help of meteorological modelling to trace the origin of acidic depositions. An emitter-receptor matrix was developed within the Norwegian 'European Monitoring and Evaluation Programme' (EMEP) which makes it possible to assign to each emission level of sulphur dioxide in country A the deposition level of this pollutant in country B (Mäler 1989, van Ierland 1990). The matrix purely represents a steady state relationship, and the differences between matrix-predicted and actual pollution transport may be substantial. Van Ierland not only considers the deposition of sulphur dioxide, but also of nitrogen oxide. Furthermore, he emphasises that it would also be important to incorporate the contribution of ammonia to acid rain as well.

In the case of global warming such direct attribution is not possible. Therefore it is generally assumed that all emissions contribute equally to global warming. Put another way, CO_2 is treated as a uniformly mixed pollutant[5]. Furthermore, analyses concentrate on the abatement of CO_2 which contributes according to the IPCC report to about 55% of the total greenhouse effect[6]. Economists have so far neglected the impact of other greenhouse gases which are emitted in smaller quantities, such as methane and nitrous oxides, but which have stronger per unit impact on global climate. An exception are the CFCs which are made responsible for the depletion of the ozone layer. Barrett (1994/c) analyses the question of why the Montreal Protocol, which deals with CFC abatement, is comparatively successful. He comes to the conclusion that a main reason for this is the Protocol set-up which makes it self-enforcing. It is, however, equally important to consider the nature of CFC pollution in this context. Unlike for global warming, there is no uncertainty about the effects of stratospheric ozone depletion. Furthermore the, thus apparent, benefits from abatement are huge while the actual abatement costs are small. The latter results from the fact that only a few companies world wide produce CFC. The small number of producers also makes regulation more easy.

Another problem arises from the fact that global warming will have different impacts on different countries. Some countries like Canada or the former Soviet Union may even gain from global warming (Cesar,1994;p.26). Yet, the uncertainty about the magnitude of benefits and damages is still substantial. Unless these aspects are

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[5]Please note that with CO_2 there is no physical deposit. The impact of the pollutant is indirect.

[6]see for example the IPCC report (1990).

clarified through further environmental research, economic models have to be based on the assumption that countries have similar incentives vis-à-vis global warming.

An aspect which has been neglected by economists so far is the interrelationship of global pollutants. Recent research, for example, reveals that SO_2 emissions can contribute to lowering the average temperature of the atmosphere[7]. It is certainly erroneous to think that therefore the emission of SO_2 could alleviate the problem of global warming; but this piece of research indicates that negotiations on TP should not only focus on a single pollutant or a single TP problem (such as acid rain)[8]. The overview of the problems encountered in TP analyses reflects the uncertainties involved with environmental issues. As a result, environmental economic studies can generally only give insight in the 'direction' of a country's optimal behaviour.

A way out of this dilemma was indicated by Ulph and Ulph (1994) who incorporate the possibility of learning in their analyses on global warming. In a two period, two player model the actors' strategic behaviour in view of a 'learning' and a 'non-learning' case are analysed. 'Learning' implies that the actors will get to know the true state of the world, i.e. they will learn to what extent greenhouse gases turn out to be harmful. Consequently they can choose the level of emissions in the last period on this basis. In the 'no-learning' case, on the other hand, they will only get to know the

[7]See Charlson, R. J. and T. M. L. Wigley (1994).

[8] It should also be noted that the synergetic effects of pollutants may just as well aggravate the damage. One might think for example of how the combination of tropospheric ozone and sulphur dioxide exacerbate the impact of acid rain.

true state of the world after they have chosen their emission level. Their main conclusions are that

> "learning is much more likely to cause emissions to be lower than they would be without learning, and this can be true of individual or of all countries; in other words, the fact that it may be possible to learn more in the future about the extent of damages is much less of a reason for governments to delay reducing emissions than would be the case if there was a single government"[9]

What is more, they find that if there is a possibility of learning in the future, the gains which are to be made from cooperation are higher than in the no-learning case.

Apart from monitoring the transport of pollution, it is necessary to evaluate its costs and benefits. In the face of uncertainties about both environmental damage and abatement costs, this turns out to be not a trivial task. Nordhaus (1991), for example, undertakes an analysis on abatement costs regarding greenhouse gases. He evaluates point estimates which assign to a target level of emissions reductions a certain international carbon tax rate. Nordhaus joins these point estimates so as to give an approximation of a marginal cost curve of CO_2 abatement. This evaluation corresponds to the 'top-down' approach in simulation analysis where, among other things, the welfare effects from different policies to reduce emissions are calculated. The other main approach is the 'bottom up' approach and involves the direct costing of implementing abatement technologies. Nordhaus' cost curve is the basis for various

[9]in: Ulph, A. and D.Ulph (1994), p.28.

game theory applications to the global warming problem (Fankhauser and Kverndokk (1992), Barrett (1992/a)). In the face of the large amount of uncertainty already involved in Nordhaus' estimations, the results of the game theory analyses can merely reflect a 'direction' or 'trend'. Where a 'bottom up' approach is feasible less uncertainty will be attached to estimates on abatement costs. Its feasibility is linked to there being a small number of polluters. For example where pollution of a river, such as the Rhine, is concerned, or when there is only a limited number of 'producers' of a pollutant (e.g. the production of CFCs).

Estimating damages resulting from TP proves to be even more difficult. Mäler (1989) applies a 'trick' in his study on acid rain to get information about damages. He assumes that each country fulfils its optimality conditions so that the marginal damage of a country equals its marginal cost. By knowledge of marginal costs, it is then possible to derive a damage function. This procedure assumes that within the borders of a country pollution externalities have already been internalised. However, there is no reason to believe that such internalisation is actually occurring. This point will be illustrated below in more depth.

Barrett (1992/b) also circumvents the need to evaluate the damage function for greenhouse gases directly by introducing an abatement benefit function. The latter is "defined as the minimum of damage plus adaptation costs avoided by greater abatement" (Barrett,1992/b;p.20). Benefit is a function of Gross Domestic Product (GDP) and total emissions. The equation is evaluated in three different scenarios, reflected by the choice of three different parameter values. In another paper on greenhouse gases, Barrett (1992/b) additionally introduces a 'vulnerability' factor which aims at taking account of the fact that different countries may be affected differently through global warming. He acknowledges that "local impacts of climate change are difficult to predict [...], and so vulnerability is difficult to assess." (Barrett,1992/b;p.17). Choosing appropriate parameter values is a further difficulty in these analyses. In general they have to be calibrated very carefully, and a variety of parameter values is often chosen for the purpose of sensitivity analysis. In the presence of large uncertainties it might be sensible to abstract from damage evaluation and choose a cost-effectiveness approach. Below, examples for such cost-effectiveness analysis will be given.

GAME THEORETIC SOLUTIONS

Considering what has been said above, one of the apparent problems with TP is that it affects several autonomous countries which have conflicting interests. Game theory, which deals with conflicting interaction, is apt to analyse strategies of the 'players' in question. On the basis of strategies, game solutions can be evaluated and compared.

In the area of economic analysis of TP several (game) solution concepts have been applied. These concepts help to uncover transboundary spillovers in terms of quantity (monetary for example), and thus hint at possible ways of improving on the current level of pollution.

In most articles which use game theory, a full cooperative outcome[10] is evaluated. The full cooperative solution would result if a central planner was to optimise the welfare of all countries with respect to the control of TP, whereby the total marginal damage equals a single country's marginal cost (see table 1). The outcome of such action is 'full-cooperative' in the sense that it optimises the overall situation[11]. This is also known as the Samuelson (1954) condition for public goods. Taken together, all the countries involved are better off under full cooperation than under any other solution concept. But individual countries might lose in comparison with non-cooperation, unless the overall gain from cooperation is shared. Full cooperation is purely a point of reference and by no means constitutes an equilibrium. In fact all countries have an incentive not to cooperate, because they would in general still be better off by breaching full cooperation: while they would incur lower or zero abatement costs, they would enjoy the pollution abatement brought about by the cooperating countries. In game theory terms this means that the condition of individual rationality is not fulfilled due to the public good character of pollution abatement. Free-riding refers, in this context, to situations where countries take advantage of other countries' abatement efforts. For example, if one country free-rides on the greenhouse gas abatement efforts of other countries, this implies that this country will benefit fully from the other's efforts, but will at the same time not incur

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[10]This concept is sometimes also referred to as Pareto optimal or central planner outcome.

[11]Full cooperation does not imply that all countries have the same bargaining power. Bargaining weights can easily be incorporated in the payoff functions of the countries in question.

any additional costs. However, it should be noted that not all TP problems are pure public goods. Acid rain, for example, is rival in consumption. Therefore there exists some 'selfish' interest in pollution abatement in a country suffering from acid rain.

Table 1: Solutions under Different Concepts

	Business as usual	Nash equilibrium	Full cooperation	Pareto Dominance
Cost-benefit analysis (assuming a payoff function $U_i=AC_i+D_i$)	$MAC_i=0$	$MD_i=MAC_i$	$\sum MD_i=MAC_i$	$\sum MD_i=MAC_i$ $P_i^p \leq P_i^n$
Cost-efficiency	$MAC_i=0$	$MAC_i=0$ which fulfils a pollution constraint	$\sum MAC_i=0$ which fulfils a pollution constraint	$\sum MAC_i=0$ which fulfils a pollution constraint, and $P_i^p \leq P_i^n$

Notes: Static game theory concepts of TP (The subscripts i stand for country i, while the superscripts p and n stand for the type of solution concept: p denoting Pareto dominance, and n the Nash outcome. MAC denotes marginal abatement costs and MD marginal damage. U is the payoff or utility function and P stands for the pollution-flow in the time considered, D denotes damage and AC abatement costs).

Beside the full cooperative solution, Pareto dominant[12] outcomes were evaluated (Mäler (1989), van Ierland (1989)). According to this concept the objective function is optimised under the constraint that no country should be worse off with than

[12] In some papers the 'Pareto dominant' outcome was named 'constrained social optimum'. See for example Folmer and Musu (1992).

without cooperation. Hence, such an outcome would make all countries at least as well off as they were before. Like full cooperation - and for the same reasons - the Pareto dominant outcome does not constitute an equilibrium.

Another way of guaranteeing that all parties are at least as well off as before cooperation, is to redistribute the additional gain from (full) cooperation via side payments. With the help of negotiations a procedure for reallocation can be selected that is acceptable to all parties. The basis defined by such negotiations is the section on the full cooperation hyper plane where all parties are at least as well off as at the Nash equilibrium. The Nash equilibrium results when countries choose their (optimal) abatement strategies in reaction to the choice of abatement strategies of all other countries. It is the best state that a country can reach in absence of cooperation. The Nash equilibrium could be referred to as a threat point: if cooperation cannot be agreed upon, the Nash situation will result.

Several allocative mechanisms of gain sharing have been put forward. There are allocative rules which take account of equity considerations. Barrett (1992/a) proposes for instance an allocation on the basis of the size of the population. Other rules are based on the idea that countries should receive payments in proportion to their contribution to the full cooperative outcome. They reward each country for coordination according to her contribution to the net gain. An example of such rules, which have been applied for the analysis of TP, is the Shapley value. It attributes to every player in the game a payoff which corresponds to her/his contribution to the (potential) gain from full cooperation. The Shapley value fulfils group rationality (a form of Pareto optimality) and a number of other properties such as symmetry and additivity.[13] Barrett (1992/b) evaluates Shapley values for the case of global warming. However, he rejects the use of the Shapley value on the basis that it is very difficult to evaluate. A particular rule for the context of international negotiations on behalf of TP was also developed: the Chandler/Tulkens (1991) cost sharing rule. While the Shapley value was only used in a static framework, the Chandler/Tulkens rule applies over time. The Chandler/Tulkens (1991) cost sharing rule is based on literature about dynamic processes for public goods and aims at devising a trajectory of feasible allocations that converges to a Pareto optimum. Their rule implies that at every stage in time the process of pollution abatement is locally strategically stable. The latter means in this context that no coalition of players can generate for itself a larger payoff along the path to the Pareto optimum[14]. Application of such a rule, however, requires information about each country's willingness to pay for a marginal improvement in environmental quality as well as knowledge about marginal abatement costs, both of which are certainly not readily available.

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[13] For further details see Friedman, J. (1986) Game Theory with Applications to Economics, 2nd edition (1991), Oxford.

[14] What is more, it turns out that for the class of games considered, i.e. 'local' games, the imputation induced by the all player strategy is the Shapley value of such a game. For more details see Chandler and Tulkens (1991) as well as Zamir and Tulkens (1979). However, as regards to the final outcome of such a process, no particular game theory property is guaranteed for (apart from Pareto efficiency and individual rationality with respect to the initial point).

Mechanisms to put through allocation rules, such as the Chandler/Tulkens rule and the Shapley value, could be an international tax, an international tradable permit scheme or mechanisms based on the ability to pay of the countries involved. Cesar (1994) analyses the possibility of making technology transfers. When talking about side payments, one should however keep in mind that side payments seem to advocate the VPP because they generally entail that polluting countries are bribed in order to reduce their emissions. Officially, however, the PPP is still purported by international agreements. It is not quite clear to overlook what consequences an explicit switch to the VPP in terms of incentives would bring about.

Full cooperation certainly constitutes the first best solution, and thus the upper limit of what is achievable in terms of international negotiations. But is there also a lower limit which could serve as a point of reference to compare with what has already been achieved? Some environmental economists (Mäler(1989); Barrett(1992/b)) take it to be the Nash equilibrium. Given the emissions of all other countries, each country maximises its net benefit and chooses the abatement level so that the marginal damage equals its marginal cost. But this implies that the public is aware of TP. If public awareness of environmental damage is not in accordance with the (scientific) 'state of the art' then such environmental problems will not be sufficiently taken into account, utility cannot be optimised in terms of Pareto efficiency. In order to evaluate how far the actual situation is located from Pareto efficient solutions a 'business as usual' (BAU) bottom reference can be evaluated. BAU assumes welfare optimisation under the assumption that there are no emissions at all, because agents do not yet perceive the pollutant as being risky or harmful (e.g. greenhouse gases). This is the approach followed by Fankhauser and Kverndokk (1992). Van Ierland (1990) estimates a reference projection for the year 1995 where he takes EC guidelines as a benchmark. In the light of these analyses, the Nash equilibrium turns out to be in both cases an improvement on the original state. The actual situation in terms of pollution might lie somewhere between the BAU and the Nash levels.

Rather than maximising the net benefit from pollution abatement, a cost-efficiency approach can be taken. This involves estimating abatement costs and choosing an abatement constraint. This procedure has the advantage of avoiding specifying an damage-emission relationship in form of a damage function. The uncertainty about such functions is generally considerable; and appropriate modelling would require the function in most cases to exhibit high nonlinearities. This in turn makes it very difficult to deal with mathematically. Tahvonen, Kaitala and Pohjola (1993) examine cost-efficiency of a Finnish-Russian SO_2 agreement. Abatement cost functions are minimised with respect to emission constraints; a Nash equilibrium as well as a full-cooperative outcome are evaluated. In the cost-efficiency context the first-order conditions look different. While for the full-cooperative outcome the sum of the marginal costs of all countries has to equal zero, the Nash outcome prescribes that the marginal costs of each country has to equal zero. Van Ierland (1990) takes this a step further by imposing a 'critical load' constraint. In his article, the critical load is taken to be the level of deposition of a pollutant that avoids 'major' damage to ecosystems, health and assets in the long-run. The values attached to critical loads vary widely between different types of ecosystems. In van Ierland's paper abatement under this scheme turns out to be even higher than abatement under full cooperation. The critical load approach in van Ierland (1990) is chosen explicitly in accordance with a popular approach in sustainable development[15]. His notion of sustainable development is based on the idea of non depletion of physical capital. Kverndokk (1993) examines the implications of a global CO_2 agreement with a cost-effective approach. He specifies abatement costs for five different world regions. He finds that under such an agreement, the industrialised nations would have to do the entire abatement, while the developing countries are allowed to increase their emissions compared to the 1990 level. But he points out that "if we take into consideration the high potential growth rates in CO_2 emissions for the developing countries, these countries will face considerable future reductions in emissions compared to BAU emissions under a cost-effective agreement" (Kverndokk, 1993;p.110). Despite the advantage of not having to specify a damage function, Barrett (1992/b) points out that it remains important to model benefits[16] directly. Taking EC negotiations on behalf of global warming as an example, he shows that incentives for cooperation might only be revealed if benefit considerations are introduced.

The main conclusion from the static game papers are that full cooperation is better than non-cooperation. In the static framework, however, it appears particularly difficult to deter players from free-riding, even if equitable cost-sharing rules are applied.

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[15]Which he takes to be the type of development that "focuses on the long term economic level that saves the environment and that avoids over exploitation of the natural environment and of natural resources." (Van Ierland, 1989;p.17).

[16] in terms of foregone damage.

DYNAMIC GAME THEORETIC MODELS

Subsequently we will turn to games which exhibit dynamic features. Dynamic TP game theory models are developed in both, discrete and continuous time. In the first case they are called 'difference games' while the notion 'differential games' applies for the second case. The incorporation of time into TP models most importantly allows us to take into account that most pollutants exhibit some form of structural time dependence. This means that not only the flow of pollution is important for the level of damage, but also the pollution stock or concentration. The latter is taken to be a 'state variable' of the dynamic game, and can be thought of as, for example, the atmospheric concentration of greenhouse gases or the acidification of soils through acid rain. The players dispose of 'control variables', i.e. instruments with which they can influence the level of pollution. Such instruments can be thought of as simply the emitted amount of pollution, the level of fossil fuel used, investment in abatement technologies and taxes. The aim of this type of game is to find the (intertemporal) optimal level of such instruments in response to the choice of all other players.

In order to take account of this aspect of pollution, TP dynamic games incorporate a 'motion equation' which depicts the changes of the pollutant over time. A general specification of this type can be as follows:

$$\dot{S} = \sum_{i=1}^{n} P_i(t) - \alpha f(S(t))$$

where S stands for the stock or concentration of the pollutant, P_i for the flow of pollutant at any one time from country i, and the last term on the righthandside of the equation denotes the assimilation capacity of the environment. The change in the pollution stock depends thus on the sum of emitted pollutant, P_i, over all n countries minus the assimilation at t.[17]

In Cesar (1994), an overview of Natural Resource models is given which includes a discussion of possible pollution constraints. In particular the issue of the specification of the assimilation function is taken up. From environmental studies, it is clear that assimilation of pollutants in the case of greenhouse gases can hardly be approximated by a linear function, although this is common practice. Cesar shows furthermore that the choice of assimilation function can influence the results from such a model quite dramatically.

In order to take account of the complex relationships between, for example, the greenhouse effect and the accumulation of CO_2, various approaches have been adopted. Tahvonen (1993) chooses to use two state variables: the change of temperature and the carbon concentration above the industrial level. A two-step framework is taken in Kaitala, Pohjola and Tahvonen (1992) for the case of acid rain between Finland and the former Soviet Union. In a first step the transport of sulphur dioxide emissions is depicted. The motion equation of the model in turn shows how

[17] An equivalent specification in discrete time would be $S_{t+1} = S_t + \sum_{i=1}^{n} P_{it} - \alpha f(S_t) \quad \forall i = 1..n$.

the quality of the soil is affected by acidification, i.e. by the deposition of the emissions as described in the sulphur transport equation. The state variable of the motion equation is defined in terms of the fraction of base cations in the soil, and hence also referred to as 'base saturation'. The major (empirical) findings are similar to Kaitala et. al.'s results from their static game version: "cooperation is beneficial for Finland, but not to the Soviet Union. Consequently, Finland has to offer monetary compensation to induce her neighbour to invest in environmental protection" (Kaitala, Pohjola and Tahvonen, 1992;p.161).

Dynamic models are essential if one is to consider interrelationships between various sectors of an economy. Pollution can affect both (environmental) amenities and the production level of an economy. Cesar (1994) introduces the notions of 'pollution input model' and 'pollution output model' for both types. Capital accumulation and population growth, as well as accumulation of human capital, have also been taken account of in dynamic gaming models. Furthermore impacts of various types of pollution reduction measures, such as abatement[18], recycling and process-integrated changes can be considered. Also the aspect of interaction among countries can be modelled in a far more realistic way: the set of strategies available to the countries is bigger than in a static framework. The free-rider incentive, for example, can be decreased by using trigger strategies[19] or renegotiation-proof strategies. Put another

[18]In the sense of 'end-of-pipe' technology.

[19]Trigger strategies are strategies where a player can punish another player for deviating from an agreement. It is assumed that he will punish forever. Renegotiation-proof strategies take up the criticism that the punishing player would be better off if

way, the strategy set of the players is bigger over time as compared to static solutions. Cesar extends the notion of trigger strategies for the differential game type[20]. Zaccour (1993) and Barrett (1994/c) have developed different types of renegotiation-proof strategies.

The game theory concepts which are evaluated in this context are slightly different from the concepts which are examined in the static framework. Economists typically analyse three different types of concepts: the open-loop Nash and the feedback Nash equilibrium as well as the Pareto optimal solution(s)[21]. While the notion of the Pareto solution is comparable to the notion used in the static framework, the two types of Nash solution have to be explained. Even though the general idea is the same as in the static case, calculation of Nash solutions here depends also on the type of information which is available to the players over the entire time-span of the game. In the open-loop case, the players only know the initial value of the state variable (for instance the concentration of pollution in the atmosphere). Along the time path, no changes in response to new information can be made. In some respect, this corresponds to a type of precommitment in the first period. Given that choices (for example in the energy

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continuation of cooperation could be achieved. Several definitions of renegotiation proofness have been devised. For an overview and extension to differential games of both concepts see Cesar (1994).

[20] With the restriction that he focuses only on points on the Pareto frontier.

[21] In fact there is an infinite number of Pareto optimal solutions, depending on which weights have been attached to the countries when maximising the overall safety function.

sector) are often irreversible, such a type of Nash solution appears nevertheless realistic. Under the feedback Nash solution it is assumed that only the current state is known[22]. The idea behind this is that as players see the value of the state variable evolve, they might adapt their policy instruments to these changes. The feedback Nash equilibrium is often also referred to as subgame perfect Nash equilibrium, because of its 'strong time consistency' or 'subgame perfectness'. The latter implies that the solution will be reached not only from any point on the time path towards equilibrium, but also from any point which is not on this time path. Typically a ranking of these solutions in terms of the state variable can be established. The general result is that the stock or the concentration of the pollutant is lowest under cooperation, and that with the open-loop Nash solution, the pollution concentration is lower than in the feedback solution. Such results come about for instance in the analyses of Hoel (1993), van der Ploeg and de Zeeuw (1992), Cesar (1994), Kaitala et. al. (1992), and Xepapadeas (1994), each in a slightly different framework. Xepapadeas (1994) gives the following intuitional explanation for the difference between open-loop and feedback Nash equilibrium. Under the feedback Nash equilibrium:

> " a country expects other countries to reduce their emissions when CO_2 concentration increases [...] . Thus it has an incentive to increase emissions and reduce contributions since it realises that the effects of its action will be partly offset by the rest of the countries' reduced emissions

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22 A third type of information structure, the closed-loop, is based on the idea that the information of both, open-loop and feedback, is available. Additionally agents have perfect recall of all the intermediate values of the state variable.

[...]. Since all countries follow the same policy, total emissions are increased."[23]

With differential games, it is also possible to incorporate capital accumulation and R&D accumulation processes. For example the possibility of investing in new abatement technologies was looked into by Cesar (1994). Cesar (1994;chapter 4) introduces the possibility that each country on her own is able to build up some energy related stock. In the steady state, the level of capital then turns out to be highest under cooperation, and the pollution level is lowest. Xepapadeas' analysis is wider since it considers not only the possibility that all countries together build up an R&D 'stock' (under full cooperation), but also how technology differentials might occur among countries. He finds, among other things, that the CO_2 concentrations are smaller and the level of technology is higher under the Pareto optimum than under both of the Nash equilibria. Another finding is that rich countries[24] may not have an incentive to commit themselves in a world-wide R&D agreement if technology differentials generate substantial benefits. This holds even though their failure to do so brings about a higher global concentration of CO_2.

[23] In: Xepapadeas (1994),p.16.

[24] Whether a country is 'rich' or 'poor' in this context depends on the country's initial value of primary input and on its growth rate.

FREE - RIDING

Another area of research focuses on the question of how free riding can be deterred. Free-riding appears to be an unavoidable phenomenon given that contracts to limit emissions are not credibly enforceable at the international level. Barrett (1992/b), Whalley (1991) and others propose to link negotiations on TP with other issues such as free access to trade. They suggest that this could reduce the need for monetary side payments if interests in interlinked topics are complementary. While linkage with trade could have negative repercussions in view of the liberalisation of international trade within the GATT agreement, linkage with other complementary environmental problems is conceivable. Barrett (1992/b) proposes the joint bargaining of CO_2 reductions and biodiversity preservation. At the Rio Conference in 1992, a Climate Convention, which was in the interest of the OECD countries, was agreed on only in exchange for guaranteeing an international deforestation convention - one of the biggest concerns of the developing countries at the moment.

Folmer, van Mouche and Ragland (1993) and Folmer and van Mouche (1993) have formalised this idea in their articles on interconnected games. The notion of 'interconnected games' incorporates the view that countries can condition their actions in the environmental area to outcomes previously observed in, say, the trade area and vice versa. The authors acknowledge the fact that in absence of an institution with the international jurisdiction to enforce agreement, such agreement must be voluntary as well as multilateral. In their analysis of tensor and direct sum games they show that linking or interconnecting games yields supplementary Nash equilibria.

Therefore, the set of possible as well as feasible outcomes is increased. Thus, interconnection may be a means to overcome a Prisoner's Dilemma type situation and to induce cooperation. Cesar (1994) also looks into the area of possible linkage of otherwise unrelated problems. He shows in a differential game framework of the global warming problem that a social optimum can be sustained with both trigger strategies and renegotiation-proof strategies, as long as cooperation is not harmful to any of the players.

The literature has also examined whether unilateral action by one country or by a coalition of countries can induce other countries to undertake abatement themselves. The idea behind this is that these countries' behaviour would be an example for other parties. This argument was put forward overall by environmental groups. However, Hoel (1991) shows this is not necessarily the case. The argument is as follows: Country A chooses unselfishly a lower emission level than that which follows from its own response function. Country B, who maximises her welfare by taking the pollution of A as given, is now faced by a lower ambient pollution level. Consequently, it is beneficial for B to increase her own emissions. However, Hoel (1991) analyses the situation within a purely static game framework, and the result might not be quite the same when a longer time span is taken into consideration. Indeed, time is an important factor in this context. The incentive to free ride will generally be smaller, the longer the time horizon which is considered: the dimension of time introduces the possibility of punishment (sanctions). Consequently, given that countries have low discount rates, cooperation might result[25].

Another strand in the area is looking at whether there are stable coalitions and explain from here the emergence of international cooperation. A stable coalition is one where there is neither an incentive to defect from the coalition nor an incentive to broaden the coalition. Carraro and Siniscalco (1991), for example, look at a situation where countries have different attitudes towards the environment. This assumption entails that some countries are committed to an environmental agreement. They show that the gains from partial cooperation of this subgroup could be used to expand the coalition. It is, however, made no attempt to justify the existence of such a subgroup. Petrakis and Xepapadeas (1994) use a similar framework. They go on to analyse the situation when it is not possible, or very costly, to measure each country's contribution to global pollution, as is the case for global warming. This creates a supplementary enforcement problem which can be circumvented by implementing a mechanism developed in their paper. Both articles do not consider time explicitly. Barrett (1992/b) suggests that a certain degree of enforceability of a global warming convention could also be achieved through legislation. He argues that the introduction of a third party to arbitrage conflicts between two member parties of a convention could prevent conflicts from occurring in the first place.

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[25] Time is thus important with respect to two aspects for TP games: on the one hand incorporating time will affect the strategies of the countries involved, and on the other hand environmental pollution exhibits in most cases structural time dependence.

Even if cooperation of all players or a subgroup of players was possible, there might still arise a problem from different information sets and structures of the countries. Pethig (1991) gives an example of TP in a two-country model with principle-agent features. He looks in particular at the 'enforcement deficit' which arises when governments which decide on pollution abatement incur costs from monitoring the agencies which ought to implement the measures.

CONCLUDING REMARKS

This overview of economic literature on TP games by no means claims to be complete. But it was attempted to give an overview of what has been done in the area, and where challenges for the future might lie. The main result from game theory applications to TP, which holds for all the papers in this area, is that cooperation will make all countries together better off as compared with the Nash solution. However, not every single country might be better off. In order to solve this problem, a side payment scheme can be devised or sanctions in areas other than TP can be threatened. Even if all individual countries happen to be better off under cooperation, a free-rider incentive still persists. Further strategies have to be looked for, e.g. trigger strategies and renegotiation proof strategies. Both of them only apply in a sequential or dynamic framework.

The economic analysis of TP so far has proceeded via theoretical as well as empirical studies. Although from theoretical work it is suggested that empirical work is necessary in order to judge situations correctly, empirical evaluation is very difficult in this context. This problem relates overall to uncertainties with respect to data. An example might be the contradictory results of studies by Fankhauser and Kverndokk (1992) on the one hand and Tahvonen (1993) on the other hand. While the latter concludes that CO_2 reductions are beneficial only for the developing world, Fankhauser and Kverndokk find that only the OECD countries (except the USA) would be able to take advantages from CO_2 abatement policy. Such differences might be resolved in the future due to improvement in information from the environmental sciences, especially in terms of transport of pollutants, their impacts on the environment, their assimilation by the environment, and the estimation of critical loads. In accordance with Folmer and Musu (1991), I would suggest that further development in this area is urgent, because of increasingly global environmental problems and growing interdependencies among countries.

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