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Keskusteluaiheita - Discussion papers

No. 344

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TRANSBOUNDARY AIR POLLUTION AND SOIL ACIDIFICATION:

A Dynamic Analysis of an Acid Rain Game Between Finland and the USSR

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ISSN 0781-6847 23.11.1990

KAITALA, Veijo - POHJOLA, Matti - TAHVONEN, Olli, TRANSBOUNDARY AIR POLLUTION AND SOIL ACIDIFICATION: A Dynamic Analysis of an Acid Rain Game Between Finland and the USSR. Helsinki : ETLA, Elinkeinoelämän Tutkimuslaitos, The Research Institute of the Finnish Economy, 1990. 29 p. (Keskusteluaiheita, Discussion Papers, ISSN 0781-6847; no. 344).

ABSTRACT: Transboundary air pollution is analysed as a dynamic game between Finland and the nearby areas of the Soviet Union. Sulphur emissions are used as the environmental control variables and the acidities of the soils as the state variables. Acidification is consequently considered to be a stock pollutant having long-lasting harmful effects on the environment. The state dynamics consist of two relationships: first, of a sulphur transportation model between the regions and, second, of a model describing how the quality of the soil is affected by sulphur deposition. The countries are assumed to be interested in maximizing the net benefits from pollution control as measured by the impacts on the values of forest growth net of the abatement costs. Cooperative and noncooperative solutions of the game are compared to assess the benefits of bilateral cooperation. Using empirical estimates of abatement costs, acidification dynamics and impacts on forest growth it is shown that cooperation is beneficial to Finland but not to the Soviet Union. Consequently, Finland has to offer monetary compensation to induce her neighbor to invest in environmental protection.

KEY WORDS: Acid rain, Differential game

1 Introduction

Acidification of soil and lakes is a well-known disruptive phenomenon in Europe, the USA, and Canada (see e.g. Alcamo et al. 1990, Kauppi et al. 1990). Its primary sources are sulphur and nitrogen emissions. These air pollutants are partially deposited onto the ground in the emitter countries in the form of wet and dry deposition but large amounts are also transported by the winds to the neighboring countries. Sulphur and nitrogen compounds affect the properties of soil, surface water and ground water. In particular, the acid neutralizing capacity of soil and water is reduced. This process is referred to as acidification. In this paper we omit the nitrogen emissions and use data on sulphur emissions only.

Acidification has direct and long-term impacts on the economies of countries, e.g. by affecting forest growth. The governments of Finland and the USSR have thus recently signed a bilateral agreement for the purpose of limiting and reducing the deposition and harmful effects of air pollutants emanating from areas near their common border. These areas include the whole territory of Finland and the following regions in the Soviet Union: Kola, Karelia, Leningrad, and Estonia. The parties have agreed, among other things, to reduce their annual sulphur emissions by 50 per cent from the levels that prevailed in 1980 by the end of 1995 at the latest (Action Programme, 1989). In this paper we carry out an analysis on the efficiency and economic implications of such an bilateral environmental agreement. For this purpose we develop a two-country dynamic game of transboundary air pollution.

It is generally accepted that the aims of the Finnish party are largely determined by her rational management of the natural resources, specifically forests (Kauppi et al. 1990). Thus, despite of the fact that the connection with forestry of the Soviet environmental policy is not as obvious to us, we take the view in this paper that the environmental and economic objectives of both countries are reflected in the value of the forestry.

The main part of this paper is devoted to the identification of the structure and the dynamics of the acid rain game. The game-theoretic framework is introduced in Section 2. The dynamics are described by considering pollution as an accumulating stock variable. Detrimental effects accumulate in the environment during periods of heavy pollutant emissions, but it may recover slowly even if the emissions are small. The costs from pollution arise from abatement activities as well as from the erosion of the environment.

Section 3 is devoted to the identification of the dynamics of the quality of the environment. Here we apply a view originating from those Finnish forestry research programs which have studied the impact on soil quality of acidification caused by the sulphur deposition (Holmberg, 1990a,b). It decreases the amount of nutrients available to the trees, and thus affects their growth. This approach is utilized in this paper by linking the quality of the soil to forest growth in Finland and by describing the evolution of the quality of the environment by the dynamics of acidification.

Section 4 defines the costs of abating sulphur in Finland and the nearby areas of the Soviet Union. The cost functions are obtained from the estimates provided by the HAKOMA project at the Technical Research Centre of Finland (Savolainen and Tähtinen 1990).

Section 5 is devoted to the estimation of the benefits from pollution control or, equivalently, of the damages from the deterioration of the environment. This task appears to be more complicated than the estimation of the emission abatement costs because the environmental consequences of the acidic precipitation and acidification of forest soil cannot be determined with the same accuracy. To estimate the effects of acidification on forestry we here apply an indirect, revealed-preference method suggested by Mäler (1990) and assume that the actual sulphur emissions (prior to the cooperative agreement between the countries) result from rational choices by the countries acting in isolation. Therefore, knowing the abatement costs, the observed emissions reveal to an outside observer the implicit marginal cost resulting from the deterioration of the environment.

The paper concludes with a comparison of the non-cooperative and cooperative game solutions in Section 6. We also evaluate the recently signed agreement and show that Finland gains from the environmental cooperation whereas the USSR may even lose from it.

2 Transboundary acid rain game

2.1 A two-country game setting

Our approach is based on an acidification model which simulates the intertemporal development of the fraction of base cations (e.g., calcium and magnesium ions) in the soil (e.g. Hari et al. 1987, Holmberg 1990a). This fraction is referred to as *base saturation.* A decrease in base saturation means an increase in the degree of acidification. The dynamics of base saturation will be more fully developed in Section 3.1. We next outline a basic dynamic model for acidification (Kaitala et al. 1990).

Let $x_1(t)$ and $x_2(t)$ denote the base saturations at time t in Finland and in the four regions of the USSR, respectively. Further, let $e_1(t)$ and $e_2(t)$ denote sulphur emissions and $d_{ij},\ i,j = 1,2$, the sulphur deposition in country i originating from country j. Finally, let d_{b1} and d_{b2} be the background depositions. Then the dynamics of the base saturation can be described as follows

$$\dot{x}_i = F_i(x_i) - c_i(d_{ii}(t) + d_{ij}(t) + d_{bi}(t))x_i,\ \ i,j = 1,2,\ \ j \neq i, \tag{1}$$

where $F_i,\ i = 1,2$ is a strictly concave function with $F(0) = F(K_i) = 0$ for some $K_i,\ 0 < K_i \leq 1$.

The depositions are determined from the emissions by using the following transportation model

$$d_{ij}(t) = w_{ij}e_j(t), \tag{2}$$

where w_{ij} denotes the fraction of the emission released by country j that will be deposited in country i. In particular, depositions d_{12} and d_{21} are consequences of the remote transportation of the sulphur emissions by wind across the common border.

The countries are assumed to maximize

$$J_i(x(0), e_1, e_2) = \int_0^\infty \exp(-r_i t)(U_i(x_i) - C(e_i))dt \tag{3}$$

s.t. (1),(2), where $x(0) = (x_1(0), x_2(0))^T$, $U_i(\cdot)$, $i = 1, 2$, is an increasing concave benefit function of the quality of the soil, and $C_i(.)$, $i = 1, 2$, is a decreasing, non-negative, and convex cost function, i.e., emission abatement cost function.

2.2 Solution concepts

In this paper we study two different types of interaction between the countries. First, the countries act unilaterally and do not cooperate or coordinate emission reductions. Second, the countries cooperate in the protection of the environment by negotiating agreements on emission reductions.

In general, the decisions on the emission abatement policies can be fixed time functions over a long time period. In that case the policies take the form $e_i(t)$ and are called *open-loop policies*. Another basic alternative for the countries is to define their emission abatement policies as a function of the state of the game (in our paper as a function of the base saturations). In this case the strategy $e_i(x_1(t), x_2(t))$ is referred to as a *feedback strategy*.

The noncooperative solution has the property that at an equilibrium no party has an incentive to deviate unilaterally from it (see Appendix 2; for formal definitions and further properties of the noncooperative and cooperative solutions, see Basar and Olsder 1982, Mehlmann 1988). It is well known that a cooperative solution is an equilibrium only in special cases. This means that whenever the countries attempt to cooperate they need to use strategies (actions, policies) other than the noncooperative ones. It follows that at least one of the countries would benefit by cheating on the other party. To prevent this the contracts have to be binding or to include some kind of self-enforcement mechanisms (for an analysis in resource economics, see Kaitala and Pohjola 1988).

This paper is an attempt to capture the essential points of the acid rain negotiation problem in a dynamic game theory setting. Thus, in the first place we confine our analysis to identification of a model for acidification dynamics that could be used in the analysis of decision making and acid rain negotiations. Second, we attempt to describe what the noncooperative and cooperative environmental policies might be if and when they are applied.

3 Identification of acidification dynamics

3.1 Acidification dynamics

We use recent models of ion exchange dynamics (Holmberg 1990a,b) to simulate the impact of the sulphur deposition soil acidification and forest growth. This process is not yet known well enough to make accurate and reliable quantitative predictions of the future dynamics of the soil as a function of different sulphur deposition histories. However, extensive research work has been carried out in Finland which facilitates some qualitative predictions.

The impact of sulphur deposition can be divided into three phases (Hari et al. 1987, Holmberg 1990a). First, the deposited ion flux affects the concentrations of acids and bases in the soil. Second, the properties of the soil change, affecting the availability of nutrients, that is, base cations. Third, these changes affect forest growth.

Trees take nutrients from the soil solution and from the solid state. The base cation content of the soil can be calculated as a weighted mean of these cations in the soil solution and in the solid state (Hari et al. 1987). We simulated the nutrient availability in mineral soils and found that the amounts of base cations in the solid state describe well enough the nutrient availability for trees. Consequently, we decided to use base saturation as a measure of the state of the soil.

Base saturation describes the fraction of the base cations in all the ions of the solid phase. Specifically, let η denote the sum of all base cations (nutrients) and let η^* denote the sum of acid cations. Then total cation exchange capacity CEC is the sum of the exchangeable ions

$$CEC = \eta + \eta^*,$$

and the base saturation is the fraction

$$x = \eta / CEC.$$

As acidification proceeds, the base saturation diminishes decreasing the availability of the nutrients in the long run.

The following functional form was used in Kaitala et al. (1991) to approximate the acidification dynamics obtained from simulations of a more complicated model of ion exchange dynamics in a poor mineral Finnish soil (Holmberg 1990a)

$$\dot{x} = ax - bx \ln x - cdx, \tag{4}$$

where d denotes the total deposition (g (S) m^{-2} a^{-1}) (for more details, see Appendix 1 and also Hari et al. 1987). A satisfactory approximation was obtained with the following parameter values:

$$a = 0.0599, \; b = 0.0140, \; c = 0.0486.$$

The main purpose of these estimations is to obtain realistic state equations for the differential games in such a form that the games can be analytically solved. It should be noted that the ability of the soil to recover from acidification is not yet well understood — the earlier economic models have neglected this problem altogether (e.g. Alcamo et al. 1987).

Figure 1 shows the outputs of the two models for some selected constant sulphur depositions. The approximations (dashed lines) tend to overestimate in the long run the simulation results obtained by Holmberg's model (solid lines). In what follows we assume that the soil dynamics in the two countries do not differ from each other, that is, $a_i = a$, $b_i = b$, $c_i = c$, $i = 1, 2$.

The estimation of the dynamics was carried out under the assumption that the deposition of base cations did not show any trend (Holmberg, 1990a) and was equal to 10 meq m^{-2} a^{-1}. More realistic dynamics may have been obtained by introducing an additional control variable describing the deposition of base cations. Such an extension would not change the qualitative results of this paper.

3.2 Sulphur emissions and remote transportation

The sulphur emissions and the related remote transportation in Finland and in the four regions of the USSR have been estimated for the year 1987 by Tuovinen et al. (1990) at the Finnish Meteorological Institute. The calculations are based on a long-range sulphur transport model developed at the Western Meteorological Centre in Oslo, Norway. Let $D^T = (d_1, d_2)^T$ and $D_b^T = (d_{b1}, d_{b2})^T$ denote the total and background sulphur depositions in Finland and in the nearby Soviet Union, respectively. Furthermore, let $E^T = (e_1, e_2)^T$ denote the sulphur emissions in these countries and let W be the matrix of sulphur transportation coeeficients between the countries. Then the relation between emissions and depositions can be shown

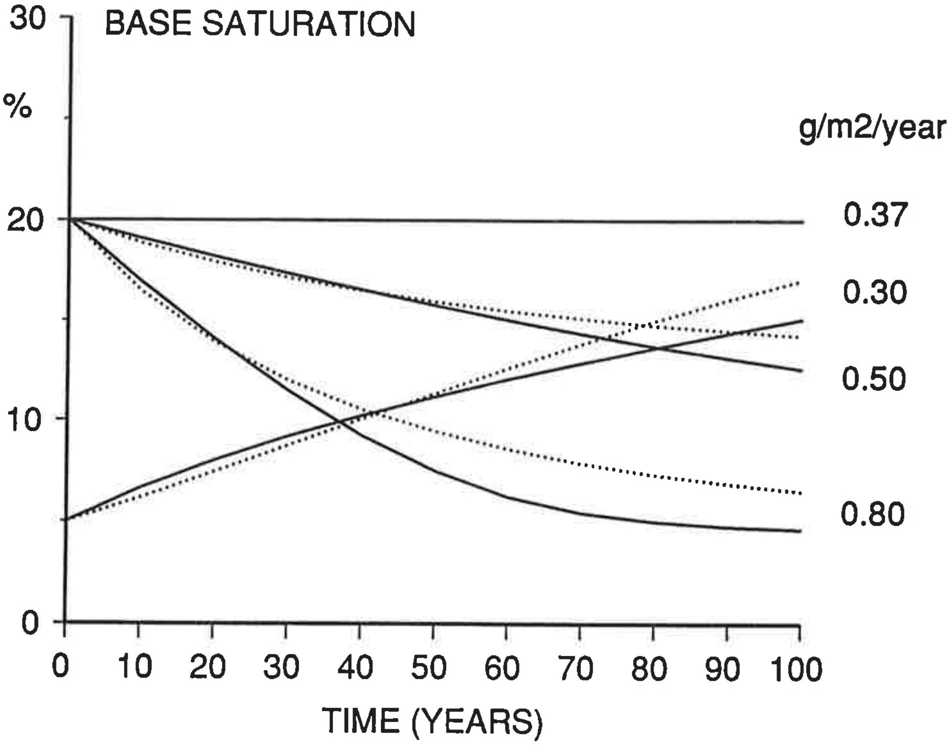

Figure 1: The outputs of two dynamic models of base saturation for some constant sulphur depositions. Dashed lines — the output of the simple acidification model (4); Solid lines — the output of the model for the ion exchange dynamics and acidification of soil (Holmberg, 1990a).

by the following transportation model

$$D = WE + D_b, \tag{5}$$

which in 1987 took the form

$$\begin{pmatrix} 210 \\ 374 \end{pmatrix} = \begin{pmatrix} 0.321 & 0.061 \\ 0.080 & 0.316 \end{pmatrix} \begin{pmatrix} 162 \\ 651 \end{pmatrix} + \begin{pmatrix} 118 \\ 155 \end{pmatrix}$$

Figure 2 illustrates the sulphur budgets, that is, the total emissions and depositions, for each country. The emissions are divided into three parts illustrating the fraction that will be deposited in the emitter's own territory, in the neighboring country and in other areas, respectively. The respective three parts of the total deposition in each country illustrate the origin (own emissions, transportation from the neighboring country, and that from other areas) of sulphur. As a whole, the own emissions together with the background deposition seem to be responsible for the acidification in each country whereas transportation between Finland and the USSR has only a minor effect. Finland receives more sulphur than it emits whereas the depostion in the nearby regions of the USSR is only 57 % of the emissions in those areas.

The units of the sulphur budgets above are given as 1000 tons of S per year. To apply the acidification model (1)-(2) we need to show the deposition data in the units of g (S) m^{-2} a^{-1}. It is known, however, that forests receive more sulphur than do the open areas. This is known as the filtering effect. Thus, we estimate the deposition data as follows. In 1987 the sulphur deposition in Finland was 210×10^3 tons. The size of the Finnish territory is 337009 km^2. Thus, the average deposition was 0.623 g (S) m^{-2} a^{-1}. Assume now that the filtering coefficient is 2, that is, the forests receive twice as much sulphur deposition as the open areas (Johansson and Savolainen, 1990). Since 70 % of the territory is covered by forests, we can estimate that the average deposition in forests was 0.733 g (S) m^{-2} a^{-1}. In the four regions

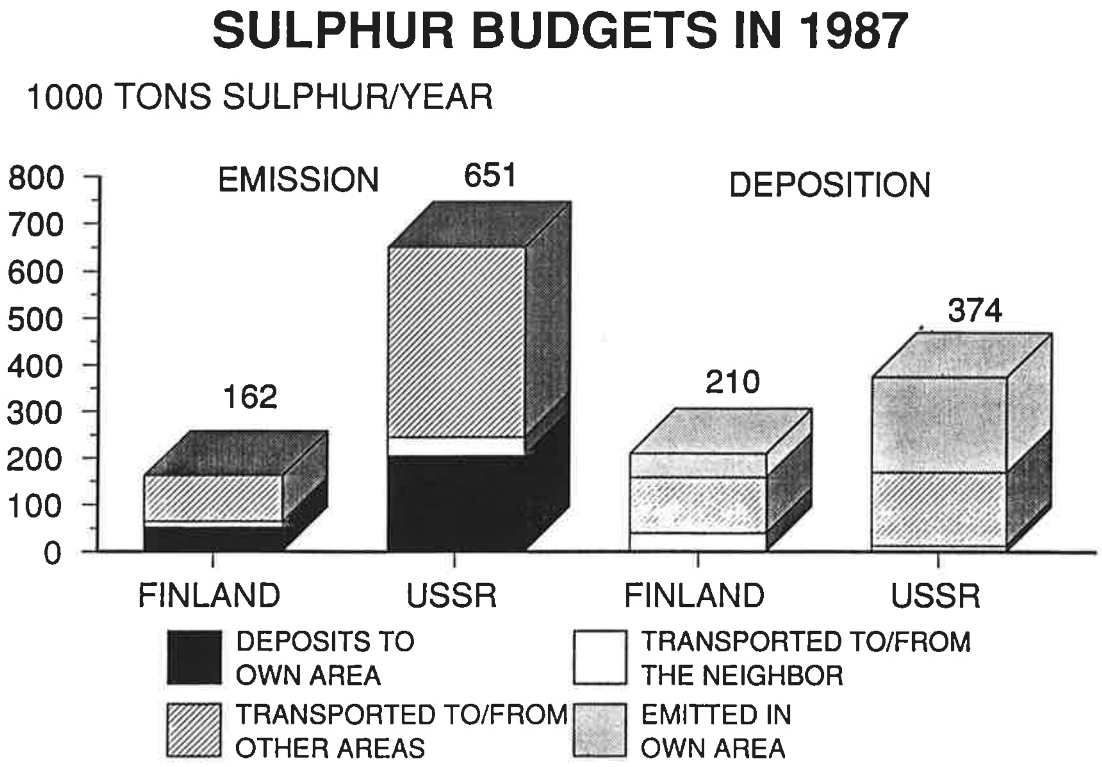

Figure 2: The total emissions and depositions in Finland and in the four regions of the USSR in 1987. The emissions are divided into three parts — own contribution, to the neighbor, and to other areas — illustrating the fraction of the emission that will be deposited in the own area, in the neighbor country and other areas, respectively. The respective three parts in the deposition illustrate the origin (own emissions, transportation from the neighboring country, and that from other areas) of the depositing sulphur.

of the USSR the sulphur deposition in 1987 was 347×10^3 tons. Assuming that 70 % of the total area of these regions (446000 km^2) is forest, we can estimate that the average deposition in Soviet forests was 0.987 g (S) m^{-2} a^{-1}.

The transportation model can be presented for the forest depositions (g (S) m^{-2} a^{-1}) as follows

$$\begin{pmatrix} 0.733 \\ 0.987 \end{pmatrix} = \begin{pmatrix} 0.00112 & 0.00021 \\ 0.00021 & 0.00083 \end{pmatrix} \begin{pmatrix} 162 \\ 651 \end{pmatrix} + \begin{pmatrix} 0.412 \\ 0.409 \end{pmatrix}, \tag{6}$$

from which we get the numerical values for w_{ij}, actual emissions in 1987 $\bar{e}_i$, and d_{bi} $i, j = 1, 2$, to be used in simulations. We assume here that the background depositions, d_{bi}, will stay constant although the European sulphur emissions have been reduced by 15 % in the period from 1980 to 1986 and although a number of European countries have agreed on further reductions (Alcamo et al. 1990). However, some of the large sulphur emitters contributing to the "attributable" background deposition (Tuovinen et al. 1990), Poland included, have not signed international agreements limiting sulphur emissions. Moreover, preliminary analyses suggest that the background deposition does not play a crucial economic role in the environmental cooperation between Finland and the USSR.

The average sulphur deposition is higher in the nearby areas of the Soviet Union than in Finland. This qualitative conclusion is in agreement with the simulations carried out in the Norwegian Meteorological Institute (Iversen et al., 1989). In practice, the sulphur deposition in the USSR is more unevenly distributed. In particular, the depositions in Kola and in the Estonian SSR are twice as large as they are in the neighboring regions in Finland.

4 Emission abatement costs

The knowledge of the costs of reducing air pollutant emissions is of crucial importance in international environmental cooperation as well as in the decision making concerning the environment. We here define the cost function $C_i(e_i)$ as the minimal cost envelop encompassing the entire range of sulphur abatement options for country i in a given time period. The costs are calculated for various sulphur reduction requirements ranging up to the maximal technologically feasible removal. The HAKOMA project at the Technical Research Centre of Finland has provided emission abatement cost functions for Finland and the nearby areas of the Soviet Union by applying an engineering approach in estimating the direct costs of sulphur reductions in both combustion processes in energy production and non-combustion processes in industries using imputs containing sulphur (Savolainen and Tähtinen 1990). The calculations are based on expected energy demands for the year 2000. The costs are measured in millions of Finnish marks per year and they included both operating and capital costs. The economic life of the plants is assumed to be 25 years and a 5 per cent annual interest rate has been used in discounting the costs.

For reasons of analytical simplicity we here use the following quadratic approximations to the original piecewise linear cost functions (Kaitala et al. 1990)

$$C_i(e_i) = \beta_{i1}(\bar{e}_i - e_i) + \beta_{i2}(\bar{e}_i - e_i)^2 + \beta_{i3}, \ i = 1, 2, \tag{7}$$

where β_{i1}, β_{i2}, and β_{i3}, are fixed parameters. Parameters β_{i1} and β_{i3} have been chosen to be equal to the estimated marginal and total costs at the emissions (10^3 tons S a^{-1}) in the base year 1987, that is, at $(\bar{e}_1, \bar{e}_2) = (162, 651)$. After these choices parameter β_{i2} is estimated by applying the least squares technique. The results are shown in Table 1. To get a better approximation to the Soviet abatement costs, the fitted curve has two components: a linear segment describing the abatement costs for initial reductions of the emissions from the 1987 level down to $e_2 = 399$ with $\bar{e}_2 = 651$, and a quadratic segment from $e_2 = 399$ downwards with $\bar{e}_2 = 399$.

Table 1: Estimated parameters for the abatement cost functions eq. (7) for Finland and the nearby regions of the USSR (Kaitala et al. 1990)

Country	β_{i1}	β_{i2}	β_{i3}	$\bar{e}_i$
Finland ($i = 1$)	4.9	0.05312	86.9	162
USSR ($i = 2$)				
$399 < e_2 \leq 651$	1.0	0.0	0.0	651
$0 < e_2 \leq 399$	1.0	0.02097	252	399

The RAINS[1] project at the IIASA[2] has produced national cost functions for all 27 European countries (Amann and Kornai, 1987). An algorithm was developed to derive country specific unit costs of abatement (DM per ton of removed SO^2) taking into account investment efforts as well as fixed and variable operating costs (for further details, see Amann and Kornai, 1987). It should be emphasized here that the cost function for Finland estimated in the RAINS projects differs from that estimated in the HAKOMA project. Moreover, the RAINS project gives an abatement cost function for the whole USSR whereas the HAKOMA project has estimated the costs for the four nearby regions of the USSR. These are the relevant areas from the viewpoint of air pollution control in Finland.

5 Benefits from the quality of the environment

The problem of estimating the benefit functions $U_i(x_i)$ for the countries (or equivalently, damages from low levels of base saturation) is more difficult than the estimation of the abatement costs since the consequences of acidification cannot be

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[1] Regional Acidification INformation and Simulation, developed for assessing long-term acidification in Europe on a regional basis.

[2] International Institute for Applied Systems Analysis, Laxenburg, Austria

identified with the same accuracy. In principle, it would be possible to estimate the monetary value of damages caused by sulphur deposition in, e.g., forestry and fisheries. Research programs are in progress in Finland on the effects of acidification on forest growth (Hari et at. 1989, Hari and Holmberg 1990), and consequently, some preliminary attempts to use acidification data in economic studies have been carried out (Kaitala et al. 1991).

It is generally accepted that the economic interests of the Finnish party can be derived from the value of the forest growth. As was discussed above, forest growth is affected by the availability of nutrients in the soil. Hari et al. (1989) propose that a Michaelis-Menten type of a saturation function could be used to approximate the decline in forest growth as a function of decreased nutrient availability. To facilitate straightforward calculations (see below) we approximate this decline by the following logarithmic function

$$g(x) = \bar{g} \ln(x_i/x_0) \tag{8}$$

where x_0 is a small number, and $\bar{g} = 1/\ln(x_n/x_0)$, the "normal level" of base saturation, x_n, is a level at which acidification has no detrimental effects on the forest growth, that is, $g(x_n) = 1$. Both the Michaelis-Menten type and the logarithmic saturation functions (with $x_0 = 1$) are shown in Figure 3.

The benefits from the forestry in country i are here specified as

$$U_i(x_i) = \gamma_i g(x_i), \tag{9}$$

where γ_i is the value of healthy forests in country i under normal conditions, that is, at $x_i = x_n$.

The base saturation usually ranges from 10 to 60 percent depending on the type of the soil. In simulations we used $x_n = 20$ percent, which approximates both rich and poor mineral soils in Finland. These forest soil types represent over two thirds of the forest area of Finland.

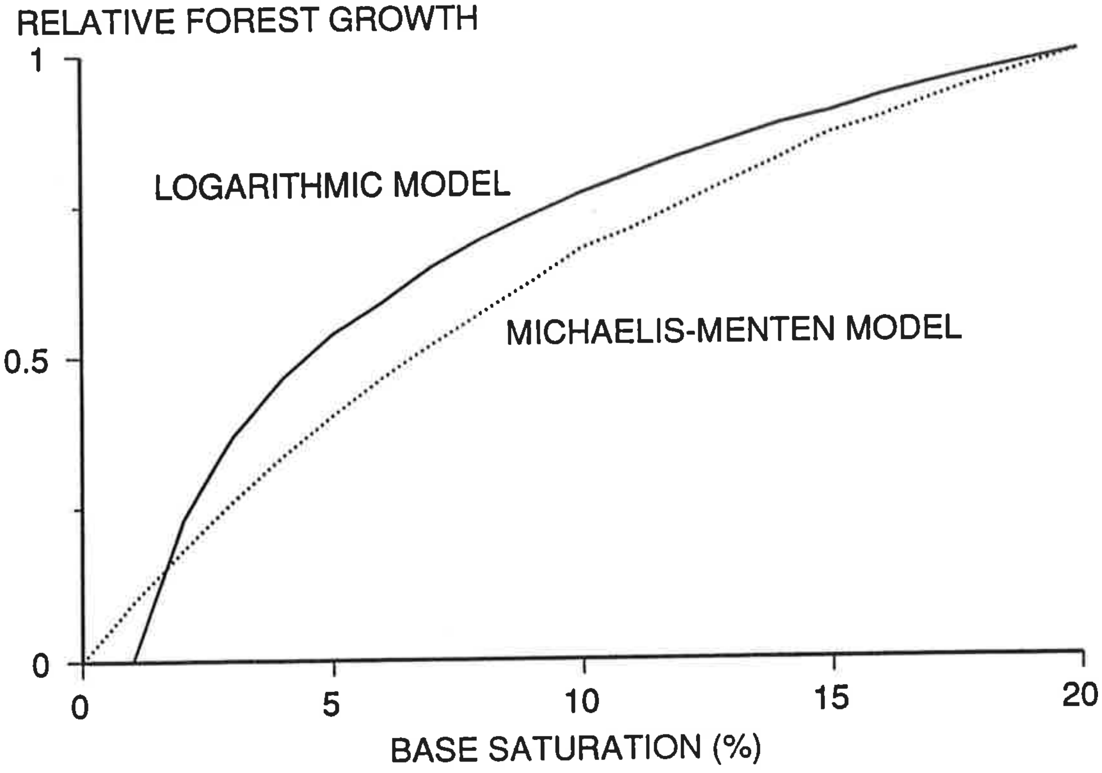

Figure 3: The logarithmic model (see eq. (8)) is used to describe the dependence of the value of the annual forest growth on the degree of the soil acidification. A Michaelis-Menten model (Hari et al. 1989) is shown for comparison.

The following example illustrates how acidification and the change in the quality of soil may affect Finnish forestry. The market value of the annual forest growth in Finland can be estimated by multiplying the allowable drains of pine, spruce, and birch by the stumpage prices of coniferous logs, pine pulpwood, spruce pulpwood, and birch, respectively. Using data from the cutting season 1987/88 yields $\gamma_1 = 8.3 \times 10^9$ FIM a^{-1} (Pajuoja, 1989, The Finnish Forest Research Institute, 1988). It has been suggested that observable losses will be caused to forest sector when base saturation drops to a level corresponding to 80 % of the normal base saturation. The decline of forest growth, according to our model, is 7.3%, and the monetary value of the annual forest growth will fall from 8.3×10^9 FIM to 7.6×10^9 FIM. If the environmental destruction is severe, say the base saturation level falls to the level corresponding to 25 % of the normal base saturation, then the decrease in forest growth will be 55.5% resulting in an annual value of 4.5×10^9 FIM.

Forestry also has broader social values than the commercial value only. Because of the obvious difficulties in getting full information about the environmental policy and the value of the environment in each country, we solve the problem of estimating the total damages from acidification by applying an indirect, revealed-preference method suggested by Mäler (1990, see also Kaitala et al. 1990). We assume that the sulphur emissions prior to the cooperative agreement between the countries have resulted from rational choices by the countries acting in isolation, that is, playing a noncooperative Nash game (Basar and Olsder 1982, Mehlmann 1988). Therefore, when the abatement cost functions are known, the actual emissions reveal to an outside observer the implicit marginal cost resulting from the deterioration of the environment. This indirect method gives an idea of how each country evaluates her environment. It should be noted that the indirect method does not identify the components of the damages. To get an estimate for the unknown parameters γ_1 and γ_2 we first have to solve the noncooperative game.

6 Noncooperative and cooperative acid rain games

The case where the countries attempt to manage the acidification process by applying unilateral environmental policies leads to an analysis of a noncooperative game whereas the case where the countries enter into bilateral negotiations on environmental policies requires a cooperative game approach. The noncooperative and cooperative game problems studied in this paper are straightforward to analyse (see e.g. Clemhout and Wan, 1985; Mehlmann, 1988; for the definitions, see Appendix 2) since the functional forms (5)-(8) allow analytical solutions for both types of problems. In this section we also complete the estimation of the environmental policies pursued in each country by applying the method of revealed preferences. The results can be derived either by applying dynamic programming or Pontryagin maximum principle approaches to deterministic dynamic games.

6.1 No environmental cooperation

When the countries do not negotiate or communicate in any other way regarding their environmental policies, each country acts unilaterally taking the environmental policy of the other country as given. Then, country i, i=1,2, faces the following maximization problem

$$\max_{e_i} J_i(x(0), e_1, e_2) = \int_0^\infty (\exp(-r_i t)[\gamma_i \bar{g} \ln(x_i/x_0) - \beta_{i1}(\bar{e}_i - e_i) - \beta_{i2}(\bar{e}_i - e_i)^2 - \beta_{i3}]dt \tag{10}$$

s.t. (1),(2),(4), where e_j $j \neq i$, is a fixed emission policy of the neighboring country j. The noncooperative emissions are given as

$$\tilde{e}_i = \bar{e}_i + \beta_{i1}/(2\beta_{i2}) - \gamma_i \bar{g} c_i w_{ii}/(2\beta_{i2}(r_i + b_i)) \; i = 1, 2. \tag{11}$$

These policies are constant in time. This property is observed only in a restricted class of differential games and follows from the fact that the control function depends only on the shadow prices, which in turn are constant over time. This also means that the open-loop solution qualifies as a subgame perfect feedback solution, that is, the same decision rule applies at any time and at any value of the state. At the steady state we have

$$\beta_{i1} + 2\beta_{i2}(\bar{e}_i - \tilde{e}_i)/c_i w_{ii} = \gamma_i \bar{g}/(r_i + b_i), \; i = 1, 2.$$

The left-hand side denotes the costs of reducing the marginal impact of home deposition on the home saturation level. The right-hand side is the marginal contribution of base saturation level with respect to the present value of forest growth. At the steady state equilibrium the marginal costs equal the marginal benefits.

Let us now complete estimating the environmental benefit functions $U_i(x_i)$ (eq. (9)). Assuming that the sulphur emissions in Finland and in the four Soviet regions were non-cooperative in 1987 (162 and 651 10^3 tons S a^{-1}, respectively), we get from (11)

$$\gamma_i = \beta_{i1}(r_i + b_i)/(\bar{g} c_i w_{ii}) \; . \tag{12}$$

Assuming the discount rates r_i to be equal to 0.05 yields $\gamma_1 = 17.2 \times 10^9$ FIM a^{-1} and $\gamma_2 = 4.8 \times 10^9$ FIM a^{-1}.

The market value of forest growth in Finland was estimated above to be equal to 8.3 10^9 FIM a^{-1}, which is only a half of the value obtained here by applying the indirect method of revealed preferences. Thus, the result suggests that the forest environment bears also other values than just the value of the forest growth. A similar comparison can be made also for the USSR. Assuming that the forestry in the nearby Soviet regions is similar to that of Finland, we get a rough estimate by scaling the value of forestry with respect to the area: $\gamma_2 = 11000 \times 10^6$ FIM a^{-1}. The estimate of 4.8 billion FIM is considerably lower than what we obtain on the basis of the area of the forestry. It should be emphasized that the cost function $C_2(e_2)$ is represented in (12) only by the parameter β_{21}. Thus, a possible bias in the estimate of γ_2 is proportional to a bias in the estimate of the marginal abatement cost at the base value of the emission, $\bar{e}_2$.

6.2 Cooperative solution

In the cooperative solution the countries solve the following joint maximization problem

$$\max_{e_1,e_2} J(x(0),e_1,e_2) = \int_0^\infty (\sum_{i=1}^{2} \exp(-r_i t)[\gamma_i \bar{g} \ln(x_i/x_0) - \beta_{i1}(\bar{e}_i - e_i) - \beta_{i2}(\bar{e}_i - e_i)^2 - \beta_{i3}]dt \tag{13}$$

s.t. (1),(2),(4). It can be shown that the cooperative emission rate of the USSR falls on the nonlinear part of the cost function $C_2(e_2)$, and thus, the cooperative emissions are

$$e_1^* = \bar{e}_1 + \beta_{11}/(2\beta_{12}) - [\lambda_1 c_1 w_{11} + \lambda_2 c_2 w_{21}]/(2\beta_{12}), \tag{14}$$

$$e_2^* = \bar{e}_2 + \beta_{21}/(2\beta_{22}) - [\lambda_1 c_1 w_{12} + \lambda_2 c_2 w_{22}]/(2\beta_{22}), \tag{15}$$

where $\bar{e}_2 = 399$, and

$$\lambda_i = \gamma_i \bar{g}/(r_i + b_i), \ i = 1, 2, \tag{16}$$

and γ_i is the revealed preference estimate. This gives $e_1^* = 159.6$ and $e_2^* = 377.1$ (10^3 tons S a^{-1}) for Finland and the USSR, respectively. Equations (14)-(16) shows that an increase in the estimate of the value of the forest environment in the own or neighboring country linearily decreases the cooperative emissions. The interaction with the neighboring country develops through the acidification dynamics of the soil.

Finland's cooperative emissions depend on the value of her forest growth as well as on the environmental policy of the USSR. A comparison of the cooperative and non-cooperative emissions shows that the Finnish cooperative emissions are smaller than the noncooperative ones, but not much smaller. The difference is one and a half percent. This result seems to follow from the relatively weak remote transportation of the sulphur emissions from Finland to the USSR and the very slow dynamics of the soil acidification.

The cooperative emissions in the USSR are, on the other hand, much lower than in the noncooperative situation. After starting cooperation with Finland the Soviet Union should reduce emissions from 651 to 377.1×10^3 tons S a^{-1}. This result is undoubtedly due to the linear part in the Soviet cost function. A small increase in the benefit from protecting the environment in Finland makes it optimal from the cooperative viewpoint to reduce Soviet emissions by a considerable amount.

We next compare the total net values for the countries in the noncooperative and cooperative games. We assume here that the emissions in the European countries do not change. Table 2 shows the differences in the current values between the noncooperative environmental policies and other game solutions. Thus, when Finland and the USSR agree on applying the cooperative emissions levels instead of the noncooperative emission levels Finland gains 5027 million FIM due to the high reductions in the sulphur emissions by the USSR. The current value of the total benefit for the Soviet Union is, however, 187 million FIM less than in the case of no cooperation. This result suggests that in order to negotiate a cooperative agreement on sulphur emission reductions Finland needs to compensate the USSR for at least the loss by sharing her gain with the USSR.

Table 2 also shows the so-called cheating solutions. The strategy pair (cooperation, noncooperation) refers to the case in which Finland has implemented the reductions in the emissions and is applying a cooperative policy whereas the nego-

Table 2: The differences between the current values of the total benefits (million FIM) in the different environmental games as compared with the total revenues of the noncooperative game. The different pairwise games are obtained when the countries apply unilaterally the noncooperative emission levels, the cooperative emission levels determined in this paper, and the emission levels agreed in the Action Programme.

			USSR	
		Noncooperation	Cooperation	Action Programme
	Noncooperation	0.0	5033, −199	5605, −1175
Finland	Cooperation	−6, 12	5027, −187	X
	Action Programme	−272, 81	X	5334, −1095

tiated cooperative policy remains unimplemented in the USSR. We see that in this case the USSR benefits 12 million FIM when compared with the noncooperative solution. When compared with the cooperative solution the difference is now 199 million. Finland suffers a loss, however, of 6 million from the unilateral investments in the technology protecting the environment and in this case the potential benefits from the cooperation will not be realized. The strategy pair (noncooperation, cooperation) in turn refers to the case in which USSR has invested in the environmental protection to reduce her emissions to the cooperative level whereas the negotiated cooperative policy remains unimplemented in Finland. In this case Finland gains 5033 million FIM which is more than in cooperation, and the USSR suffers a loss of 199 million FIM. This example shows that the cooperative solution is not an equilibrium. Both parties have an incentive to cheat their partner. Implementing a cooperative agreement having the property that no country will be tempted to deviate from it may be a complicated problem and is not considered in this paper (see Kaitala and Pohjola 1988).

To evaluate the impact of the tendency of some European countries to decrease their sulphur emissions in the near future we computed the total noncooperative and cooperative values also under the assumption that the European countries immediately reduce their emissions by 60 % from the 1980 level. The current values of the total benefits are now increased due to the increased quality of the environment although changes in the background depositions do not affect the emission levels of Finland and the USSR. The total benefits in the noncooperative and cooperative games are 318.963 and 323.991 billion FIM for Finland and 82.143 and 81.956 billion FIM for the USSR. As far as the bilateral negotiations are concerned the qualitative conclusions remain unchanged since the economic differences between noncooperation and cooperation remain the same. This does not mean, however, that the two countries are not interested in the developments in Europe. The economic benefits obtained from a decrease in the background deposition may be comparable to the benefits obtained from bilateral cooperation.

Consider next the recently signed Action Programme (1989) in which the countries have agreed on reductions in air pollutant emissions. If the countries reduce, as agreed, the total annual sulphur emissions by 50 percent by the end of 1995 from the 1980 levels, then the emissions will be 146×10^3 tons S a^{-1} for Finland and 346×10^3 tons S a^{-1} for the four Soviet regions. Table 2 shows that Finland gains 5334 million FIM from the implementation of this environmental program and the USSR loses 1095 million FIM. Again, emission reductions in the four nearby regions of the USSR might not be carried out without financial or technical support from Finland. Our analysis thus suggests that if the countries are not able to negotiate a satisfactory compensation agreement then the USSR may be tempted to renegotiate the target levels of the action plan.

Finally, Table 3 illustrates the resulting degrees of soil acidification in each game. The normal level of base saturation in our model was taken to be 20 %. Thus, we

Table 3: The resulting base saturations (%) in different environmental games. The background deposition is assumed to remain at the 1987 level. The initial level of the base saturation is 20 %.

			USSR	
		Noncooperation	Cooperation	Action Programme
	Noncooperation	5.94, 2.53	7.21, 5.44	7.37, 5.94
Finland	Cooperation	5.99, 2.54	7.27, 5.45	X
	Action Programme	6.21, 2.56	X	7.83, 6.01

immediately see that the emission levels in each game result in a period of 150-200 years in a severe disruption of the environment. The worst situation will be realized in the USSR if she continues a unilateral environmental policy and declines to cooperate in the protection of the environment. It should be noted that the disruption of the environment proceeds even in the case of the cooperation as well as in the case of the action plan despite their economic efficiency. This discrepancy between the resulting quality of the environment and the economic efficiency follows from the extremely slow dynamics of the acidification. Two thirds of the economic gain will be received during the two first decades during which the acidification process has not proceeded very far (see Figure 1). Most of the development is due to the own emissions in each country. A decrease of 60 percent in the emissions of the European countries would increase the resulting levels of base saturation to 7.83 and 3.30 percent in the noncooperative case and to 9.59 and 7.12 percent in the cooperative case in Finland and in the four regions of the USSR, respectively.

7 Conclusions

The results obtained in this paper suggest that the USSR may see environmental cooperation on reducing sulphur emissions as being too costly. A condition for efficient bilateral cooperation is, however, that neither of the participants suffers from the actions to be taken. Thus, our study suggests that to negotiate a bilateral agreement on reductions of sulphur emissions Finland needs to compensate the USSR for the loss. If the environmental cooperation will be carried out under the Action Programme, then our study suggests that it may be reasonable to renegotiate the target levels for the sulphur emissions. It should be noted, however, that other countries such as Sweden and Norway also suffer from the emissions originating from the four Soviet regions. Therefore, an action plan carried out on a multi-country basis rather than as a bilateral agreement might allow more efficient cooperative compensation policies.

As a whole, data on the Finnish economy are more easily available than data on the Soviet Union. In this respect, our conclusions should be considered as preliminary since new Soviet data on the economics of acidification may make new analyses possible. Also, the view that we have taken of the acidification game setting may be questioned. All the aspects of acidification are currently subject to intense research work. Consequently, new views on the dynamics describing the acidification of soil, and its impact on forest growth, may give new insight into the negotiation dynamics.

Values other than forest growth could be presented at the negotiation table because acid rain has also other, broader consequences. Quite dramatic changes in ecosystems in Finland have been attributed to the acidification process (Kauppi et al. 1990). For example, studies on fish show that fish populations usually change in response to acidification resulting in extreme cases in local extinctions of commercial, recreational and other fish species. Moreover, acid rain causes also economic damage to man-made structures such as buildings, fabrics, and metals, and affects human health (Newbery, 1990). Taking all these damages into account in an economic analysis is a challenge to both the theoretical and empirical work in environmental economics.

Elsewhere we have analysed the acid rain game between Finland and the USSR in a static framework (Kaitala et al. 1990), in which environmental dynamics was not included, and in a dynamic framework by estimating the benefit function directly through the market values of the forest growth in each country (Kaitala et al. 1991). The results obtained in these studies coincide qualitatively with the results obtained in this paper: efficient cooperation entails financial transfers from Finland to the USSR, first because it is cheaper to abate sulphur there, and second because the action plan signed recently (Action Programme 1989) is not rational from the Soviet Union's viewpoint and may thus not be observed without monetary support (side payment) from Finland.

Appendix 1. The simulations of the ion exchange dynamics were carried out by using parameter values that are typical of the poor mineral soil in Finland. The following parameter values were used: CEC = 8000 meq/m^2, P = 1.0 m a^{-1}, ET = 0.65 m a^{-1}, recidence time = 0.714 years, flow = 1.4 l a^{-1}, soil wetness = 0.25 m^3/m^3, soil depth = 1 m, $K^{exch} = 3 \times 10^4$ l/eq, weathering =0.02 eq m^{-3} a^{-1}. The organic cycle was omitted in the simulations ($s_1 = s_2 = 0$).

Appendix 2. The noncooperative solution has the property that at an equilibrium no party has an incentive to deviate unilaterally from it. Formally, let E_i, $i = 1, 2$, denote the set of admissible emission abatement policies of country i.

Definition A.1. An admissible policy pair $(\tilde{e}_1, \tilde{e}_2) \in E_1 \times E_2$ is an *equilibrium* at $x(0)$ if

$$J_1(x(0), \tilde{e}_1, \tilde{e}_2) \geq J_1(x(0), e_1, \tilde{e}_2) \text{ for all } e_1 \in E_1, \tag{A.1}$$

$$J_2(x(0), \tilde{e}_1, \tilde{e}_2) \geq J_2(x(0), \tilde{e}_1, e_2) \text{ for all } e_2 \in E_1. \tag{A.2}$$

Definition A.2. A strategy pair $(e_1^*, e_2^*) \in E_1 \times E_2$ is a *Pareto-efficient* solution at $x(0)$ if and only if for any other pair $(e_1, e_2) \in E_1 \times E_2$ either

$$J_i(x(0), e_1, e_2) = J_i(x, e_1^*, e_2^*),$$

or for $i = 1$ or 2, $J_i(x(0), e_1, e_2) < J_i(x, e_1^*, e_2^*)$.

Acknowledgements. Frequent discussions with P. Hari and M. Holmberg were always encouraging and improved the study considerably. M. Holmberg kindly allowed (and taught) V.K. to use acidification simulations programs. I. Savolainen and M. Tähtinen gave us access to unpublished data on emission abatement costs. M. Hongisto, M. Johansson, and J.-P. Tuovinen provided us with valuable references. V.K. and M.P. acknowledge financial support from the Yrjö Jahnsson foundation.

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