Transboundary Pollution and International Cooperation

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1 INTRODUCTION

In its early days environmental economics was almost exclusively limited to environmental problems which take place within national boundaries. In the 1960s when the environmental revolution started, research focused primarily on the valuation of environmental resources and the design of policy instruments. Since the early 1980s it has become increasingly clear that most environmental problems directly or indirectly have an international dimension in the sense that their impacts are not confined to the country where the pollution originated. There are a number of reasons for the delay in the emergence of interest of economists in international environmental problems. Environmental economics did not seriously take off before the 1970's and in the early days only a limited number of isolated economists were working in this area. Also, insights into the physical aspects of transboundary pollution were only slowly gained by economists.

The first transboundary problem to receive extensive attention in environmental economics was acid rain which relates to the emissions of sulphur and nitrogen oxides. The destruction of forests and lakes in Scandinavia and central Europe became important news and policy items and triggered off a substantial amount of research in both the natural and the social sciences including environmental economics. An important finding by the research in the natural sciences was that a substantial proportion of the acid depositions in Scandinavia were generated elsewhere, in particular in the United Kingdom and the European Continent. Mäler's (1989) seminal 'Acid Rain Game' was

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the first in a series of papers dealing with the economic aspects of acidification. In his analysis Mäler made use of findings of research in the natural sciences, in particular the dispersion of sulphur emissions in a given country over the other European countries. The author addressed the evaluation of the net benefits of international cooperation as well as the possible need for financial transfers to achieve efficient abatement programs.[1]

The focus on the acid rain problem was soon followed by interest in problems such as the pollution of international rivers and seas, photochemical smog, ozone layer depletion and climate change. Similar developments can be observed in resource economics, though the international dimension is probably a little less dominant than in environmental economics. In traditional resource economics attention focused on the optimal exploitation of renewable resources and the depletion of non-renewable resources in a situation where a private or public agent is in a position to implement the exploitation program. At a later stage international aspects came to the forefront. For instance, since the 1970s there has been a growing interest in fisheries economics in the dynamics of open access resource utilization and the design of a regulation policy that effectively and equitably corrects the problem of overexploitation (Björndal and Munro, 1998).[2] There also exist potential international property rights problems with respect to natural resources in e.g. Antarctica. As a final example we refer to the exploitation of tropical rain forests which has become an international problem from both an environmental and resource perspective.

In addition to the above mentioned problems where pollutants actually move across borders or where there is a common resource problem, there exist international environmental problems which are characterized by non-physical relationships. The latter kind of problems may take different forms. For instance, individuals in a given country may be concerned with developments regarding natural resource exploitation or the environment in other countries. The lack of protection of rare species, tropical deforestation and nuclear power programs (in particular in the former Soviet Union) are typical matters of concern.

Another economic problem with an international environmental dimension relates to international trade. Anderson and Blackhurst (1992), Whalley (1991) and Ulph (1997), among others, argue that international trade and trade policies have impacts on the environment by altering the volume and international location of production and consumption. The environmental impacts of trade on a national economy can be positive or detrimental. For example, a positive effect will occur if trade leads to the diffusion of cleaner technology or to relocation of production from a location with poor environmental endowments to one with robust, superior endowments. A possible negative effect is environmental degradation as a consequence of trade induced economic growth. Not only does international trade have an impact on the environment, there is also a reverse relationship: domestic environmental policy may also affect international trade. Environmentally motivated taxes, subsidies and standards can alter

[1] Some other papers and monographs dealing with transboundary aspects of acidification are Kaitala et al. (1991, 1992), Tahvonen et al. (1993), Mäler (1994), Kaitala et al. (1995), Kruitwagen (1996), Kaitala and Pohjola (1998) and Mäler and de Zeeuw (1998).

[2] For an analysis of an interesting example of the dynamics of a free access fishery see Björndal and Conrad (1987).

international competitiveness and hence affect international patterns of production.[3]

International environmental problems display both similarities and differences compared to domestic environmental problems. The main similarities relate to the negative externality feature, the public good nature and the free rider tendency. International environmental commodities such as the ozone layer or the present climatic system are part of consumers' preferences or producers' production processes worldwide. They are affected by production or consumption decisions in a given country that are made without particular attention to their effects on utility or production functions of agents in other countries. Environmental services do not involve market transactions domestically or internationally and there are no prices for environmental goods. At both levels environmental commodities are characterized by non-excludability; their services can be enjoyed without paying for them and suppliers may be unable to recoup the costs of providing them. From these perspectives international environmental problems do not differ from domestic environmental problems. The main distinguishing feature, however, is that in contrast to the domestic scene, at the international level there is no single institution or 'government' with the jurisdiction to initiate and enforce environmental policy. The importance of this feature is critical in the context of the development and enforcement of international environmental policy. In particular, international environmental policy requires the development of mechanisms to induce countries to adopt and implement a given policy. Broadly speaking, international environmental policy could be defined as domestic environmental policy with the additional dimension of developing a substitute for national government action, in particular enforcement. It is precisely for that reason that the analysis of international environmental problems has developed as a subdiscipline of its own within environmental economics.

The distinguishing characteristics of international environmental problems are interdependent, multi-country decision making in situations characterized by lack of property rights, the existence of externalities and the absence of an institution to enforce policy. These characteristics have led to the application of non-cooperative game theory as the main theoretical approach for analyzing these types of problems and for developing appropriate policy tools. For a thorough understanding of the theoretical literature in this area a solid background in non-cooperative game theory is essential.[4]

This paper presents an overview of the nature of international environmental problems and instruments to induce cooperation. In subsection 2.1 a classification system

[3]It should be observed that there exists an asymmetry in terms of discretion between importing and exporting countries in the imposition of environmental policy affecting trade flows. The asymmetry follows from the present rules of the World Trade Organization (WTO). According to these rules, there are few constraints to a country's right to protect its own environment against damage from either the consumption of imported products or domestically produced goods or domestic production, provided the home product and imported product are treated equally. However, imposition of restrictions on international trade to protect the home environment on the basis of the method of production of imported goods (e.g. produced in an energy intensive way) is extremely limited and surrounded with uncertainty. The rationale is to restrict the possibilities to use environmental policies as covert barriers to trade. Consequently, a country has more discretion to impose environmental measures affecting its exports than its imports (see Folmer and de Zeeuw (2000) for further details). At the regional level, e.g. the European Union, there usually are more possibilities (in contrast with the WTO) to apply trade measures to protect the environment via restrictions on imports from other member states (Folmer and Howe, 1991).

[4]Cooperative game theory has also been applied in this area, although to a lesser extent. For applications see Tulkens (1998) and the references therein.

for transboundary environmental problems is suggested. In subsection 2.2 we distinguish four main approaches that countries can take to these kinds of problems, that is, the market approach, the non-cooperative, a cooperative and the full cooperative approach. Moreover, we shall argue that the full cooperative approach is the most desirable in terms of social welfare,[5] efficiency and environmental effectiveness. We shall also discuss the main obstacles to the full cooperative approach. In section 3 we shall focus on the main instruments used to overcome these impediments, that is, side payments, retaliation and interconnection. As mentioned above, game theory has become an important methodological approach in the theory of international environmental problems and policy. The literature however, is not readily accessible. Moreover, results are occasionally derived under imprecise conditions. In order to overcome these problems we formally present the basics of an internal environmental problem in a game theoretic framework in section 4. Moreover, some game theoretic results are derived and presented under precise conditions.

This paper focuses on the nature of international environmental problems and instruments used to promote cooperation. Other issues related to these problems, such as trade and the environment (see Ulph (1997) for an overview), will not be dealt with or only incidentally. Moreover, the specific form of international environmental agreements and specific instruments of international environmental policy like Joint Implementation, Clean Development Mechanisms or international permit trading are beyond the scope of this paper. Finally, we will restrict ourselves to physical transboundary pollution and ignore non-physical international environmental problems as well as international resource problems. Some results, however, like the benefits of cooperation and instruments used to achieve such an outcome also apply to these problems.

2 NATURE OF INTERNATIONAL ENVIRONMENTAL PROBLEMS

2.1 Characterization and Classification

As mentioned in the previous section, international environmental problems are characterized by interdependent, multi-country decision making in situations where there are no property rights, externalities exist and no institution exists to enforce policy. Below we shall explain some of these characteristics in greater detail.

Prevalence of a non-property or open-access regime is a characteristic shared with many domestic environmental problems.[6] Open-access regimes allow countries to make use of scarce environmental or natural resources without regard for the interests of other countries who may also seek to make use of the same resources (Bromley, 1997). Since open-access regimes are fundamentally situations where there is no law

[5]The notions '(total) net benefits' and ' (social) welfare' will be used as synonyms.

[6]Both at the national and the international level environmental problems may also occur under a common-property regime. An example in an international setting is the ownership and control over the natural resources in Antarctica. In the sequel we shall restrict ourselves to non-property regimes. The results obtained in this context also apply to common-property regimes.

and where property rights are absent, the first country to exploit the resource becomes the beneficiary of the stream of yields arising from the resource.

Absence of a single international institution or 'government' to initiate and enforce environmental policy in all relevant countries is typical for an international environmental problem and distinguishes it from a domestic environmental problem. Domestically the government can intervene in the economic process and develop and enforce policies to restrict the exploitation of environmental and natural resources. Internationally, however, development, implementation and enforcement of environmental policy is basically at the discretion of the governments of sovereign countries.[7] They can decide whether or not to participate in the development of a common policy and whether or not to implement such a policy domestically. Moreover, the government of a sovereign country can decide to change its involvement in a policy previously agreed upon. In the most extreme case it can decide to pull out completely.[8]

The following observation applies. Under customary law, countries are supposed to comply with the agreements they sign up to. In the case of deviation, they can be expected to be punished. Usually an international agreement specifies sanctions for deviation and a punishment mechanism. The enforcement power of an international court, however, is limited. In principle a country can ignore the sanctions or get around them, a practice not uncommon in the international arena. However, there also exist additional, though more diffuse, punishments in international relationships. For instance, a deviant can be punished by retaliation in another area of interest. Trade sanctions are probably most common in this connection. Moreover, the punishment can be more diffuse, with other countries being more reluctant to engage in relations with the deviant in the same or other areas. See section 3 for further details on these issues.

In the context of international cooperation on environmental problems, it is important to take the direction of transboundary pollution into account. Incentives for abatement of a transboundary pollution problem vary by direction. The relevant distinction is between unidirectional and reciprocal transboundary pollution. In the first case a given country (the upstream country) pollutes another country (the downstream country), but not vice versa. In the latter case, a given country pollutes one or more other countries but is itself also a victim of pollution generated by other countries. Under reciprocal pollution a given country usually has stronger incentives to abate than under unidirectional pollution.[9]

Another distinction relates to the number of polluters and pollutees. The rationale

[7] At present there are almost 200 multilateral agreements in force. Some well-known examples are the convention on International Trade in Endangered Species of Wild Fauna and Flora (1973), the Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (1989), and the Montreal Protocol on Substances that Deplete the Ozone Layer (1987). Moreover, at the 1992 UN Conference on Environment and Development, Agenda 21 was adopted. This is a working agenda for the international community addressing the major environmental problems and development priorities for the next decades. Agenda 21 includes the so-called Rio Declaration on Environment and Development, the Global Environmental Facility and the Forests Declaration. From Agenda 21 also emerged the Kyoto agreement and the Buenos Aires agreement.

[8] It should be observed that international organizations, such as the United Nations have been authorized to coordinate international environmental policy. These institutions, however, have limited power to enforce agreements.

[9] A river passing through two countries is an example of unidirectional transboundary pollution and global warming of reciprocal transboundary pollution.

for this distinction is that as far as the origin of pollution is concerned, identification of the size of an individual country's contribution to a given problem is usually negatively influenced by the number of polluters. In the case of one source all the pollution can conclusively be attributed, whereas in the case of several sources the extent of pollution by a specific country may not be so clear. Moreover, in the latter case there is the problem of allocating abatement programs among the polluters. The number of pollutees is relevant in the context of incentives for abatement policies. For instance, in the case of several victims the incentives for abatement are likely to be stronger than in the case of one victim.

Taking into account both the direction and the number of polluters and pollutees, the following possibilities arise: (i) One source - one victim; (ii) One source - several victims; (iii) Several sources - one victim; (iv) Several sources - several victims. Case (iv) is the more general one and the most complicated one to solve. The other ones can be viewed as special cases of (iv). Therefore, we shall primarily focus on (iv) in the sequel.

2.2 Market, Non-cooperative, Cooperative and Full Cooperative Approach

In this subsection four approaches to international environmental problems are described: the market approach, the non-cooperative, a cooperative and the full cooperative approach. Associated with these approaches are specific outcomes: the market outcome, the non-cooperative, a cooperative and the full cooperative outcome.[10] The meaning of these notions will now be explained below.

The market outcome maximizes the net benefits of each country ignoring environmental damage.[11] The market approach is rather rare in industrialized countries nowadays because of growing environmental concerns.

In the non-cooperative outcome each country maximizes its net benefits taking environmental damage costs into account. However, the country ignores the effects of its emissions on the other countries and takes the policies and emissions of the other countries as given. This means that a given country will continue increasing its emissions as long as the benefits of each additional unit of pollution exceed the damage costs to the country itself. In other words, the optimal level of pollution is determined by the equality between marginal benefits and marginal damage costs in the home country.

The full cooperative outcome is the outcome which maximizes the sum of individual countries' net benefits.[12] In this outcome each country maximizes its net benefits, internalizing the adverse effects of its pollution on its own welfare and on the welfare of all the other countries in the system. This implies that it equates marginal benefits to the marginal social damage costs. The full cooperative approach leads in general to higher social welfare than the market or non-cooperation approach.

In a cooperative approach countries negotiate and sign a treaty. These treaties may take many forms but a natural assumption is that they select an outcome that is Pareto

[10]Notice that we wrote 'a' cooperative approach (outcome) instead of 'the' because there may be more than one cooperative approach (outcome). This contrasts to the other approaches (outcomes).

[11]A synonym for market approach would be non-environmental approach.

[12]In dealing with the full cooperative outcome one assumes transferable utility.

efficient. Since international law requires countries to negotiate and to discuss their problems openly, countries should have no problem selecting such an outcome.[13] The set of Pareto efficient outcomes comprises several allocations including the full cooperative outcome and the Nash bargaining solution. Below we restrict ourselves primarily to the full cooperative outcome, since it has received most attention in the literature so far.[14]

The following observation applies. A cooperative and in particular the full cooperative approach do not only lead in general to higher social welfare than non-cooperation, they are usually also superior in terms of effectivity and (cost) efficiency.[15] The former derives from the fact that unilateral actions or actions by a small proportion of the countries involved in an international environmental problem are usually futile. For instance, in the case of global warming abatement the involvement of developing countries is a prerequisite. The reason is that the main growth in energy demand between 2000 and 2020 will occur in these countries. Efficiency derives from the fact that there usually exist substantial differences in abatement costs among countries. Efficiency requires that abatement takes place at the least cost option. To sum up, efficiency and effectivity usually require cooperation.

In spite of the attractiveness of (full) cooperation, in practice it is often difficult for countries to (fully) cooperate, judging by e.g. the considerable problems involved in reaching an agreement on global warming abatement.

We now turn to the impediments of the full cooperative approach. First, the full cooperative approach may imply welfare losses for some countries and, at the same time, substantial gains to others. This is most likely in the case of a unidirectional externality. The classical example is one upstream country that pollutes one downstream country. In the case of full cooperation, the benefits of pollution reduction to the downstream country would usually be at least as large as those accruing to the upstream country.[16] Moreover, the abatement costs would be borne by the upstream country only. If its abatement costs outweigh its benefits, the upstream country would incur a net benefits loss. Hence, it has an incentive to adopt the non-cooperative approach rather than the full cooperative. A similar result holds in the case of one upstream and several downstream countries. The downstream benefits, however, would be at least as large and, in most cases, larger than in the case of one downstream country, ceteris paribus. The potentially larger benefits in their turn could lead to increased pressure on the upstream

[13] In fact, it would be collectively irrational to select a Pareto inefficient outcome from the perspective of the countries involved.

[14] The four approaches considered here are extremes and in practice hybrid forms are observed. For instance, a country may take some environmental impacts into account which is a hybrid form between the market and the non-cooperative approach. Similarly, a country may take some damage in some other countries into account. The characteristics of the hybrid approaches are mixtures of the characteristics of the 'pure' or extreme forms. In the sequel we will restrict ourselves mainly to the extreme forms.

[15] The relations between emissions levels under the non-cooperative and full cooperative outcome are discussed in subsection 4.1.

[16] There could be exceptions with respect to the benefits. For instance, in the case of rapidly dissolving pollutants that cause most of the damage in the pollution-generating country, the upstream country would benefit more from abatement than the downstream country. Similarly, other physical conditions could play a role, such as the degree of pollution exposure. For instance, if the length of the polluted river is much longer in the upstream country than in the downstream country, the benefits of abatement would be larger in the former than in the latter, ceteris paribus.

country to adopt the full cooperative approach. Also, in the case of several upstream polluting countries and one or several downstream victims, there exist strong incentives for the former to adopt the non-cooperative approach if their abatement costs outweigh the domestic benefits of abatement. The downstream countries on the other hand would prefer the full cooperative approach.

When there are reciprocal externalities, that is, each country is both a generator of pollution and a victim, all the countries have an incentive to take unilateral action. The full cooperative approach would be the most cost efficient for all the countries together. However, also in this case, the full cooperative approach may imply a net loss relative to the non-cooperative approach for some countries. This would be an incentive for these countries not to fully cooperate or to defect from a concluded agreement.

The foregoing is empirically illustrated by Mäler (1989) with his acid rain game.[17] As mentioned above, this paper relates to depositions of sulphur in Europe. It shows that the full cooperative outcome would require the total emissions to be reduced by about 40% relative to the situation in 1984. The full cooperative outcome, however, implies widely varying reduction percentages and substantial deviations from the non-cooperative outcome for the individual countries. Most countries would incur net gains from the full cooperative outcome, except Italy, Spain, Finland, Luxemburg, and, notably, the United Kingdom, which would lose. The main reason for their losses is the upstream position of these countries. In particular, the substantial loss for the United Kingdom explains why it has been so reluctant to participate in European sulphur emissions reduction programs. Mäler's paper showed that the full cooperative outcome is preferable to the non-cooperative outcome as it leads to a lower level of pollution and substantial cost savings.

The differences between the full cooperative and the non-cooperative outcome need not necessarily be large as Barrett (1990) showed. For a given number of countries, he showed that the difference depends on the ratio of the slopes of the marginal abatement cost and marginal benefits. curves. If the ratio is 'large', the full cooperative outcome will not call for large abatement levels because of the high costs and the relatively small benefits involved. This case corresponds to mildly innocuous pollutants that can only be abated at relatively high costs. The full cooperative outcome will not lead to much additional abatement relative to the non-cooperative outcome. Under neither outcome does the cost benefit ratio warrant substantial abatement. Consequently, the discrepancy between the full cooperative and non-cooperative outcomes will tend to be small. A similar result holds for a 'small' ratio. This case corresponds to very damaging pollutants for which abatement yields large benefits at relatively little cost. In this situation countries will usually initiate substantial abatement programs unilaterally, that is, in a non-cooperative setting. It follows that the discrepancy between the full cooperative and non-cooperative abatement levels will tend to be large when the slopes of the marginal benefits and marginal abatement cost curves do not differ very much. This applies to damaging pollutants that are costly to abate and mildly innocuous pollutants that can be abated at little cost. The former case causes the greatest concern because of

[17] The acid rain game provides in fact a quite general framework that can be applied to a variety of physical problems including acid rain, global warming, ozone layer depletion and the pollution of international rivers and seas.

the great risks involved. An example is global warming.[18]

A second impediment to the full cooperative approach is that even if the net benefits of cooperation are positive, a country has an incentive to free-ride. The reason is that by staying out of an agreement or by defecting from a concluded one, it may be possible for a country to reap virtually the same benefits of pollution control as by joining it. It would avoid, however, paying its share in abatement costs. Free-riding is especially an attractive option in the 'small country' case, that is, when a country's share in total pollution is relatively small. The reason is that the loss of benefits for not cleaning up its act is small. This applies in particular to global environmental problems because in that case each country's contribution is rather a small proportion of total pollution.

Free riding is especially a problem in situations where an international environmental treaty is concluded for a limited spell of time and will be revised a limited number of times (finitely repeated game) or not at all (one shot game). The reason that commitment is a problem under these conditions is that there often exist no credible punishments for defection.[19]

The following observations apply. First, Hoel and Schneider (1997) assume that countries have preferences to commit whereas Carraro and Siniscalco (1993) assume different kinds of partial commitment. However, this begs the question why countries make commitments. Secondly, as commitment is a problem in a finitely repeated game, the question arises under what conditions a finitely repeated treaty could be concluded. A discussion of so-called self-enforcing agreements can be found in amongst others Barrett (1994).

The success of international cooperation is inter alia dependent on the form of the agreement. Often international environmental agreements take the form of a uniform percentage rate reduction.[20] Hoel (1992) showed that not all countries find it in their best interest to participate in such an agreement.[21] In particular, the smaller the amount of emissions allowed to each participant, the fewer countries will participate.

A uniform percentage reduction takes an intermediate position between the full cooperative and the non-cooperative outcome. It deviates from the former in the sense that not all the damage caused to other countries is internalized. On the other hand, it deviates from the non-cooperative outcome because possible damage to other countries is not completely ignored.

It follows from the above that a variety of forces undermine the adoption of (full) cooperation. However, in terms of welfare, environmental efficacy and economic efficiency, a (full) cooperative approach is desirable. In particular, effective and efficient environmental policy usually requires the involvement of a minimum number of countries including those which play a crucial role in a given pollution problem. Therefore, research on international environmental problems has strongly focused on the develop-

[18] A complicating factor affecting abatement both in a cooperative and non-cooperative setting is uncertainty about costs and benefits, as in the case of global warming. See, for instance, Kelly and Kolstad (1999).

[19] This is in contrast to infinitely repeated games which allow possibilities for punishing a defection (see subsection 3.2).

[20] An example is the so-called 'Thirty Percent Club', which is an agreement by several European countries to reduce their long-range sulphur emissions by 30%.

[21] Uniform percentage reductions are inefficient in the sense that the same goal could be achieved at lower costs through a distribution of reductions such that the marginal emissions reduction costs are the same for all participating countries.

ment of instruments to stimulate countries to adopt a (full) cooperative approach. We will now turn to a discussion of these instruments.

3 INSTRUMENTS TO INDUCE FULL COOPERATION

In this section we discuss various instruments to overcome the impediments to full cooperation. In subsection 3.1 we pay attention to side payments and in subsection 3.2 to punishment or retaliation to deter non-cooperation. Finally in subsection 3.3 we turn to interconnection. In passing we will also discuss ways to overcome obstacles to (not full) cooperation.

3.1 Side Payments

Side payments or compensations are transfers to those countries whose net benefits from cooperation would be negative. The use of side payments in the context of cooperation on transboundary pollution was first brought up in the above mentioned paper by Mäler (1989). He showed that most European countries would gain from a full cooperative approach with respect to the reduction of sulphur emissions and that total net benefits would be more than sufficient to cover the net losses of the UK, Finland, Italy, Luxemburg and Spain (the 'losers'). So, in order to induce the losers to fully cooperate, the countries that would gain from full cooperation (the 'winners') could offer to compensate the losers for their losses.[22]

At first sight the use of side payments looks like a reasonable and powerful instrument to stimulate cooperation because it opens the possibility for the losers to get compensated for their net losses without turning the net benefits of the winners into a loss. In other words, all parties could be made better off relative to the non-cooperative outcome. Finally, in the case of strong asymmetries as between rich and poor countries, side payments may be instrumental in transforming the cooperation problem from one in which every country undertakes abatement to one in which the rich countries make the money available for abatement by the poor countries (Joint Implementation and Clean Development Mechanism).

In spite of these positive aspects, there exists resistance to the implementation of side payments. First, there is the problem of the allocation of the net benefits. Compensation of the net losses of the losers is only one out of a set of possible allocations. In particular, the losers might also want to share in the net benefits from cooperation. Possible allocations in this context are a uniform distribution over the countries involved or an allocation based on each country's contribution to abatement. The foregoing implies that the allocation of the side payments opens up a whole new game for which no generally accepted rules exist.

Secondly, the anticipation of side payments may induce countries to act strategically and minimize environmental policies even below the level determined by the non-cooperative approach. The rationale is that the potential beneficiaries may not

[22] Similar results have been obtained by amongst others Kaitala and Pohjola (1998).

only have the discrepancy between the full cooperative and the non-cooperative outcome covered by side payments, but also part of the costs they would incur on the basis of the non-cooperative approach. That is, the losers have an incentive to strategically lower their non-cooperative level of abatement. Moreover, the winners would have an incentive to downplay their net gains. The risk of strategic behaviour will be particularly relevant in the case of imperfect information about the preferences for environmental quality and abatement costs. As mentioned above, such a situation is typical for most environmental problems and international environmental problems in particular.

Thirdly, Mäler (1990) argues that side payments may have a prejudicing effect of characterizing the compensating country as a 'weak negotiator'.[23] The loss of reputation is not only relevant with respect to future negotiations on the same problem at hand, but to other problems, environmental as well as non-environmental. Consequently, loss of reputation may imply substantial future costs.[24]

Finally, side payments signify application of a 'victim pays' principle rather than a 'polluter pays' principle. Not only at the national but also at the international level, the polluter pays principle has become quite generally accepted.[25]

3.2 Retaliation

In this subsection we pay attention to compliance (cooperation) in an infinitely repeated game context. What are the incentives for a country to comply with the obligations it has signed up to in such a context? Before going into detail we observe that finitely repeated games lack possibilities for punishment, as standard game theory shows. The basic idea is that for such a game, in case the stage game has a unique Nash equilibrium, say $\mathbf{n}$, (as is often the case in applications), the only subgame perfect Nash equilibrium[26] is to play $\mathbf{n}$ in each period. In the present context this means that the non-cooperative approach will be adopted in each period.

For an infinitely repeated game the situation is different. This can be seen as follows. An important motive for a country to cooperate is that it expects the total benefits to outweigh the total costs. In this context the discounted net benefits over the entire (infinite) spell for which the agreement holds are relevant. Hence, it is in the country's interest that the agreement does not break down prematurely, as this would imply a loss relative to a situation of continued cooperation. The potential net loss from a break down forms an instrument to prevent defection. As soon as some countries violate the agreement to obtain some short-run advantage, the other countries can retaliate

[23] For detailed information about reputation effects, see Friedman (1991) and Fudenberg and Tirole (1991) and the references therein.

[24] Mäler (1990) argues that this is one of the reasons why side payments are rare in the practice of international policy on transboundary pollution.

[25] For instance, the Treaty of Rome, as amended by the Single European Act, states that Community environmental policy shall be based on the principle that 'the polluter should pay' (article 130 r(2)).

[26] A subgame perfect Nash equilibrium is a Nash equilibrium for the game that also gives a Nash equilibrium in every proper subgame of the game. Subgame perfectness is only one of the refinements one can impose on Nash equilibria in order to make threats to become more credible. For example, renegotiation proofness is also an important one.

by changing their actions to non-cooperative behaviour (Nash threat), thus turning the short-run advantage into a long-term loss. This would prevent deviation.[27]

The risk that an agreement may not be concluded may also form an incentive for a country to join an agreement instead of being a free-rider. By staying out of an agreement it increases the risk that the full cooperative outcome does not come into being at all. Consequently, the country would incur a net loss.[28]

The following observations are in order here. Barrett (1994) suggests that Nash threats, although they are subgame perfect, may not be credible because countries have an incentive to renegotiate away from an inefficient retaliation (as described above), if they were actually called upon to implement it. In that context Cronshaw (1998) suggests Abreu's (1986) 'stick and carrot' punishment as a more credible alternative. This strategy involves one 'bad period' (punishment) which is followed by a 'good future' (restored cooperation). The prospect of a good future gives the players an incentive to go along with the single punishment period. Moreover, in contrast to the Nash punishment which is continued forever, the stick and carrot punishment allows for different behaviour depending on whether players accept their punishment or not.

Secondly, Jeppesen and Andersen (1998) consider commitment. The main question they examine is why countries cooperate in reality, in spite of strong tendencies not to do so. They introduce the notion of commitment in Barrett's (1994) simulation model of international cooperation that analyzes the number of signatories of an international agreement, the global abatement level and the global net benefits corresponding to the number of signatories. They show that if commitment is credible, then the number of signatories of an international environmental agreement increases and finally full cooperation is achieved. As a possible rationale for commitment they suggest Rabin's (1993) notion of fairness which is closely related to altruism. This notion turns the focus away from the (subgame perfect) Nash equilibrium as a solution concept to an alternative where countries are rewarding the 'good guys' and punishing the 'bad' ones. In the present context it means that countries are prepared to sacrifice some of their own profit in order to benefit others (the good guys) or to hurt others (the bad guys). In the context of international cooperation on transboundary pollution problems, this implies inter alia that emissions abatement in one country depends positively on abatement in another country. It should be observed that this work is still at a preliminary and hypothetical stage and that a theoretical and empirical connection between commitment and fairness is still to be made.

3.3 Interconnection

A third instrument to induce countries to adopt the full cooperative approach is by exchanging concessions in fields of relative strength. As an example, consider two countries, A and B, that are simultaneously involved in a transboundary pollution problem and a trade dispute. Country A would like to see country B reduce its emissions, whereas country B would like country A to discontinue its restriction of imports from B. In order to induce country B to clean up its act, country A could offer trade con-

[27] See (1) in subsection 4.2 for a quantitative result in this context.

[28] The foregoing can be formalized with repeated games. (See also subsection 4.2.)

cessions. This instrument has been denoted 'interconnection' (Folmer et al. 1993) or 'issue linkage' (Cesar, 1994).[29] A well-known example is the desalinization of the Colorado River where it crosses the US-Mexican border. In the 1960s, the US responded to complaints about the quality of the water by the Mexican authorities by several measures including the costly construction of a desalinization plant. From the viewpoint of the US environmental interest, and in isolation from other US interests, these measures can only be interpreted as irrational, as the costs for the US by far outweighed their benefits. If other interests are taken into account, however, such as the relationships of the US with Mexico in general, the US desalinization policy makes sense. A similar example is the Columbia River Treaty between the US and Canada. Krutilla (1966, 1968) found a gain of of approximately US$ 250 million for Canada and a loss of US$ 250 to US$ 375 million for the US. The reason for the US to accept the treaty was that there were other interests at stake, such as the interests of US companies in the resurgence of the Canadian air force. The benefits of the other interests by far outweighed the loss due to the Columbia River Treaty. As a final example, we refer to Bohm (1990) who suggests that some countries may have chosen to sign the Montreal Protocol on CFCs even though abatement costs exceed benefits. A reason for joining may have been that these countries simply want to be part of a cooperative movement so as to benefit from the side-effects such as avoiding the risks of losing partners for other forms of international cooperation, including cooperation on international environmental problems.[30]

Interconnection may also take the form of a threat to withdraw some extended advantage. Trade restrictions are often used to induce a country to change its policies including military, human rights and environmental policies. An example of the last is the the Packwood-Magnuson Amendment to the US Fishery Conservation and Management Act which requires the US government to retaliate when foreign countries violate the Convention for the regulation of Whaling. An offending country would lose half its allocation of fish from US waters. If the country did not improve its behaviour in a year, it would completely lose its right to fish in US waters (Barrett, 1990).

The following observations are in order here. First, interconnection in order to achieve full cooperation (as discussed above) presupposes the existence of reversed interests. Moreover, interconnection will be affected by the magnitude of the interests: the larger the asymmetry, the more difficult the interconnection and hence induced cooperation. Another limitation of interconnection is that it is likely to complicate negotiations. This is particularly true if the number of issues that are being linked increases. Moreover, Tollison and Willett (1979) argue that interconnection increases the number of decision makers and thus transaction costs.

Secondly, the increasing interdependencies among countries, in economic, political, and cultural areas as well as in terms of different environmental problems such as global warming, ozone layer depletion and biodiversity strongly increases the possibilities of interconnecting a given environmental problem to other problems. This applies

[29]Interconnection in national political settings is very common. For instance, it plays a major role in the context of the formation of coalition governments such as in the Federal Republic of Germany and the Netherlands.

[30]Reputation effects and fairness may also have played a role. Moreover, the costs of banning CFCs are rather small for most signatories. This applies in particular to the industrialized countries. Moreover the developing countries were given a long time span to phase out CFCs.

in particular to unions of independent states. For instance, in the European Union the member states have experienced a substantial increase in interdependency in virtually all areas and this has increased the opportunities for interconnection substantially.

Interconnection has been modeled by means of interconnected games. The first, as far as we know, who considered interconnection by means of game theoretic notions were Stein (1980) and Raiffa (1982). McGinnis (1986) considered interconnection of two repeated prisoners' dilemma games. The effect of interconnection upon collusion in the context of two repeated Bertrand oligopolies was studied in Bernheim and Winston (1990). The formal theory of interconnection of repeated games was introduced in Folmer et al. (1993). This paper also presents an application to international environmental problems. Folmer and v. Mouche (1994), Ragland (1995), Cesar (1996) and Cesar and de Zeeuw (1996) elaborate upon both the theory of interconnected games and present applications to international environmental problems. (See section 4 for further details on these papers.) An attempt to interconnect differential games with an application to environmental problems can be found in Cesar (1996). Interconnection in the context of cooperative games (games in characteristic form) is dealt with by Kroeze-Gil and Folmer (1998); interconnection of negotiation games is considered by Peters (1986). Fisher et al. (1988) deal with interconnection in the context of general equilibrium models.

Until now most of the research on interconnection has been theoretical. However, recently some empirical studies have been published. Kroll et al. (1998) tested whether or not interconnection influences cooperation using an experimental laboratory approach. Moreover, the authors explored the difference between interconnecting games through an informal and a formal institution. The latter implies one joint institutional framework that integrates distinct actions into a single payoff before any decisions are made on how to play the game. An informal context involves two parallel institutions where the players make the interconnection themselves during the play. One finding was that interconnection does affect the outcome of a game and leads to more cooperation. The authors also found that the institutional setting matters, although the two institutions are theoretically equivalent. In particular, efficient outcomes are far more common in the formal institution case. The authors also investigated pre-play communication or 'cheap talk'. The results showed that cheap talk does not add to efficiency.

Botteon and Carraro (1998) empirically tested interconnection as a strategy with respect to the profitability and stability of international cooperation relating to CO_2 emissions abatement on the one hand and R&D on the other. Their results confirmed that linkage of an environmental problem to other economic issues (such as R&D cooperation) may be useful. Such linkages reduce the constraints that asymmetries impose on the emergence of stable environmental agreements and increase the number of signatories in the stable coalition.[31]

[31]The authors correctly conclude that more theoretical and empirical research on interconnection is required.

4 FORMAL PRESENTATION

In this section we deal with the non-cooperative and the full cooperative outcome in a formal (mathematically rigorous) manner.[32] The starting point is Mäler's acid rain game which we generalize in subsection 4.1 to a 'formal transboundary pollution game'. The proofs of the results there can be found in Folmer and v. Mouche (2000). Next, in subsection 4.2, we pay attention to retaliation by considering repeated formal transboundary games. Finally in subsection 4.3 interconnection has its place. In order to keep the presentation there simple we content ourselves by discussing a example.

4.1 Formal Transboundary Pollution Games

Definition 1 introduces the notion of formal transboundary pollution game.

Definition 1 *A (smooth regular) formal transboundary pollution game (among N countries), abbreviated as FTPG, is given by a game in strategic form*[33]

$$Z := (X^1, \ldots, X^N; f^1, \ldots, f^N)$$

for $N(\geq 2)$ players where for each player j:

1. $X^j = [0, M^j]$ *with* $M^j > 0$;
2. $f^j(\mathbf{x}) = \theta^j(x^j) - D^j(\sum_{l=1}^N T_{jl} x^l)$ *with* $\theta^j : X^j \to \mathcal{R}$, $D^j : [0, r^j] \to \mathcal{R}$ *where* $r^j := \sum_{l=1}^N T_{jl} M^l$ *and all* $T_{jl} \geq 0$;
3. $T_{jj} > 0$;
4. D^j *and* θ^j *are continuous;*
5. D^j *is (even) twice continuously differentiable and* $\theta^j : (0, M^j] \to \mathbb{R}$ *is twice continuously differentiable;*
6. ${\theta^j}'(x^j) > 0$ $(x^j \in (0, M^j))$ *and* ${D^j}'(Q^j) > 0$ $(Q^j \in (0, r^j])$;
7. ${\theta^j}''(x^j) < 0$ $(x^j \in (0, M^j])$ *and* ${D^j}'' \geq 0$;
8. *For each multi-action* $\mathbf{x}^{\hat{j}}$ *of the other players, there exists a right (left) neighbourhood of* 0 *(of* M^j*) where the function* f^j *as a function of* $x^j \in X^j$ *is strictly increasing (strictly decreasing) and there exists a right (left) neighbourhood of* 0 *(of* M^j*) where the function* $\sum_{j=1}^N f^j$ *as a function of* $x^j \in X^j$ *is strictly increasing (strictly decreasing).*

Moreover:

9. $T := (T_{ij})$ *is not a diagonal matrix.*

[32] We suppose that the reader has some familiarity with the basics of games in strategic form and repeated games.

[33] Thus X^j is the action space of player j and f^j is its payoff function.

We introduce the following correspondence between standard game theoretical terminology and FTPG terminology. Player $\leftrightarrow$ *country*; action $\leftrightarrow$ *emission level*; multi-action $\leftrightarrow$ *emission vector*; action space $\leftrightarrow$ *emission space*; payoff function $\leftrightarrow$ *net benefits function*.

A possible real world interpretation of such a game is as follows. There are N countries (denoted by superscripts $j = 1, ..., N$). X^j is the set of country j's *emissions* (with elements x^j). Associated with the emission of each country j is a *production function* θ^j and a *damage cost function* D^j. Because of transboundary pollution, the emissions generated in a given country cause damage in countries other than the generating country. This process is represented by means of a $N \times N$ *transport matrix* T with elements T_{ij}. The 'portion' $T_{ij}x^j$ of country j's emission level x^j is deposited in country i. This implies that for the emission vector $(x^1, \ldots, x^N)$ the *deposition* in country j is $Q^j = \sum_{l=1}^{N} T_{jl}x^l$. Combining the above functions gives the above net benefits function

$$f^j(\mathbf{x}) := \theta^j(x^j) - D^j(\sum_{l=1}^{N} T_{jl}x^l).$$

The following observations apply. (i) 7 gives the usual assumptions regarding increasing marginal damage costs and strictly decreasing marginal production. (ii) 'Regular' refers to 8. These conditions will be used to guarantee that there is no country whose emission level in a Nash equilibrium or in a full cooperative emission vector is at the border of its emission space. These assumptions facilitate the analysis.[34] (iii) 'Smooth' refers to the differentiability properties of the production and damage cost functions. These smoothness properties are not (always) necessary in order to develop the theory, but they make the presentation easier. (iv) If T were a diagonal matrix, then the payoff function of each country would only depend on its own emissions. (v) In the literature one often assumes identical countries (that is, all production functions are the same and all damage cost functions are the same) and identical transport matrix coefficients to facilitate the analysis. Below we will consider the more realistic assumptions of uniformly distributed transboundary pollution, proportional production and identical damage cost functions to simplify the analysis. (vi) A FTPG can also deal with the greenhouse problem by setting all $T_{jl} = 1$.[35]

We denote $\mathcal{N} := \{1, \ldots, N\}$. We complete our vocabulary with the following definitions.

Definition 2 *Given a FTPG Z.*

1. *We speak of* uniformly distributed transboundary pollution *if, for each l, $T_{1l} = \cdots = T_{Nl}(=: T_l)$.*
2. *We speak of* proportional production functions *if for each pair of countries their production functions differ by a positive multiplicative constant: $\theta^j = \beta_{j1}\theta^1$ $(j \in \mathcal{N})$.*

[34]Our setting differs from the acid-rain game of Mäler in the sense that we don't allow unrealistic arbitrarily high emission levels.

[35]However, in that case it does not make sense to speak of 'depositions'.

3. *Country j is said to be* (in)sensitive to emissions *from country l if $T_{jl} > 0$ ($T_{jl} = 0$).*[36]

The first problem we are going to address concerns the question whether a country has a dominant emission level.[37]

Proposition 1 *The best reply correspondence of a country is a function with values in the interior of the emission space of that country.*

Less formally Proposition 1 says that given the emission levels of the other countries, there exists exactly one emission level of country j that maximizes its net benefits and moreover that this emission level is not 0 or M^j.

The best reply function is in general not constant. So a country in general does not have a dominant emission level. However:

Proposition 2 *A sufficient condition for a country to have a dominant emission level (and even a strictly dominant emission level) is that this country is insensitive to emissions from every other country. Another sufficient condition is that the country has an affine damage cost function.*[38]

It follows from the above that there exists a (unique) strictly dominant equilibrium in the case where each country has an affine damage cost function. Next we consider the existence and uniqueness of a Nash equilibrium and of a full cooperative emission vector.[39]

Theorem 1 *Each FTPG has a Nash equilibrium and a unique full cooperative emission vector. Both objects are in the interior of the set of emission vectors.*

Proposition 3 *A FTPG with uniformly distributed transboundary pollution has a unique Nash equilibrium.*

We now address Pareto efficiency (in the weak sense) of Nash equilibria.[40]

Theorem 2 *Sufficient and necessary for each Nash equilibrium to be Pareto inefficient in the weak sense is that each country is sensitive to emissions from at least one other country.*

Thus Theorem 2 states in particular that if each country is sensitive to emissions from at least one other country, there exists for each Nash equilibrium $\mathbf{n}$ an emission vector that is a unanimous Pareto improvement of $\mathbf{n}$.

[36]Of course, because $T_{jj} > 0$, each country j is sensitive to emissions from country j.

[37]That is, an emission level that is optimal for this country, independent of the emission levels of the other countries.

[38]It is possible that a country has a strictly dominant emission level even though none of these conditions holds.

[39]That is, a emission vector where the sum of all the net benefits functions is maximal.

[40]That is, Nash equilibria for which there does not exist a unanimous Pareto improvement, that is, a strict improvement for each country.

Corollary 1 *If each country has an affine damage cost function and if each country is sensitive to emissions from at least one other country, then the FTPG is a prisoners' dilemma game.*[41]

Because each strong Nash equilibrium[42] is Pareto efficient in the weak sense, we have:

Corollary 2 *A FTPG where each country is sensitive to emissions from at least one other country does not have a strong Nash equilibrium.*

The next question is whether a FTPG has a positive social welfare loss.[43] To answer this question, we first mention:

Theorem 3 *For the full cooperative emission vector, each country for which there is another country that is sensitive to emissions from it can increase its net benefits by a suitable enlargement of its emission level (while the other countries do not change their emission levels).*

Corollary 3 *A Nash equilibrium and the full cooperative emission vector are two different emission vectors.*

The (general game theoretical) fact that the set of Nash equilibria of a FTPG is compact, together with Corollary 3 imply:[44]

Corollary 4 *Each FTPG has a positive social welfare loss.*

Next we consider a Nash equilibrium $\mathbf{n}$ and confront it with the full cooperative emission vector $\mathbf{y}$. We address the question: How do the emission levels in $\mathbf{n}$ relate to those in $\mathbf{y}$? There seem to be misunderstandings in the literature concerning these questions. One misunderstanding is that for each country, the emission level in $\mathbf{y}$ would be less than or equal to that in $\mathbf{n}$ (and that consequently for each country, the deposition in the full cooperative emission vector is less than or equal to that in the Nash equilibrium). Moreover, there is the misunderstanding that the total emission level in $\mathbf{y}$ is less than or equal to the total emission level in $\mathbf{n}$.

To see that we have indeed here two misunderstandings, one can consider the following extreme case of two countries where country 1 is insensitive to emissions from country 2, country 1 has an affine damage cost function and the damage cost function of country 2 is strictly convex. In this situation it is indeed possible that $y^1 < n^1,\ y^2 > n^2$

[41]We call a game in strategic form a *prisoners' dilemma* if each player possesses a strictly dominant action and if the unique dominant equilibrium is Pareto inefficient in the weak sense.

[42]A multi-action of a game in strategic form is called a *strong Nash equilibrium* if there is no non-empty coalition that can improve on it. See, for example, Moulin (1981) for a precise formal formulation of this notion.

[43] We define the *social welfare loss* D of a game in strategic form as the difference between the maximal total payoff P and the maximal total Nash equilibrium payoff S. 'Total' refers to the sum over all players. (The precise definition involves of course the 'supremum'.)

[44]Corollary 4 should not be misinterpreted. It merely states that the total net benefits increases if the countries switch from the Nash equilibrium to the full cooperative emission vector.

and $y^1 + y^2 > n^1 + n^2$ may hold (at the same time) for some configurations of the parameters.

The cause for both misunderstandings is that one (sometimes even tacitly) assumes affine (and even linear) damage cost functions for each country. In that case Theorem 4 applies.

Theorem 4 *Consider the case where country j has an affine damage cost function. Then $y^j \leq n^j$ and even the strict inequality holds if there is another country that is sensitive to emissions from country j.*

We now consider the relationship between $\mathbf{n}$ and $\mathbf{y}$ in greater detail.

Proposition 4 *In the case of uniformly distributed transboundary pollution and identical damage cost functions, $\mathbf{y} \ll \mathbf{n}$ holds.*[45]

Proposition 5 *It is impossible that $\mathbf{y} \geq \mathbf{n}$; in particular it is impossible that the emission level for each country in a Nash equilibrium is lower than in the full cooperative emission vector.*

An interesting question is whether the total deposition in $\mathbf{n}$ is always at least as high as that in $\mathbf{y}$. The answer is: no!

Now we address the question: When is the full cooperative emission vector $\mathbf{y}$ a unanimous Pareto improvement of a Nash equilibrium $\mathbf{n}$? We first note that the definition of full cooperative emission vector and $\mathbf{y} \neq \mathbf{n}$ (that is, Corollary 3) imply that there exists at least one country k for which $f^k(\mathbf{y}) > f^k(\mathbf{n})$. But (as one can show for example with concrete examples), $\mathbf{y}$ is in general not a unanimous Pareto improvement of $\mathbf{n}$ (not even if all damage cost functions are affine). Here is a general result:

Proposition 6 *Given uniformly distributed transboundary pollution, proportional production functions, identical damage cost functions and $T_l = \beta_{l1} T_1$ $(l \in \mathcal{N})$, for countries j and k satisfying $T_j \leq T_k \leq \frac{1}{N} \sum_{r=1}^{N} T_r$, the inequality $f^k(\mathbf{y}) > f^j(\mathbf{n})$ holds.*

Corollary 5 *Sufficient conditions for $\mathbf{y}$ to be a unanimous Pareto improvement of $\mathbf{n}$ are that the countries are identical and the transport matrix coefficients are identical.*

Finally we consider the minimax payoffs for the countries in a FTPG. These are of fundamental importance in the analysis of repeated formal transboundary pollution games.

Proposition 7 $\mathbf{M}_i := (M^1, \ldots, M^{i-1}, M^{i+1}, \ldots, M^N)$ *is an optimal punishment against country i.*[46]

Proposition 7 implies, that for the minimax payoff $\overline{v}^i$ for country i we have $\overline{v}^i = \sup_{x^i \in [0, M^i]} f^i(x^i; \mathbf{M}_i)$.

For repeated FTPG's (which we will consider in subsection 4.2) it is important to know whether the net benefits vector for the full cooperative emission vector is

[45] That is $y^j < n^j$ for all j and $\mathbf{y} \neq \mathbf{n}$. And $\mathbf{y} \leq \mathbf{n}$ means $y^j \leq n^j$ for all j.

[46] Remember that M^j denotes the maximum emission level of country j.

individually rational, that is, whether $f^j(\mathbf{y}) \geq \overline{v}^j \ (j \in \mathcal{N})$. That this does not hold in general can easily be seen by referring to the extreme situation of a country which is insensitive to emissions from any other country. In this case the minimax payoff for that country will equal its highest possible net benefits, which is usually higher than its net benefits at $\mathbf{y}$. Of course, in the case where the full cooperative emission vector $\mathbf{y}$ is a Pareto amelioration of a Nash equilibrium, the net benefits vector for $\mathbf{y}$ is individually rational.

We say that a game in strategic form has a *j-defect* if for player j the payoff in each full cooperative multi-action is less than his minimax payoff (that is, is not individually rational for player j). We have seen that for a FTPG there may be a j-defect. However, in the exceptional case of identical countries and identical transport matrix coefficients Corollary 5 implies that there is no j for which the FTPG has a j-defect.[47]

Finally, we mention some problems for formal transboundary pollution games that need further research.

A. In the case where each country is sensitive to emissions from every other country, does there exist for each Nash equilibrium $\mathbf{n}$ a Pareto improvement $\mathbf{p}$ of $\mathbf{n}$ for which $\mathbf{p} < \mathbf{n}$?

B. Does there exists a FTPG with more than one Nash equilibrium?

C. Indicate a situation other than that presented in Corollary 5 where the full cooperative emission vector is a unanimous Pareto improvement of each Nash equilibrium is.

4.2 Repetition Enables Cooperation

It is well known that the theme 'repetition enables cooperation' (that we discussed in subsection 3.2) may be modeled by means of repeated games. We are now going to formally describe this theme by considering a repeated formal transboundary pollution game[48] denoted by RFTPG.

We define for a repeated game the *average social welfare loss* $[D]$ as the difference between the maximal average total payoff [P] and the maximal average total subgame perfect Nash equilibrium payoff $[S]$,[49] that is, $[D] = [P] - [S]$; it should be noted that average refers to periods. Let D, P, S be these objects for the stage game. One has of course $P = [P]$ and (because aggressive play of a Nash equilibrium of the stage game is a subgame Nash equilibrium of the repeated game) $S \leq [S]$; hence $[D] \leq D$. Of course, if a repeated game has a full cooperative subgame perfect Nash equilibrium, then there is no social welfare loss, that is, $[D] = 0$.

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[47] We think that most acid rain games in practice, like that of Mäler, have a j-defect for some j.

[48] Each repeated game in the rest of this section is assumed to be with discounting. Moreover each player is assumed to have the same discount factor $\delta \in (0, 1)$. And if we consider several repeated games (with the same players) together, then it is assumed that in each of them the discount factor is the same.

To avoid technicalities we always assume in this paper that in the case of an infinite horizon (that is, of infinitely many repetitions of the stage game) each payoff function of the stage game is bounded.

[49] See also footnote 43. Of course also the social welfare loss (that is, without 'average') of such a game is defined.

An alternative (but less attractive) definition would be to allow all Nash equilibria (that is, not only the subgame perfect ones) in the definition of $[S]$. This convention was taken in Folmer and v. Mouche (1994).

Lemma 1 *Each repeated game with a stage game with j-defect for which the convex hull of the payoff vectors is closed has a positive welfare loss.*

Proof.— The proof of Proposition 4.2 in Folmer and v. Mouche (1994) also applies here. □

The following notations and notions will be used. For two multi-actions $\mathbf{x}$ and $\mathbf{y}$ of the stage game of a repeated game, the multi-strategy $\ll \mathbf{x}, \mathbf{y} \gg$ is defined as follows: Player i plays x^i in period 0, and thereafter as long as every other player will play x^j; otherwise he will play y^i. A multi-strategy $\boldsymbol{\sigma}$ is called a *Friedman-trigger multi-strategy*[50] if there exists a Nash equilibrium of the stage game $\mathbf{n}$ and a unanimous Pareto improvement $\mathbf{p}$ of $\mathbf{n}$ such that $\boldsymbol{\sigma} \ = \ll \mathbf{p}, \mathbf{n} \gg$. In the case when the repeated game has an infinite horizon, the *critical discount factor* for each Friedman trigger multi-strategy $\ll \mathbf{p}, \mathbf{n} \gg$ is defined by $\delta^\star = \max_{j \in \mathcal{N}} \frac{\phi^j(\mathbf{p}^{\hat{j}}) - f^j(\mathbf{p})}{\phi^j(\mathbf{p}^{\hat{j}}) - f^j(\mathbf{n})}$ where ϕ^j denotes the best reply payoff function of player j. The *negotiation set* of $\mathbf{\Gamma}$ is the intersection of the closed convex hull of the set of its possible payoff vectors and its set of individually rational vector payoffs.[51]

It is well known that each average Nash equilibrium payoff of a repeated game belongs to the negotiation set of its stage game and that in the case of an infinite horizon, for a Friedman trigger multi-strategy $\boldsymbol{\sigma}$ of a repeated game, one has:

$$\boldsymbol{\sigma} \text{ is a Nash equilibrium } \Leftrightarrow \delta \geq \delta^\star. \tag{1}$$

$$\boldsymbol{\sigma} \text{ is a Nash equilibrium } \Rightarrow \boldsymbol{\sigma} \text{ is subgame perfect.} \tag{2}$$

We are now in a position to formulate the following theorem.

Theorem 5 *If each country is sensitive to emissions from at least one other country, the average social welfare loss of the RFTPG with infinite horizon is for discount factor close enough to* 1 *less than the social welfare loss of its stage game.*[52] *However, it will not be zero if the stage game has a j-defect for some j.*

Proof.— Because $[P] = P$ we have to show that $S < [S]$ in order to prove the first statement.

Because the set of Nash equilibria of a FTPG is compact, there exists a Nash equilibrium $\mathbf{n}$ such that $S = \sum_{j=1}^N f^j(\mathbf{n})$. Theorem 2 gives the existence of a unanimous Pareto improvement $\mathbf{p}$ of $\mathbf{n}$. Because of (1), the Friedman-trigger strategy $\ll \mathbf{p}, \mathbf{n} \gg$ is for discount factor close enough to 1 a subgame perfect Nash equilibrium of the RFTPG with average total net benefits equal to $\sum_{j=1}^N f^j(\mathbf{p})$ and thus higher than $\sum_{j=1}^N f^j(\mathbf{n})$. Hence $[S] > S$. To prove the second statement we first note that the set of net benefits vectors of a FTPG and consequently also its convex hull is compact and then apply Lemma 1 to the RFTPG. □

So Theorem 5 says that in general, infinite repetition of a FTPG implies, if countries are sufficiently patient, a social welfare improvement in the sense that its average social

[50] or *Nash threat*.

[51] A negotiation set may be empty.

[52] Remember (from Corollary 4) that a FTPG has a positive social welfare loss.

welfare loss is smaller than that of the stage game. The reason is that repetition enables cooperation induced by the threat of retaliation. However, if for some country the net benefits is less than its minimax payoff, the average welfare loss of the RTFPG will (still) not be zero. It is here that side payments may become relevant or, alternatively, interconnection which will be discussed in the next subsection. So a major problem for a (R)FTPG, and the underlying international environmental problems, is that in general it has a social welfare loss.

4.3 Four Themes for Interconnection

Similar to the theme 'repetition enables cooperation' for repeated game theory, the theme 'interconnection can sustain more cooperation' is typical for interconnected game theory. This theme can be modeled by means of so called tensor games which are a special type of repeated multiple-objective games. Because tensor games are less well known we will explain this notion here by means of an example.[53]

We consider two unrelated problems in which two countries are simultaneously involved. We assume that each problem is modeled by a repeated prisoners' dilemma game, where the countries simultaneously choose in any game one of two actions: C (cooperate) and D (defect[54]). We denote these repeated games by $< {}_1\mathbf{\Gamma} >$ and $< {}_2\mathbf{\Gamma} >$ where ${}_1\mathbf{\Gamma}$ and ${}_2\mathbf{\Gamma}$ are the following stage games:

$$(A) \qquad {}_1\mathbf{\Gamma} = \begin{pmatrix} 2;\ 1 & -3;\ 2 \\ 5;\ -1 & 0;\ 0 \end{pmatrix}, \qquad {}_2\mathbf{\Gamma} = \begin{pmatrix} 1;\ 2 & -1;\ 5 \\ 2;\ -3 & 0;\ 0 \end{pmatrix}.$$

Observe that ${}_1\mathbf{\Gamma}$ possesses a unique full cooperative multi-action, namely (D, C) and that the payoff vector $(5, -1)$ at (D, C) is not individually rational for player 2. (See also Figure 1.) So ${}_1\mathbf{\Gamma}$ has a 2-defect.[55] Lemma 1 implies that $< {}_1\mathbf{\Gamma} >$ possesses a social welfare loss. For $< {}_2\mathbf{\Gamma} >$ one can deduce similar conclusions, since ${}_2\mathbf{\Gamma}$ is the mirror game of ${}_1\mathbf{\Gamma}$. (Again see Figure 1.)

In principle, the two countries can interconnect the two problems by allowing strategic interactions among them. This comes down to four actions for each country: $\begin{pmatrix} C \\ C \end{pmatrix}$, $\begin{pmatrix} C \\ D \end{pmatrix}$ $\begin{pmatrix} D \\ C \end{pmatrix}$ and $\begin{pmatrix} D \\ D \end{pmatrix}$, where the first coefficient refers to game 1 and the second to game 2. Suppose (again) that it is meaningful to sum the payoffs in the two problems,[56] that the actions in both games are taken simultaneously and that the discount factors in both problems are the same. This gives the following repeated game with stage game

$$(\oplus\mathbf{\Gamma})_\alpha := \begin{pmatrix} 3;\ 3 & 1;\ 6 & -2;\ 4 & -4;\ 7 \\ 4;\ -2 & 2;\ 1 & -1;\ -1 & -3;\ 2 \\ 6;\ 1 & 4;\ 4 & 1;\ 2 & -1;\ 5 \\ 7;\ -4 & 5;\ -1 & 2;\ -3 & 0;\ 0 \end{pmatrix}$$

[53] This example is designed in such a way that it illustrates two other typical properties for interconnection.
[54] or non-cooperate.
[55] See subsection 4.1 for this notion.
[56] More generally a weighted sum of payoffs could be considered. Here we take for simplicity reasons all weights equal to 1 and denote this particular choice by (the subscript) α.

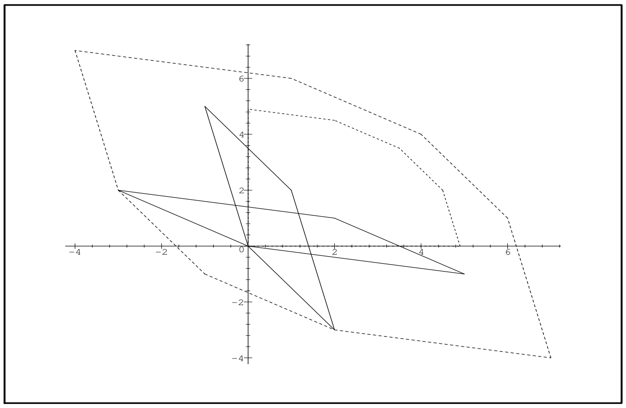

Figure 1: (A) Everywhere expansion.

that is, $< (\oplus\mathbf{\Gamma})_\alpha >$ which we will also denote by $(\otimes\mathbf{\Gamma})_\alpha$. This game is called a *tradeoff tensor game* and the game $(\oplus\mathbf{\Gamma})_\alpha$ is called a *tradeoff direct sum game*.[57]

If there are at least 2 periods, $(\otimes\mathbf{\Gamma})_\alpha$ contains new strategies which are not provided in a natural way by the (so called) constituting isolated games $< {}_1\mathbf{\Gamma} >$ and $< {}_2\mathbf{\Gamma} >$; we call such a strategy *really interconnected*. Indeed, with the multi-actions

$$\mathbf{P} := (\begin{pmatrix} D \\ C \end{pmatrix}, \begin{pmatrix} C \\ D \end{pmatrix}) \text{ and } \mathbf{N} := (\begin{pmatrix} D \\ D \end{pmatrix}, \begin{pmatrix} D \\ D \end{pmatrix}),$$

the multi-strategy $\mathbf{\Sigma} := \ll \mathbf{P}, \mathbf{N} \gg$ is than an example of a really interconnected multi-strategy.[58] Notice that $\mathbf{P}$ is a full cooperative multi-action, that $\mathbf{N}$ is a Nash equilibrium and that $\mathbf{P}$ is a unanimous Pareto improvement of $\mathbf{N}$; on the other hand, neither ${}_1\mathbf{\Gamma}$ nor ${}_2\mathbf{\Gamma}$ possesses a full cooperative multi-action that is a unanimous Pareto improvement of a Nash equilibrium.

From now on we assume in this example that the horizon is infinite. So by applying (1) and (2) (see subsection 4.2) to $\ll \mathbf{P}, \mathbf{N} \gg$ we obtain the interesting conclusion that the tensor game $(\otimes\mathbf{\Gamma})_\alpha$ for discount factor at least equal to the critical discount rate $\delta^\star = \frac{1}{5}$ (for $\ll \mathbf{P}, \mathbf{N} \gg$) has a full cooperative subgame perfect Nash equilibrium and therefore no social welfare loss. This may be interpreted as: Interconnection may eliminate social welfare losses.

In order to state our next theme we limit ourselves for simplicity reasons for the moment to multi-strategies of the type $\ll \mathbf{b}, \mathbf{a} \gg$ where $\mathbf{b}$ is an unanimous Pareto improvement of $\mathbf{a}$. The repeated game $< {}_k\mathbf{\Gamma} >$ now has a unique multi-strategy of this type, namely $\ll (C, C), (D, D) \gg$. Its critical discount factor ${}_k\delta^\star$ is equal to

[57] In fact $(\oplus\mathbf{\Gamma})_\alpha$ is the tensor sum of the bi-matrix ${}_1\mathbf{\Gamma}$ with ${}_2\mathbf{\Gamma}$.

[58] See Theorem 4.3 in Folmer et al. (1993) for a formal proof of this statement.

$\frac{3}{5}$. Note that $\delta^\star < \min({}_1\delta^\star, {}_2\delta^\star)$, an inequality which may be interpreted as follows: Interconnection can facilitate cooperation.

Now let us consider the negotiation sets. Let ${}_kH$ be this set for ${}_k\mathbf{\Gamma}$ and H_α for the trade-off direct sum game $(\oplus\mathbf{\Gamma})_\alpha$. Also ${}_1H + {}_2H$ is interesting, since it represents 'the negotiation set when the games are not interconnected'. In Figure 1 these four sets (that is, ${}_1H,\ {}_2H,\ {}_1H + {}_2H$ and H_α) can be distinguished: In this figure we first draw the (closed) convex hull of the payoff vectors of ${}_1\mathbf{\Gamma}$ and of ${}_2\mathbf{\Gamma}$. Since the minimax payoff vectors are **0** in ${}_1\mathbf{\Gamma}$ and in ${}_2\mathbf{\Gamma}$, the sets ${}_1H$ and ${}_2H$ can be distinguished. Then ${}_1H + {}_2H$ is calculated and drawn; in the figure it is the boldfaced polygon. Because the minimax payoff vector for $(\oplus\mathbf{\Gamma})_\alpha$ is (as a consequence) also **0**, the set H_α can be distinguished. From this figure we see that we have the (strict) inclusion ${}_1H + {}_2H \subset H_\alpha$. This may be interpreted as follows: Interconnection can sustain more cooperation. Moreover we see from Figure 1 that at each point $\mathbf{w}$ of $\mathrm{MAX}({}_1H + {}_2H)$, that is, of the Pareto boundary of ${}_1H + {}_2H$, there is expansion, that is, a point of the Pareto boundary of H_α which is a unanimous Pareto improvement of $\mathbf{w}$; we say therefore that there is *everywhere expansion*. This may be interpreted as follows: Interconnection can bring Pareto improvements.

The results for the above example suggest the following themes (for tensor games):

T1. Interconnection can sustain more cooperation.

T2. Interconnection may eliminate social welfare losses.

T3. Interconnection can bring Pareto improvements.

T4. Interconnection can facilitate cooperation.

(Figure 1 illustrate clearly the Themes T1-T3.)

The explanation of the (in fact related) themes T1-T4 finds its origin in the fact that in general each player in a tensor game has many more strategies than the totality of the strategies in the constituting isolated games.[59]

The question arises whether the above example is not an artefact and so for what situations T1-T4 are valid. This question with respect to T3 is further elaborated in Figures 2-4.

These figures relate respectively to the games:[60]

$$(B) \quad {}_1\mathbf{\Gamma} := \begin{pmatrix} 7;\ 1 & -3;\ 3 \\ 10;\ -2 & 0;\ 0 \end{pmatrix},\ {}_2\mathbf{\Gamma} := \begin{pmatrix} 1;\ 7 & -2;\ 10 \\ 3;\ -3 & 0;\ 0 \end{pmatrix};$$

$$(C) \quad {}_1\mathbf{\Gamma} := \begin{pmatrix} 2;\ 2 & -2;\ 4 \\ 4;\ -2 & 0; 0 \end{pmatrix},\ {}_2\mathbf{\Gamma} := \begin{pmatrix} 2;\ 2 & -1;\ 1 \\ 1;\ -1 & 0;\ 0 \end{pmatrix};$$

$$(D) \quad {}_1\mathbf{\Gamma} := \begin{pmatrix} 2;\ 2 & -2;\ 10 \\ 10;\ -2 & 0;\ 0 \end{pmatrix},\ {}_2\mathbf{\Gamma} := \begin{pmatrix} 3;\ 3 & -3;\ 4 \\ 4;\ -3 & 0;\ 0 \end{pmatrix}.$$

[59]This statement can be formalized by, for example, Theorem 4.3 in Folmer and v. Mouche (1994).

[60]Notice that all these games, with the exception of ${}_2\mathbf{\Gamma}$ in (C), are prisoners' dilemma games.

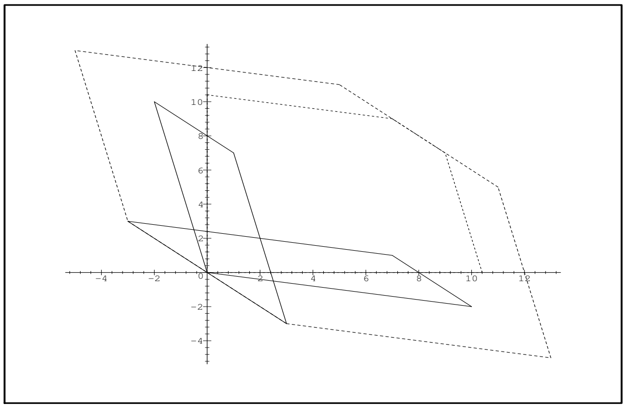

Figure 2: (B) Partial expansion.

Figure 3 shows a situation where the statement in Theme T3 does not hold: There is *nowhere expansion* in this situation. In the situations of Figures 2 and 4 there is *partial expansion* (that is, not nowhere expansion but also not everywhere expansion).

Themes T1, T2 and T4 are dealt with in Folmer et al. (1993) and in Folmer and v. Mouche (1994). T1 is elaborated in Ragland (1995), who also initiated an analysis of T3. Cesar and de Zeeuw (1996) deal with T1 and T2 and initiate an analysis of renegotiation proofness.[61]

We will now propose in the rest of this subsection a programme for further research with respect to the Themes T1 and T3. To this end we start by considering, in the general case of M constituting isolated games, the relationship between the negotiation sets ${}_kH$ of the stage games involved and the negotiation set H_α of the trade-off direct sum game:

Proposition 8 $\sum_{k=1}^{M} \; {}_kH \subseteq H_\alpha$.

Proof.— See Theorem 4.2 in Folmer and v. Mouche (1994). □

Given Proposition 8, we formulate the research question with respect to Theme T1 as: When does the strict inclusion $\sum_{k=1}^{M} {}_kH \subset H_\alpha$ hold?

Theme T3 deals with the Pareto boundaries of ${}_1H + \cdots + {}_MH$ and H_α. We formulate the following research question for it: Determine the type of expansion (that is, everywhere, partial or nowhere). Of course there is nowhere expansion if $\sum_{k=1}^{M} {}_kH = H_\alpha$ (which happens for instance when all ${}_kH$ are identical or when a ${}_kH$

[61] It should be observed that the above mentioned papers deal almost exclusively with constituting isolated games that are (exact) mirror games of each other (not excluding that each constituting isolated game has asymmetries, that is, that it is not a symmetric game). But it can be shown that T1-T4 hold more generally, but this will be not done in this review paper.

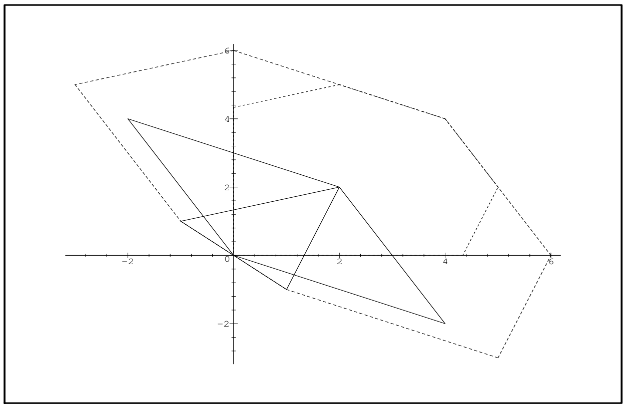

Figure 3: (C) Nowhere expansion.

is empty). But $\sum_{k=1}^{M} {}_kH \neq H_\alpha$ does not imply that there is somewhere expansion as Figure 3 shows.[62]

5 CONCLUSIONS

This paper deals with international environmental problems and policy, in particular international cooperation. The first part (sections 1-3) sets out the main result in this area in a non-technical fashion. The second part (section 4) spells out the features of transboundary pollution problems and international cooperation in a formal and mathematically rigorous way. The rationale for the latter approach is to present the precise conditions for further technically oriented research in this area.

Typical for international environmental problems and policy is that the players in

[62]Figures 1-4 are intriguing. They make it clear that T1 and T3 involve a geometric problem. It is worth formulating this problem, without referring to game theory at all, which needs further research, separately (taking $\mathbf{0}$ for the minimax payoff vectors):

(Geometric problem.) Given convex compact subsets ${}_kF$ $(1 \leq k \leq M)$ of $\mathcal{R}^N$ let

$${}_kH \ := \ {}_kF \cap \mathcal{R}^N_+, \ H \ := \ \sum_{k=1}^{M} {}_kH \text{ and } H_\star \ := \ (\sum_{k=1}^{M} {}_kF) \cap \mathcal{R}^N_+.$$

One easily verifies that $H \subseteq H_\star$. Denoting $\mathrm{MAX}(H)$ as the set of maximal elements of H with respect to the natural partial ordering on $\mathcal{R}^N$, let

$$\mathrm{EXP} \ := \ \{\mathbf{x} \in \mathrm{MAX}(H) \mid \text{ there exists a } \mathbf{y} \in H_\star \text{ with } y^j > x^j \ (1 \leq j \leq N)\}.$$

1. Under what conditions is $H = H_\star$?
2. Under what conditions is $\mathrm{EXP} = \emptyset$ and when is $\mathrm{EXP} = \mathrm{MAX}(H)$?

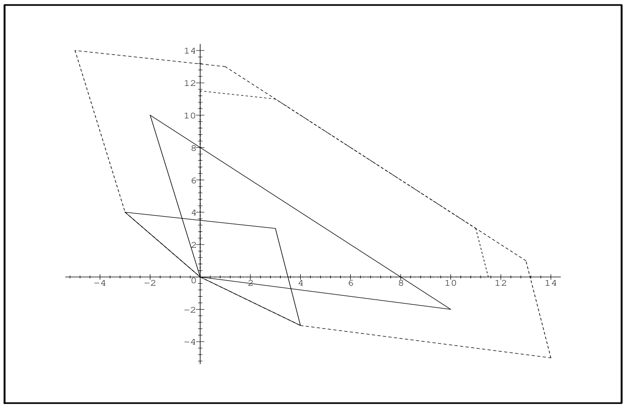

Figure 4: (D) Partial expansion.

the international arena are sovereign states. This implies that participation in and implementation of international environmental policy is at the discretion of the governments of the counties involved. In contrast to domestic environmental problems international environmental policy is voluntary. This feature has turned non-cooperative game theory into an indispensable tool for analysing international environmental problems and policy.

Countries can take a market, a non-cooperative or a cooperative approach to international environmental problems. In the first, environmental degradation and its welfare impacts are ignored, whereas in the non-cooperative approach a country only takes the impacts of its emissions on its own welfare into account. In the case of a cooperative approach a country selects an allocation that is Pareto efficient, which need not hold for a market or a non-cooperative approach. The set of Pareto efficient allocations comprises several approaches including the Nash bargaining solution and the full cooperative approach. Special attention is paid to the latter. It is characterised by the fact that a country not only takes the impacts of its emission on its own welfare into account but also on all the other countries. In subsection 2.2 we argue that the full cooperative approach is superior to the non-cooperative approach in terms of effectivity and efficiency. Relationships between the non-cooperative and the full cooperative approach are spelled out in subsection 4.1. In particular, we show there in the context of a formal transboundary pollution game that it is a misunderstanding that the emission level for each country in the full cooperative outcome is less than or equal to that in the non-cooperative outcome. Similarly total emissions in the former are not necessarily less than or equal to more in the latter.

In spite of the attractive features of a cooperative and the full cooperative approach in particular, it is often difficult for countries to (fully) cooperate. An impediment to the full cooperative approach is that it may imply net welfare losses for some countries and net welfare gains to others. Another impediment to the full cooperative approach is that even though the net benefits of full cooperation are positive, a country has an incentive to free-ride. By staying out of an agreement or by defecting from a concluded one, it may be possible for a country to obtain virtually the same benefits of pollution control as by joining it. Free-riding is especially a problem in situations where an international environmental agreement is concluded once and for all and where it is agreed upon in advance that the treaty will hold for a limited period only (finally repeated games). The reason that commitment is a problem under these conditions is that there often are no opportunities for punishing a defection under these conditions.

In subsection 3.1 we first discuss the use of side payments as an instrument to induce (full) cooperation. Side payments are transfers to those countries whose net benefits from full cooperation would be negative. However, there exist several objections to the use of side payments. First, there exist no rules with respect to the allocation of side payments. In particular, the question arises how large the losers share in the net benefits should be. Secondly, the anticipation of side payments may induce countries to act strategically and minimize their environmental policy even below the level determined by a non-cooperative approach covered by side payments. Thirdly, side payments may weaken the compensating countries negotiating position. This may apply to environmental as well as non-environmental problems.

Lack of (full) cooperation can be deterred by punishing a deviant by defection from the agreement by the other players. In the case of defection from an agreement a country can at first instance be expected to be punished by sanctions specified by an international organisation. However, because of its souvereignity, a country can ignore such sanctions. In that case further possibilities for punishment exist if the other countries stop cooperating. The potential net loss from a break down of the agreement forms an incentive not to defect. The conditions for retaliation in an infinitely repeated games context, using Nash threats, are spelled out in subsection 4.2 in a technical sense and in an informal fashion in subsection 3.2. In the latter subsection also some alternatives to Nash threats which are relentless are mentioned. In particular, Abreu's more realistic carrot and stick punishment comes down to a period of punishment followed by continued cooperation if the deviant accepts this punishment.

A final instrument to stimulate cooperation is interconnection which comes down to an exchange of concessions in fields of relative strength. For instance, consider a country which would like to see another country reduce its emissions whereas that other country would like the first country to discontinue its restriction of imports. The first country could offer trade concessions in order to induce the other country to clean up its act. A prerequisite for interconnection is the existence of reversed interests. By means of a simple example we show in subsection 4.3 that interconnection can sustain more cooperation, eliminate welfare losses, lead to Pareto improvements and facilitate cooperation. In subsection 3.3 some real world examples of interconnection in the international environmental arena are mentioned. Some empirical support for the advantages of interconnection are also briefly described. Finally we point out that although the literature on international environmental problems and policy has been rapidly expanding, especially research on interconnection is still in its infancy.

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