Chapter 12

THE ACID RAIN GAME*

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1 INTRODUCTION

During the last couple of years, the problems connected with emissions of sulfur- and nitrogen oxides and the resulting damages on eco-systems have come more and more in the focus. The death of forests in central Europe and Scandinavia have been quite important news items and rightly so, because if the European eco-systems will change so drastically there will be a substantial reduction in timber supply, that will effect not only nature conservationists but also everyday man because of the economic consequences in a conventional sense. Thus, the problems of acid rains seem to be a very important issue for economists to analyse. Moreover, it offers a fascinating multitude of intellectual challenges, one being that the information on causes and effects is very uncertain, another being that it concerns the use of a common property resource in a very asymmetric way, a third being that it is about a game with incomplete information and with many players so that problems with incompatible incentives will be at the heart, and finally, the parties involved are different nations with no agreed rules of the game. In addition to these challenges, there are of course a multitude of equally challenging empirical problems.

The objective of this paper is to give a skeleton of an analytical model in which some of the above problems, and in particular the problems of international cooperation, will be analysed. However, in view of the complexities of the interactions between national

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emissions and the resulting environmental damage, we will make a few, rather serious simplifications. Our basic model will concentrate on national sulfur emissions in different countries in Europe. Thus, we will not look into the very relevant issue of spatial distribution of the emissions in each country. Nor will we look into the spatial distribution of damages within each country. Finally, we will neglect the effects of nitrogen oxide emissions and the formation of ozone, although it seems clear that these factors are perhaps as much to be blamed as sulfur emissions for the observed damages to forests. Moreover, it should be stressed that this paper is one in a series of different papers, analysing different aspects of international cooperation in the environmental field.

Thus we will discuss the following scenario. Each European country is emitting sulfur oxides, the amount of which depends on energy consumption, sulfur content in the burnt fuels, the combustion technology and stackgas cleaning technology. By switching to fuels with lower sulfur content, by changing combustion technology, by reducing energy consumption etc. it is possible to reduce the emissions of sulfur, but at a cost. Thus we will postulate a cost function for reducing the emissions. The expected control cost function for country i will be denoted $C_i(E_i)$ where E_i denotes the emission in country i. This function is, of course, decreasing in E_i, as the cost of abatement increases with abatement. We will also assume C_i to be strictly convex (although in some simulation it will be linear or piecewise linear). Moreover, we will assume it to be sufficiently smooth.

The emissions will have local effects due to the resulting ambient concentrations of sulfur oxides. These local effects are health effects, corrosion to materials, damage to vegetation etc. We will for the discussion in this paper assume that we have a monetary damage function for these local effects so that we can form the net control cost function by subtracting the local damage from the control cost function. [1] We will in the sequel reinterpret C_i as the expected net control cost function. The cost functions actually used in the simulations presented in this paper are, however, gross, i.e. do not include local damage costs.

The sulphur emitted will be transported by winds in the atmosphere and will also be transformed by chemical processes from sulfur oxides to sulphates. Ultimately, the

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[1] This construction is not completely correct as the local damage from increased ambient concentrations of sulfur oxides is not directly related to the emissions but also to the height of the stack, the location of the stack etc. We will, however, neglect those factors here.

sulphates will be removed from the atmosphere by direct "dry" deposition or by rains-"wet" deposition. It turns out that there exists at least one meteorological model that describes this transportation and transformation and is simple enough to be used for an economic analysis of the acid rain problem and is accepted by most European countries as giving a fair description of the actual processes, namely the EMEP model. The EMEP model is based on a grid by which Europe is divided into about 700 squares. The model assumes sulfur emissions in these squares and by using observations on actual winds etc. the air package above a square is followed as it moves from one square to another. The model predicts the chemical changes within the airpackage and the removal of sulfur from the package in the form of deposition. With steady state climatic conditions, the model reduces to a transfer matrix with a dimension equal to about 700 times 700. An element in the matrix gives the amount of sulfur deposition in one square, following the emission of one ton in another square. However, for the purpose of this study, the matrix is aggregated into a country times country matrix, i.e. with a dimension 28 times 28, so that a typical element in the matrix describes the deposition in one country that is due to the emission of one ton in another country.[2] However, Iceland has been excluded, so the actual matrix is of order 27 times 27. Finally, as the contribution to the acid rain problem from Luxemburg is negligible, Luxemburg has been deleted from all tables containing results from the calculations.

The transfer is denoted by the matrix A. If E is the vector of emission levels in the European countries and if Q is the vector of sulfur deposition in the countries, the steady state model for the transport of sulfur is simply $Q = AE$.

The deposition of sulfur gives rise to various environmental damages. The first environmental problems from acid rains to be observed were acidification of surface water. It was noted, mainly in Scandinavia, that the Ph-level of lakes and streams was falling, and in some cases to such low levels that further life of traditional species was inhibited.[3] It soon became quite clear that even the ground water was affected and that in the long run, the growth of the forests would be reduced. These effects are now being observed both in Scandinavia and central Europe.

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[2] See Binmore and Dasgupta (1986).

[3] One of the early reports on environmental damage from acid rains is to be found in the Swedish case study to the U.N. conference on human environment in Stockholm 1972.

However, the experts on forest ecology are not in agreement on the factors behind the damages.[4] There seems to be three explanations that have been put forward. According to the first, the forest damages are due to acidification of and the resulting chemical changes in the soil. The acidification of the soil is then explained by the deposition of sulfur from the atmosphere. Another explanation gives the blame to increased ambient concentrations of nitrogen and sulfur oxides. These concentrations are very high close to the points of emissions but fall very rapidly with the distance. One of the main sources of nitrogen oxides is the automobile, and it is possible in many countries to watch dying trees close to motorways. If this would be the only explanation of forest damages, then the international aspects of the problem would be negligible and it would be almost completely a domestic issue. (Recently, research results have, however, indicated that NO_x may also be transported by winds for long distances.)

Finally, there is the "stress theory", which in a way integrates the two previous ones, namely that the defense to extra stress the trees can provide is reduced by pollution. Thus the explanation would consist of many different factors. It should be clear from above that there is no simple answer to the question: what are the environmental consequences from acid rains? In fact, the uncertainty is so great that one could imagine that acid rains have nothing to do with the death of forest and also that they are the main and only culprit. (It should be added that the damage from acid rains to surface and ground water is much more firmly established.)

Because of this uncertainty, we should then talk about an expected damage function of deposition of sulfur. We, therefore, posit the existence of an expected damage function for each country which relates the deposition of sulfur to a monetary measure of damage. Assume that the deposition in country i is Q_i. Then we will denote the expected damage cost function (or simply damage function) by $D_i(Q_i)$. For each country we thus have an expected net control cost function and an expected damage cost function. We will assume that these functions as well as the EMEP matrix that relates the emissions from one country to deposition in all other countries, are known by all countries.

The net control cost functions, the EMEP matrix and the damage functions define a non-cooperative game, in which the strategy for a country consists of choosing an emission level and the payoff is equal to minus the sum of the net control cost and the

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[4] For a summary of different hypotheses explaining the death of forests, see Hinrichson (1986).

damage cost (except for an uninteresting constant). This game is quite similar to the ones analysed for common property resources, except that those games generally deal with a symmetric situation while this acid rains game deals with a highly asymmetric case. The reason this 'acid rain game' is asymmetric is that the matrix A is non-symmetric because of the prevalent wind directions. Emissions in some countries are more harmful than in others simply because of their locations. In section 2, different non-cooperative solutions to this game are defined and analysed and compared with the full cooperative solution (i.e. the solution that would emerge if all countries would cooperate and maximize their joint payoff, assuming that utility is transferable). In the following sections different cooperative equilibrium concepts are defined, discussed and illustrated by simulations.

2 NON-COOPERATIVE EQUILIBRIA AND THE FULL COOPERATIVE SOLUTION

The purpose of the simulations to be presented in the next section is to get a feeling for the gains from cooperation the European countries could expect. Ideally, one would therefore be interested in the core and related equilibrium concepts of the acid rain game. In section 6 these concepts are defined and discussed in more detail. In this section the interest is focused on the "full cooperative solution". This was defined in the previous section as simply that vector E of emission levels that minimizes the expected total cost, i.e.

$$\min \sum_{i} (C_i(E_i) + D_i(Q_i))$$

$$\text{subject to } Q = AE.$$

This solution concept implicitly requires transferable utility, i.e. that gains in one country can be transferred to other countries in order to achieve another distribution of gains and losses. As both cost and damage functions are measured in monetary units we thus assume that utility is linear in income and transferable between countries (which incidentally requires that the current exchange rates are equilibrium rates).

The reason the solution is defined as the minimum of expected cost (expected instead of simply cost) is that in general both damage- and control costs are uncertain. However, we shall in the sequel disregard this kind of uncertainty. Thus, the full cooperative solution could as well be defined without the expectation operator.[5] There is another kind

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[5] The expectation operator has been included because in some companion papers the role of uncertainty is the focus of analysis.

of uncertainty which we must look into, however. This has to do with the information one country may have about costs and damage in other countries. In general, the control costs and environmental damage in one particular country is known only to that country (under the present assumptions). The lack of information is, in fact, so great that total emissions of sulfur in one country are unknown to other countries and the total deposition of sulfur in one country can only be estimated with the aid of the EMEP-model given the assumptions about the pattern of emissions. In this report, this aspect will be neglected. Instead, in a subsequent paper, this aspect will be the main problem to be discussed.

The full cooperative solution is a special case of the "Pareto-efficient" outcome. A vector $(E,Q) = \{E_1, E_2, ..., E_n, Q_1, ..., Q_n\}$ is said to be Pareto efficient if there does not exist another feasible vector (E', Q') such that the total cost (control- and damage cost) for each country at these alternative emission and deposition levels is less than or equal to the total cost at the (E, Q) level. If the feasible set is convex (which it is with our assumptions on the control- and damage cost functions and the linearity of the transport models), then all Pareto-efficient outcomes can be characterized as vectors (E, Q) that minimize

$$\sum_i \alpha_i\{C_i(E_i) + D_i(Q_i)\}$$

for a certain selection of $\alpha_1, ..., \alpha_n$, with $\alpha_i > 0, i = 1, ..., n$.

If (E', Q') is any allocation of emissions and depositions that is feasible (i.e. $Q' = AE'$), then P(E', Q') denotes the set of feasible allocations of emissions and depositions that Pareto dominates (E', Q'), i.e.

$$P(E', Q') = \{(E, Q); C_i(E_i) + D_i(Q_i) \leq C_i(E_i') + D_i(Q_i'), Q = AE\}$$

A subset of the Pareto efficient allocations is thus a subset of the boundary of P(E', Q'). Note that for a given (E', Q'), the full cooperative solution need not be a member of P(E', Q'). If that is not the case when (E', Q') is the initial situation, then the full cooperative solution will not be obtained unless there are sidepayments among the countries.

We can define (at least) two different non-cooperative equilibrium concepts.

i) Dominant equilibrium (E_k^*, Q_k^*), $Q_k^* = A E_k^*$, $k = 1,...n$ is a dominant equilibrium if for all E, Q such that $Q = AE$ it is true that for all $k = 1,...n$

$$C_k(E_k^*) + D_k(Q_k^*) < C_k(E_k) + D_k(Q_k)$$

Thus, a dominant equilibrium is characterized by a set of strategies E_k^* such that irrespective of what other countries do, it would not be beneficial for country k to change its strategy.

It is very easy to see that in general no dominant equilibrium will exist and we will give a proof in connection with the discussion of Nash equilibrium. However, under one special condition which is the basis for the simulations discussed later, a dominant equilibrium will exist. This condition is that the expected damage function is linear so that the marginal damage is constant. If that is the case the cost minimization emission in a country is determined by the condition that marginal abatement cost equals the marginal damage times the proportion of the emission that will be deposited in the own country. As the marginal damage is independent of the emissions in other countries, it follows that the cost minimizing emission is independent of the emissions in other countries and thus constitutes a dominant strategy.

ii) Nash equilibrium. A Nash equilibrium is defined as a pair (E^*, Q^*) such that

$$C_k(E_k^*) + D_k(Q_k^*) \leq C_k(E_k') + D_k(Q_k'), \quad k=1,\ldots n$$

where Q' is defined by

$$Q' = AE'$$

$$E_l' = E_l^* \qquad l=1, \ldots, n, \ l \neq k$$

Thus a Nash equilibrium is characterized by the condition that if all other countries are emitting their Nash equilibrium quantities, then it is optimal for the remaining country to do that too.

The Nash equilibrium concept has a very solid base in economic theory and the intuitive reasons behind the concept should be clear.[6] It is based on the idea that the countries are rational. That means that they, if they have the necessary information, can calculate the optimal behavior of all other countries (including the other's optimal response to the amount emitted in the own country) and therefore the own optimal response. This rationality is based on one crucial assumption, however, namely that each country has complete information on the others' emissions, control costs, depositions and damage costs. As was noted above, such is not the case and the Nash equilibrium concept (at least as it has been defined here) cannot be rigorously defended. However, in spite of this we will for the rest of this section disregard this criticism and continue as if the game under consideration is a game with complete certainty.

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[6] See Binmore and Dasgupta (1986).

In order to be able to prove the existence of a Nash equilibrium we will make the following assumptions:

a) The control cost-and damage functions are twice continuously differentiable;

b) $D_k'(Q_k)$ (here and in the sequel the symbol ' attached to a function denotes the derivative) goes to infinity with Q_k (that is, we are looking at the other extreme compared with the assumption of constant marginal damage made above);

c) C_k' goes to zero with E_k;

d) all elements a_{kk} of matrix A are different from zero for all countries k.

The best reply of country k given that the other countries emit E_l, $l=1, ..., n$, $l \neq k$, is given by the function $\phi(E)$ defined as the emission that minimizes the total cost in country k given the emissions in the other countries.

It is easily seen that for each $k=1, ..., n$ there exist $\overset{o}{E}_k$ such that there exists an E' within the cube defined by the origin and $\overset{o}{E}_k$, $k=1,...,n$ in $n+1$ space, such that $C_k(E_k') + D_k(AE')$ is less than the corresponding costs for points outside the cube. Thus we can restrict ourselves to this compact set when searching for a Nash equilibrium. But then the feasibility sets of all players are compact and the payoff functions are continuous and there exists a Nash equilibrium.

It is easily seen that under the assumptions made, the best reply functions are implicitly defined by

$$dC_i/dE_i + a_{ii}\, dD_i/dQ_i = 0, \quad i = 1, 2, ..., n.$$

The Jacobian of this system of equations is given by

$$\begin{bmatrix} C_1''(E_1) + a_{11}^2 D''(Q_1) & ...a_{11}a_{1n}D''(Q_1) \\ ... & \\ a_{nn}\, a_{n1}\, D''(Q_n) & ...\, C_n''(E_n) + a_{nn}^2\, D''(Q_n) \end{bmatrix}$$

where the symbol " denotes the second derivative.

The sum of the off-diagonal elements in row i is equal to

$$\sum_{j\neq i} a_{ii}a_{ij}\, D''(Q_i)$$

and the diagonal element is

$$C_i''(E_i) + a_{ii}^2 D''(Q_i)$$

The Jacobian has therefore a dominant diagonal if

$$C_i'' + a_{ii}D'' (a_{ii} - \sum_{j \neq i} a_{ij}) > 0.$$

Scrutiny of the EMEP model reveals that the term within paranthesis is positive for most European countries. In the cases where this term within paranthesis is less than zero, it has a rather small magnitude (in the order of .1). Multiplied with a_{ii} the second term will be small and it seems reasonable to assume that the Jacobian has a dominant diagonal. This means, however, that the Nash equilibrium is unique according to well-known theorems.[7] Thus, it seems reasonable to assume that there exists a unique Nash equilibrium in the European acid rain game as it has been formulated in this section.

What are the differences between the full cooperative solution and the Nash solution? This question is interesting from the following points of view. A natural hypothesis would be that the present situation can be characterized as a Nash equilibrium. A comparison between the Nash equilibrium and the full cooperative solution would then indicate first the gains from cooperation but second, and more importantly, the allocation of the necessary reductions of sulfur oxide emissions among different countries. However, the assumption that the present situation can be characterized as a Nash equilibrium may appear to be far removed from reality. In fact, there are a number of international agreements on reductions of sulfur emissions in Europe and it is questionable whether these agreements can be interpreted as part of a Nash equilibrium. However, so far no transnational payments have been involved in these agreements, which could be interpreted by saying that the present situation must belong to the set $P(E^n,Q^n)$ of allocations that dominate the Nash equilibrium (E^n,Q^n). If it can be shown that the full cooperative solution does not belong to the set $P(E^n,Q^n)$, then one can conclude that some kind of side payments are called for when the full cooperative solution between the European countries is looked for.

3 SIMULATION RESULTS

In order to enable numerical simulations of the Nash equilibrium, the set of allocations that dominates that equilibrium and the full cooperative solution, the following strategy has been followed:

a) Control cost functions were guesstimated on the basis of some plots produced by the Acid Rains Project at IIASA, Laxenburg.[8] These cost functions were taken to be quadratic

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[7] See for example James Friedman (1986), Chapter 5.3, Theorem 2.6.

[8] Amann, M., and G. Kornai (1987).

(with the exception of German Democratic Republic). The IIASA cost functions have the drawback that they do not include fuel substitution or switch to fuels with lower sulfur content and that they assume exogenous given energy demands. In particular, the cost functions are estimated on the basis of the expected energy demands for the year 2000. In spite of this, the functions have been applied in this paper to the energy consumption pattern 1984. Moreover, based on the information from IIASA, maximum amounts of pollution control have been assumed for the different countries. This grossly overstates the cost of control of sulphur emissions.

b) The damage cost functions were assumed to be linear, so that the marginal damage cost is constant, independent of the amount of deposition. If the initial situation is a Nash equilibrium then the absolute value of the marginal damage cost times the appropriate diagonal element in the EMEP matrix must be equal to the marginal control cost i.e.

$$-dC_i/dE_i = a_{ii}dD_i/dQ_i.$$

By using this necessary condition for a Nash equilibrium, the damage cost function can be calibrated such that the marginal damage cost is equal to the marginal control cost divided by a_{ii}. In particular, this means that the damage cost function represents the evaluation of the damage that the respective governments make today. It thus corresponds to what is usually called revealed preferences. It is, however, important to understand that this does not necessarily mean that the damage cost function estimated by conventional methods would be equal to the assumed damage cost function. The approach taken here is simply to assume that the damage evaluation revealed by actual policy decisions is used for the simulations.

In the discussion on acid rains in Europe, it is often claimed that some countries are using too low estimates of the damage. Therefore, in some simulations it has been assumed that the marginal damages in GDR and Czeckoslovakia are 50 percent higher than what the corresponding control cost would generate, and for Poland, the damage cost has been assumed to be 100 percent higher. However, these adjustments turned out to be of minor importance, and these simulations are not reproduced in this paper.

It is obvious that changed information will change the perceived damage and therefore the chosen strategy also. Our numerical illustrations therefore only represent the current perception of damage. As the following will show, this does not really matter so long as the perceptions change uniformly over countries.

c) This calibration thus yields a damage cost function for each country that can be used to calculate the set of Pareto efficient outcomes, the full cooperative solution and other solution concepts such as the core. However, if the true damage cost function is convex instead of linear, which seems probable, then this calibration will yield an underestimate of the true damage cost function. In particular, one may end up with overestimates of the gains from cooperation, as the benefits from reductions in sulphur deposition will be overstated. It is therefore very important to bear this bias in mind when the following results are interpreted. Moreover, although this assumption of constant marginal damage enables explicit calculations, it also removes one important and interesting connection between the European countries. With constant marginal damage, the best strategy choice in one country is independent of what other countries do, and the Nash equilibrium turns out to be a dominant equilibrium.

d) The way the game is set up implies that the utility can be measured in monetary terms and that the cost (damage- and control cost) figures have the same meaning for all countries involved. This requires that the exchange rate is an equilibrium one and that the cost of capital (freely transferable across national borders) is the same in all countries. We know for sure that this assumption is not correct, partly because some of the European countries experience different economic systems than others.

e) All simulations have been carried out with GAMS - General Algebraic Modelling System, a software developed at the World Bank.[9] The data in the matrix of transport coefficients and the initial emissions (1984) and the assumed maximal emission reductions are taken from Lehmhaus, Saltbones and Eliasson (1986).

4 FULL COOPERATIVE SOLUTION WITH SIDEPAYMENTS (Fcs)

We will start by looking at the "full cooperative solution" when sidepayments between the different countries are possible. This means that the net benefits for some countries may turn out to be negative but these countries can be compensated by cash payments if the total European benefits are positive. The results are given in Table 1.

The calculations show that the total emissions in Europe would be reduced by about 40 percent in the full cooperative solution compared with the present situation (emissions 1984), that almost all countries would gain from the full cooperative solution and that a few countries - UK, Italy and Spain - would loose from participating in the cooperation.

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[9] GAMS was developed at the World Bank by David Kendrick and Alexander Meeraus. It is now marketed by The Scientific Press, 507 Seaport Court, Redwood City, CA 94062, USA.

(The losses that Finland and Luxemburg would experience are negligible). Spain's loss is also almost negligible, while Italy would experience a moderate loss and the UK a substantial loss. Obviously, the UK would have no incentives to participate in organized cooperation to reduce the sulfur emissions in line with the full cooperation.

These results do not depend crucially on the assumed control cost functions. If we have assumed too high a value for the marginal control cost for a particular country, this

TABLE 1

Net benefits from the full cooperative solution.

	Emission control 1000 ton SO_2	Percentage reduction	Benefits mill. D Mark
ALB	10	42	22
AUS	31	21	324
BEL	112	36	191
BUL	179	36	28
CZE	1219	75	152
DEN	130	86	119
FIN	25	14	-2
FRA	104	10	879
GDR	1040	80	11
FRG	1183	86	328
GRE	303	86	52
HUN	635	77	5
IRE	27	38	71
ITA	634	33	-84
NET	105	62	565
NOR	3	6	272
POL	560	27	599
POR	15	19	10
ROM	83	83	420
SPA	231	14	-29
SWE	6	4	606
SWI	10	23	192
TUR	299	62	0
USSR	107	2	1510
UK	1494	81	-336
YUG	465	79	346
TOT	9011	39	6248

would to a certain extent be compensated by too high a value for the marginal damage cost, because of the way we calibrate the damage cost function. In fact, sensitivity analysis yields the expected result that it is the EMEP matrix that is crucial as long as we are willing to make the assumption that the damage cost function is linear.

A few things should be noted about the figures in this table (some of which also apply to later tables). First, a few countries are required to abate their emissions of sulphur up to the maximum amount. In this group are the UK, Czeckoslovakia, East and West Germany and a few others. In view of the rather arbitrary upper limits on emission reductions that have been imposed on the solutions, it can be concluded that these countries would have to reduce their emissions further given a more realistic cost of abatement function. Furthermore, it should be observed that the total emission reduction required is about forty percent, which is more than the thirty percent agreed upon in the "30-club".[10]

One should also note that the abatement requirements vary very much among the countries. In general, the Scandinavian countries are required to abate less than the central European countries. One reason for this is that abatement in the Scandinavian countries has already driven up the marginal control cost so that it would be cheaper from an European perspective to reduce the emissions elsewhere. But, perhaps a more important factor is that Scandinavia is downstream or "downwind" in the EMEP model relative the rest of Europe. Moreover, the Mediterranian countries are at average, not required to do as much abatement as the countries in Central Europe. This is so because the damage in Africa and Middle East from their emissions is not included in the analysis.

Finally, a few countries will end up with net losses. It would not be rational for any country to sign a binding agreement by which they would expect losses. Therefore, we can conclude that even if binding agreements between countries on emission reductions could be made, we should not expect a full cooperative solution to result, unless the strategy space for each country is expanded to include sidepayments. Without sidepayments, we would not expect the UK, Italy and Spain to agree on an emission control plan that would result in non-negligible losses.

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[10] The "30-club" is a group of European and North American countries that have agreed to reduce their emissions by at least 30 percent.

5 PARETO DOMINANT OUTCOMES

Assume that sidepayments are not feasible. What would be a "good" outcome if the countries would cooperate? One such outcome would be an agreement on emission reductions that would minimize the total European damage- and emission costs but that would leave no country worse off. That outcome (the Pareto dominating outcome - Pdo) is given in Table 2.

TABLE 2

Net benefits when no country is made worse off (Pdo).

	Emission control 1000 ton SO_2	Percentage reduction	Benefits mill. D Mark
ALB	11	42	22
AUS	33	22	314
BEL	123	40	96
BUL	181	36	27
CZE	1219	75	148
DEN	130	86	119
FIN	24	14	8
FRA	119	12	696
GDR	1026	79	0
FRG	1183	86	242
GRE	303	86	52
HUN	635	77	2
IRE	57	82	6
ITA	508	27	0
NET	119	70	464
NOR	3	6	225
POL	571	28	565
POR	26	32	2
ROM	83	83	416
SPA	116	7	0
SWE	6	3	549
SWI	10	24	173
TUR	299	62	0
USSR	444	7	1437
UK	747	40	0
YUG	465	79	329
TOT	8440	37	5892

The total benefits are reduced by about 6 percent compared to the full cooperative solution with sidepayments if sidepayments are not allowed. The total emission control in Europe would also be about 6 percent smaller in the Pdo than in the full cooperative solution. The main difference between the two solutions is the level of emission control in the U.K. In the Pdo the U.K. is required to abate 40 percent of the initial emissions while in the full cooperative solution it is required to abate 81 percent. However, when side payments are not feasible, it is not certain that the countries would agree on minimizing the total European damage- and control costs. The main reason for choosing the minimization of the total damage- and control cost is that this would yield a maximal surplus which could be distributed among the countries in some way and thereby secure

TABLE 3

Maximum potential gains from individual minimization; million D mark.

Countries	USSR	Sweden	UK	Poland	Germany
ALB	17	16	17	17	17
AUS	115	246	97	76	39
BEL					
BUL		11			
CZE	253	209	232	96	62
DEN	131	122	129	130	
FIN					3
FRA		687	629		
GDR	24	6			300
FRG	477	330	224	407	890
GRE	57	56	57	57	57
HUN	20	11	19		2
IRE	10	7		10	1
ITA		49			
NET	477	434	335	477	146
NOR	224	131		222	
POL		190		864	
POR					
ROM	455	440	452	388	423
SPA		2	6		
SWE		608			
SWI	176	135	146	176	125
USSR	1737	1492		1276	1360
UK			96		
YUG	386	345	368	349	316

for each country a maximum payoff. With no sidepayments, the interests of the countries are much more in conflict with each other. In order to analyse this issue, the following simulations were carried out. The optimal allocation of emission control was calculated when the objective was to minimize the total damage and control cost in the USSR, Sweden, the U.K, Poland and the two Germanies combined, respectively. Each of these calculations then shows the maximum potential gain each of these countries could expect from participating in the cooperation. The reason The Federal Republic of Germany and the German Democratic Republic are combined is simply that they are very similar with respect to the atmospheric transport model. The results are given in Table 3.

Table 3 is quite revealing. It is quite clear that Sweden should have a very strong interest in reducing the total emissions. When the Swedish net benefits are maximized, she gains only 11 per cent compared with the Pdo and only 0.3 percent compared with the full cooperative solution. The important role the UK is playing is also clear. If the British benefits are maximized, the net benefits in many countries would drop to zero. It is also clear from the table that Czeckoslovakia would gain quite a lot, irrespective of which country is maximizing. If the Germans would be successful and more or less dictate the emission control strategy, Poland would suffer because it would then be forced to reduce its emissions to such an extent that its own net benefits would fall to zero. Anyhow, the table shows that the countries have quite disparate wishes in negotiations on voluntary restrictions of emissions.

6 COALITION FORMATION

Instead of either paying some countries for reducing their emissions (with side payments) or in some other way making concessions (for example by making extra big emission control efforts) in order to achieve an agreement involving all European countries, some countries could try to form coalitions to find out whether they could do better than on their own. In theory, this should be analysed with the aid of cooperative game theory, but as has already been pointed out, the sheer number of countries makes it almost impossible to calculate the characteristic function and the equilibrium concepts that are based on it.

However, a few analytical results can be derived. Assume that the vector E of national emissions is a candidate for an agreement. That vector is blocked by a coalition M of countries if there exist emission levels E_i' for the countries in the coalition such that no country in the coalition is worse off and at least one is better off, irrespective of what the other countries do. A vector E is said to belong to the core if it cannot be blocked.[11] An allocation of emissions among countries that is in the core has thus a certain stability. No coalition can do better for itself than it can with a vector in the core, because the countries outside the coalition can "revenge" by making certain changes in their emissions. However, this concept is not terribly interesting because all Pareto efficient allocations will belong to the core. The reason is that a coalition trying to block a vector in the core can be met by big increases of emissions from the countries outside the coalition. Only if the coalition consists of countries that do not import any sulfur from other European countries, would it be able to block a Pareto efficient allocation. The only such coalition would consist of Iceland alone, a not very interesting case. Moreover, the only way countries outside a coalition M can prevent M from blocking is by increasing emissions and thereby increasing their own damage cost. This threat is therefore hardly credible.

A more interesting equilibrium concept is the strong equilibrium.[12] This concept is based on a more restricted assumption of what countries outside the coalition will do. In particular, a coalition can upset a vector E if there exists E_i', for all i in the coalition, such that none of the countries in the coalition is worse off with E_i', given that the countries outside the coalition will not find it to their advantage to change their behaviour (i.e. their emissions). In terms of the model in this section, this means that a coalition could gain by playing the noncooperative game against the coalition of all other countries. It is shown in the Appendix that if the EMEP matrix were symmetric, the set of emission allocations that are strong equilibria would be empty if the number of countries is sufficiently large. However, it is possible to extend that argument to an asymmetric EMEP matrix as long as all countries are damaged by acid rain and they also contribute to the rains. Thus, in the European acid rain game, one should therefore not expect to find strong equilibria. Any Pareto efficient allocation of emissions can therefore be upset by a coalition that can do better on its own compared with a complete European agreement.

However, in spite of this rather negative result, quantitative studies of the economic

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[11] This concept and the following one - the strong equilibrium - is defined and discussed in most textbooks on game theory. For a lucid discussion see Luce and Raiffa (1964). The concept of strong equilibrium is discussed in Dasgupta and Heal (1981), Chapter 2.

[12] See Dasgupta, Heal, op.cit.

TABLE 4

Net benefits with coalition formation.

Coalition members	Emission control 1000 ton SO_2	Percentage reduction	Benefits mill. D Mark
ALB	9	37	22
AUS	29	20	277
BEL	106	35	50
BUL	127	34	33
CZE	1219	75	125
DEN	124	82	127
FRA	91	9	466
GDR	1040	80	-47
FRG	1183	86	78
GRE	303	86	51
HUN	635	77	-9
IRE	11	15	-1
NET	99	58	400
NOR	3	6	175
POL	560	27	544
POR	5	6	0
ROM	83	83	398
SWE	5	3	478
SWI	8	19	95
TUR	299	62	
USSR			1377
YUG	465	79	253
TOT	9011	39[1]	6002
Non-coalition members			
FIN			5
ITA			148
SPA			5
UK			87
TOT			246
EUROPE		40	

1) average for all countries

incentives for various coalitions may yield further insights. In this section, one particular coalition will be studied, namely the coalition of all countries that are not making a negative net benefit in the full cooperative solution. Thus, we will look at the coalition consisting of all countries except Finland, Italy, Spain and the UK. These countries, not in the coalition, are assumed to maximize their net benefits. As the marginal damage cost does not depend on the emissions in other countries, it follows that they will carry out their Nash-strategies, i.e. they will stick to their initial emissions, whatever the coalition decides to do. The result is shown in Table 4.

The total net benefits accruing to the coalition is less than what the coalition could have obtained by having cooperation with all countries and compensating those countries that would have experienced negative net benefits. The net benefit to the coalition would in that case have been 6248 million D-Mark after sidepayments of the order of 451 million D-Mark had been made. Moreover, the emission control in Europe would be significantly lower with the non-coalition countries outside an agreement.

However, Table 4 shows that both Italy and the UK have strong incentives to stay out of any agreement. By staying outside and sticking to the Nash-strategies, both countries can gain significantly. This is probably what can be seen today on the scene of international negotiations on emission control, at least for the role played by the UK. Thus, although this analysis is far from complete, in that it does not study the coalition formation systematically, it gives some insights into the possibility of international bargaining.

7 SUMMARY

In this paper, an attempt has been made to accomplish two objectives: to create an analytical framework for problems of international cooperation on transboundary pollution and to present a first round of estimates of the incentives different European countries may have to participate in such cooperation on controlling sulphur emissions.

The framework chosen has been the theory of cooperative games. The formulation of the conflicts between different European countries as variable sum game has certain advantages. First of all, it points out and identifies the strategic aspects of the behaviour of the different countries at the negotiating table. It also identifies the kind of gains that a cooperative outcome would imply. Finally it gives a means of quantifying the net benefits to the countries from participating in European cooperation. More specifically, the present situation was assumed to represent a Nash non-cooperative equilibrium, in which each country optimizes its own net benefit, taking the strategies and payoffs of the other countries into account. By assuming that the damage cost function is linear in the deposition of sulphur and by using some crude estimates of the cost of controlling sulphur emissions it is possible to calibrate the damage cost function with the help of the EMEP atmospheric transport model in such a way that the present situation represents a Nash equilibrium in the corresponding model of the game. Having thus calibrated the damage cost function, calculations of the gains for the different countries from different cooperative solutions can easily be made. The common conclusion from almost all simulations was that there is a need for international transfers in order to motivate all countries to participate. Thus some countries should be bribed to reduce their emissions. Only if the cooperative agreement is such that not all possibilities of mutual gain are exploited it will be unnecessary to make such transfers. However, even the full cooperative solution in which the countries agree to reduce their emissions in such a way as to minimize the total European damage- and control cost is not stable for coalition formation. It was shown that the set of strong equilibria, i.e. agreements on reductions such that no coalition of countries could do better on their own, given that the other countries minimize their costs, is problably empty. Thus, it may very well be so that for every possible agreement, there exists a coalition that could upset that agreement. The reason the conclusion is rather vague is due to the fact that it was shown for a symmetric game of managing a common property resource that if the number of players is great enough, there is no strong equilibrium. However, we have no indication on the precise meaning of "great enough". Moreover, the European acid rain game is highly asymmetric.

Nevertheless, as long as countries are mainly concerned with their own welfare, it seems that international transfers are necessary to support European wide agreements on emission reductions. In this paper, these transfers have been assumed to be cash payments. However, other kinds of transfer of wealth or command over resources are possible.

APPENDIX

Assume there is a common property resource which is exploited by n agents. Let the benefit to agent i from exploiting the resource be $B^i(x_i, \sum_j x_j)$, where x_i is the amount of exploitation on part of agent i. B^i is assumed to be increasing in its first argument and decreasing in its second argument. In terms of the acid rain game, B^i could be interpreted as the negative of the damage and control cost in country i, x_i emission in country i and $\Sigma\, x_j$ the deposition of sulphur in country i (thus the EMEP matrix would simply consist of "ones" in all cells).

Let us assume that the benefit functions are the same for all agents. That makes the game completely symmetrical and each equilibrium concept will give the same value of x_i for all agents.

The Nash equilibrium is defined as x^N defined by

$$B_1(x^N, nx^N) + B_2(x^N, nx^N) = 0$$

where B_1 and B_2 are the partial derivatives with respect to the first and second argument resp.

The Pareto efficient equilibrium $\hat{x}$ is defined from

$$B_1(\hat{x}, n\hat{x},) + nB_2(\hat{x}, n\hat{x}) = 0.$$

where subscripts denote derivatives.

We will show that for n great enough, there does not exist a strong equilibrium. Let M be a coalition of agents that tries to upset $\hat{x}$. Let M have m members and let the complementary coalition have s = n - m members.

Assume that the members of M chooses x_m in such a way that

$$B(x_m, mx_m + sx_s) = \max_x B(x, mx + sx_s).$$

In a similar way, the complementary coalition will choose x_s in such a way that

$$B(x_s, mx_m + sx_s) = \max_x B(x, mx_m + sx).$$

If n is sufficiently greater than m, x_s will be close to $\hat{x}$ and it follows that

$$B(x_m, mx_m + sx_s) \geq B(\hat{x}, m\hat{x} + sx) \simeq B(\hat{x}, m\hat{x} + s\hat{x}) = B(\hat{x}, n\hat{x}).$$

Thus if the number of agents is sufficiently large, it is possible to find a coalition that would upset the Pareto efficient solution.

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