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Eco-Correlation in Acidification Scenarios

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Eco-Correlation in Acidification Scenarios

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10. September 2001

Abstract: The bulk of acid depositions, which have harmful effects on the environment, are caused by foreign emissions in many European countries. Therefore, if some countries emit more acids, one cannot be sure that countries that emit less will benefit from reduced acid depositions. However, numerical simulations with the RAINS model indicate that differences in costs and acid depositions are negatively correlated when equally expensive *cost-effective* scenarios for Europe are compared, and scenarios only differ with respect to the constraints on depositions at various locations. The negative correlation is twofold: both the *signs* of changes for individual countries and the *magnitude* of changes between countries are negatively correlated. The novelty of this paper is to explain these findings. It is shown how the *structure of atmospheric transport coefficients* must be accounted for in order to understand the numerical findings. Since the atmospheric transport coefficients are constant, the hypothesis is that the two types of correlation will exist for all targets on acidification in Europe. This insight can help policymakers to agree upon a methodology for calculating targets for acidification, and maybe it also can help them to find a consensus upon more ambitious policies towards acidification.

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JEL classification: D62, H77, Q25, Q28

1. Introduction: Theories and Policies for Reduced Acidification in Europe and USA

For many European countries, the bulk of acid depositions, which have harmful effects on the environment, are caused by foreign emissions (SO_2, NO_x and NH_3). Therefore, if some countries emit more acids, one cannot be sure that countries that emit less will benefit from reduced acid depositions. However, some numerical optimisations indicate that differences in costs and acid depositions are negatively correlated when equally expensive *cost-effective* scenarios for Europe are compared, and scenarios only differ with respect to the constraints on depositions at various locations. The negative correlation is twofold: both the *signs* of changes for individual countries and the *magnitude* of changes between countries are negatively correlated.

The novelty of this paper is to provide explanations for these results. In particular it is shown how they can be explained by the structure of atmospheric transport coefficients. The hypothesis is therefore that the two types of correlation will exist *no matter* how the targets on European acidification are calculated. This insight can help policymakers to agree upon a methodology for calculating targets for acidification, and maybe it also can help them to find a consensus upon more ambitious policies. Additional evidence for the existence of the two types of negative correlation are also offered.

A basic lesson from environmental economics is that, in absence of regulations, emission levels will typically be too large from a social point of view since emitters impose a negative externality upon society. The simplest textbook answer to such problems is to internalise the externality either by an appropriate Pigovian tax or by a system of tradable emission permits. If it is assumed that the emitters' location are unimportant, which is the case for instance for greenhouse gases' impact on the climate, both these policy instruments will typically generate optimal decentralised solutions where marginal abatement costs are the same for all emitters. However, this solution does not work for acidification since the damage caused by an emitted amount of acids depends on the emitter's location.

Many contributions in the economic literature concerned with acidification deals with modified emission-trading systems. The discussion of *emission* trading versus *pollution* trading in Montgomery (1972) is a classical reference point in this literature. In the emission trading system the holder of a permit has an allowance to emit a certain amount of the substance under consideration, for instance SO2. In the pollution trading system, however, the holder of a permit has an allowance to pollute a certain amount at the location that the permit is valid for. For acidification, a pollution permit could be an allowance to deposit a certain amount of acids at a particular location.[1] Montgomery (1972) showed that emission permit trading typically fails to be cost-effective when the location of emitting sources are important, while trading in pollution permits generate cost-effectiveness. So, according to the analysis of Montgomery, a decentralised social optimum may be reached for acidification too.

Both Krupnick *et al*. (1983) and Tietenberg (1985) argue that Montgomery's analysis is based on too simple assumptions. In particular, they argue that transaction costs, which are neglected in Montgomery (1972), would be substantial in the pollution permit market since all emitters must buy pollution permits for all locations where their emissions cause any depositions. If one believe that these transaction costs are sufficiently large, it can be argued that the emission trading system is a better system than pollution trading even though the former system ignores the differences in damage caused by emissions at different locations.

In USA, sulphur emission permits are traded in a nation-wide permit market for electricity producers, which accounts for nearly 70% of the sulphur dioxide (SO2) emissions. There are no restrictions on trade apart the local ambient air quality standards. However, it is uncertain whether the expected reduction in acid deposition will be met in the sensitive areas (Klaassen and Nentjes 1997). The disadvantages with emission trading compared to pollution trading are therefore illustrated, and, according to Rodríguez (1999), these disadvantages *exclude* the possibility of using an emission permit system in Europe. The differences between ecosystems' sensitivity to acid depositions are also larger in Europe (Klaassen and Nentjes 1997). Consequently, an emission permit market is probably better for USA than for Europe.

Several other trading systems are also studied in the literature. See for instance Burtraw *et al*. (1998), Krupnick *et al*. (1983), Klaassen *et al.* (1994), Førsund and Nævdal (1998) and Rodríguez (1999). Taken together, these contributions search for a trading system where the potential cost-savings in an emission permit trading system can be combined with the more secure environmental benefits in the pollution permit trading system. However, even though joint implementation was an intention in the Second Sulphur Protocol (UN/ECE 1996), parties have to this date not agreed on how this should be done in practice. Instead, the European policy has followed a dual track of (a) national emission ceilings, without any trade between countries, and (b) legislation on standards, for instance on the maximum sulphur content in fuels. The obligations are signed upon in protocols within the UN/ECE Convention on Long-Range Transboundary Air Pollution (LRTAP). For individual European, Klaassen and Nentjes (1997) did not find any evidence for trades where permissions to emit were transferred from one party to another in exchange for money.

The RAINS[2] model has been used extensively within LRTAP both during the negotiations on the Second Sulphur Protocol (Amann *et al.* 1996; Heyes *et al.* 1997) and during the negotiations on the new multi-effect, multi-pollutant protocol.[3] The model can be used to calculate cost-minimising emission reductions, subject to environmental constraints on acidification, eutrophication and ground level ozone in 150x150 km grids covering all Europe (Alcamo and

Hordijk 1990; Amann *et al.* 1998c). According to UN/ECE (1996), obligations in the Second Sulphur Protocol are in fact calculated by optimisation. If one believes that the RAINS model

- is able to calculate the cost-effective allocation of acid emissions between countries, and
- differences in damage caused by emissions from various locations within countries are neglected,

the outcome of RAINS simulations mimics the allocation of emissions between countries that would occur in a pollution permit trading system. Now, if countries

- agree to abate the amount specified by a RAINS optimisation and
- they implement national obligations by a domestic emission trading systems or a country-specific Pigouvian tax,

then each country can obtain the secure environmental benefit of the pollution trading system without the excessive transaction costs that Krupnick *et al*. (1983) and Tietenberg (1985) associates with this system. A similar argument is offered in Krupnick *et al*. (1983). They discuss a system where some administrators first distribute emission permits according to the cost-effective solution, and then permits are traded in zones on one-to-one basis. However, they disregard this system since it is a potential nightmare for the administrators who face the enormous task of calculating, and continuing readjusting, the cost-effective solution. However, thanks to the RAINS model, the task is manageable for Europe now.

Even though parties within the convention are conscious of the need for a cost-effective approach to combating air pollution, there have been some discussions about alternative rules for calculating environmental targets at various locations, called *targeting principles* (Amann *et al.* 1998a, 1998b, 1998d). For instance, one can require a certain reduction in acidification compared to an initial situation (*gap closure*) or, alternatively, the acidification can be constrained by the same amount everywhere (*ceiling*). In addition, acidification can be measured in several ways. For instance one can measure how much the acid deposition on average exceeds the tolerance of ecosystems at a particular location (*mean accumulated excess*), or, alternatively, one can measure the share of ecosystems that have a tolerance less than the deposition level (*share unprotected area*). The constraints on acid depositions can therefore be calculated in many ways. Also, since the environmental constraints have a decisive influence on the distribution of abatement costs and environmental benefits in the optimal solution, it is not surprising that there is a controversy about the targeting principles within LRTAP.

Fortunately, when two equally expensive cost-effective solutions, which differs only with respect to the selected targeting principles, are compared, a given country typically have to carry largest abatement costs in the scenario where they obtain the largest reduction in acidification. In addition, if the net increase in abatement costs from one optimisation to another optimisation is larger for a particular country than for another country, the former country typically also obtains a larger net reduction in mean acidification. At least this is the case in Wolfgang (forthcoming) where three different targeting principles and the resulting distribution of costs and acidification are analysed (figure 1 illustrates some of the results). However, no explanations have been offered for these findings yet.

(Figure 1 about here).

The combination of the two types of negative correlation is called the Eco-Correlation hereafter, where the word Eco refers to Economy and Ecology. The finding that Eco-Correlation exists in acidification scenarios is of course encouraging since it could be hard for negotiating parties within LRTAP to agree on any targeting principle in the opposite situation.

For the purpose of this paper, additional evidence of the Eco-Correlation in acidification scenarios is offered here. Figure 2 illustrates the differences between the Central and High ambition level scenarios in Amann *et al*. (1998d).

(Figure 2 about here).

The negative correlation appears also for all other comparisons of acidification scenarios in Wolfgang (forthcoming) and Amann *et al.* (1998d).

The main purpose of this paper is, however, to provide an explanation for the Eco-Correlation. This insight can help policymakers to agree upon a methodology for calculating targets for acidification, and maybe it also can help them to find a consensus upon more ambitious policies towards acidification. If Finus and Tjøtta (1998) are correct, there is certainly a need for more ambitious policies. In a game-theoretic framework they show that, for most countries, emission ceilings specified in the Second Sulphur Protocol are larger than the emitted amounts in the estimated Nash-equilibrium, given by the emission levels countries would emit in absence of any international agreements. Their approach is similar to the approach of Mäler (1989). Mäler concludes that there is a need for international transfers in order to motivate all countries to participate in the optimal co-operative solution for reduced acidification. Such transfers are not a part of the protocols within LRTAP at present. On the other hand, Tjøtta (1999) uses statistical methods to show that the signing of the First Sulphur Protocol (UN/ECE 1996) had considerable positive effects on countries' emission reductions. This result undermines a central assumption made in Finus and Tjøtta (1998), namely that emissions were at Nash-equilibrium levels before the Second Sulphur Protocol was signed. Consequently, one cannot interpret the findings in the literature such that the obligations within the LRTAP convention have no effects on acidification.

It can be argued that one should try to find and understand features of cost-effective solutions rather than the features of results from RAINS optimisations like those shown in figures 1 and 2. However, it is not possible to observe cost-effective abatement policies. Empirical data must therefore be based on numerical models, and the RAINS model is probably the most reliable tool to analyse these kinds of problems at present. A proper understanding of this model has large own value too since it has a central position within the UN/LRTAP convention. However, it is hard to identify reasons for particular results in RAINS simulations since the model is large and complex. First, the model uses a lot of information about abatement costs, atmospheric transport of substances and the sensitivity towards depositions in various ecosystems. Secondly, there are a lot of variables and simultaneous equations in the model. Therefore, some delegates within UN/LRTAP have felt a need for simpler explanations for results than the documentation of RAINS model.

The formal model that is offered in this paper captures some of the basic properties of the RAINS model, even though it has a simpler structure. The simplified model is also analytically manageable, and the mechanisms that lead to the Eco-Correlation will be identified.

The remainder of the paper is organised as follows. Section 2 offers a formal model for cost-effective reductions of acidification in Europe. The observation that the atmospheric transport coefficients on average are larger to domestic grids than to foreign grids is emphasised by the simplified model. Some characteristics of optimal solutions are also derived in this section, while the effects of changed targets for acidification are evaluated in section 3. In general, the model shows how the structure of atmospheric transport coefficients can explain the Eco-Correlation shown in figures 1 and 2. Section 4 offers a numerical example, while section 5 concludes the analysis.

2. The Model

In this section a model for cost-effective reductions of European acidification is developed. Each country is assumed to emit an acid substance and atmospheric transport coefficients show how emissions are dispersed and deposited at various locations. However, countries can abate their emissions at certain costs. A cost-effective solution is an emission vector that minimises the sum of abatement costs, subject to constraints on acidification in all regions. The properties of first-order conditions for this particular problem is well known from the literature. However, the Eco-Correlation has not been explained yet.

We consider a group of n countries. Let i be the index for countries and I be the set of countries such that $i \in I = \{1,...,n\}$. Only one emission type, for instance sulphur dioxide, is taken into account, and the abated amount for a country (r_i) is defined to be the difference between an exogenous no-control level of emissions (e_i^{nc}) and any other emission level (e_i).

$$r_i \equiv e_i^{nc} - e_i \tag{1}$$

The abatement cost functions (c_i) are assumed to be convex power functions in the abated amount, and the power (b>1) is the same for all countries. However, it is reasonable to assume that a given emission reduction is cheapest to obtain in countries where no-control emissions are relatively large. A country specific technology parameter (A_i) accounts for this.

$$c_i(r_i) = A_i r_i^b \quad \text{for } r_i \geq 0 \tag{2}$$

A large technology parameter (A_i) implies large abatement costs for a given abated amount. It is therefore reasonable to assume large technology parameters for those countries that have small no-control emissions. In a special case where $A_i = A / {e_i^{nc}}^{b-1}$, marginal abatement costs are the same for all countries that abate the same share of their no-control emissions. The cost functions in (2) are generalised versions of cost functions used in Mäler and de Zeeuw (1998).

The emissions give acid depositions at m different locations under consideration. Let j be the index of locations (grids) and J be the set of locations such that $j \in J = \{1,...,m\}$. Constant atmospheric transport coefficients (a_{ij}) show how much the acid depositions increase at location j if emissions are increased by one unit in country i, while a grid specific constant (d_j) accounts for depositions caused by other sources, like emissions at sea, transatlantic emissions and natural sources. Total deposition levels at a location (D_j) is given by[4]

$$D_j = \sum_i a_{ij} e_i + d_j = \sum_i a_{ij} \left(e_i^{nc} - r_i \right) + d_j \ , \tag{3}$$

while reduced depositions are caused by abatement and given by

$$R_j \equiv D_j \left(e^{nc} \right) - D\left(e \right) = \sum_i a_{ij} r_i \ . \tag{4}$$

In optimisation, all environmental targets on acidification must be translated into constraints on acid depositions. The cost-effective solution is therefore given by the abatement vector (which is equivalent to an emission vector) that minimises the sum of abatement costs, subject to the constraints on acid deposition $\left(D_j \leq \overline{D}_j \right)$.

Commonly, a non-negative constraint on abatement $\left(r_i \equiv e_i^{nc} - e_i \geq 0 \right)$ is added too. However, Wolfgang (1999) has shown that this is unsatisfactory on theoretical grounds since emission levels in principle can be larger than no-control. It is therefore assumed that marginal abatement costs take the same sign as the abated amount. It is also common to restrict emissions downward by zero. However, the cost of removing all acid emissions in a country will be so large in real life examples that this is an irrelevant restriction. The optimisation problem is therefore given by

$$\begin{aligned}&min_{r_i} \sum_i A_i r_i^b \\ &subject\ to\ \overline{D}_j \geq \sum_{i=1}^{n} a_{ij} e_i + d_j \qquad j = 1,...,m.\end{aligned} \tag{5}$$

In general, this formulation illustrates the type of optimisation done by the RAINS model. Still, there are several differences between RAINS optimisations and (5). Firstly, emissions are usually restricted upwards in RAINS by (a) what is agreed on in existing protocols, and (b) calculated emissions using current legislation on standards and energy consumption projections (Amann *et al*. 1997). Secondly, not all types of abatement possibilities are accounted for in RAINS. For instance, the model doesn't consider the possibility of reducing emissions (a) by switching between main types of fossil fuels like coal and gas or (b) by cutting the overall consumption of fossil fuels (Cofala and Syri 1998a and 1998b), even though reduced production typically reduces emissions at zero marginal costs in no-control (see for instance McKitrick 1999 or Wolfgang 1999). Consequently, there is an upper bound on abatement called *maximum feasible reductions*. Thirdly, RAINS cost-curves are step-wise linear and based on the assumption that abatement efforts already taken are continued into the future. Finally, several types of emissions are accounted for and several environmental problems can be considered simultaneously in RAINS optimisations. For simplicity, these complicating elements are not accounted for here. The Lagrangian function for (5) is

$$L = -\sum_i A_i r_i^b + \sum_j \lambda_j \left(\overline{D}_j - \sum_i a_{ij} e_i - d_j \right), \tag{6}$$

and the first order conditions are

$$A_i b r_i^{b-1} = \sum_j \lambda_j a_{ij} \qquad \forall i \tag{7a}$$

$$\overline{D}_j \geq \sum_i a_{ij} e_i + d_j,\ \lambda_j \geq 0 \qquad \forall j \tag{7b}$$

$$\lambda_j \left(\overline{D}_j - \left(\sum_i a_{ij} e_i + d_j\right)\right) = 0 \quad \forall j, \tag{7c}$$

where λ_j is the shadow price on the constraint on acidification at location *j*. The value of λ_j shows the increase in minimal abatement costs that occurs if the maximum amount of acid depositions at location *j* is reduced by one unit. Typically there are only a few binding constraints in RAINS optimisations when grid-based acidification targets are used (see for instance Amann *et al*. 1998b or Wolfgang forthcoming). Consequently, there are typically only a few strictly positive λ_j. However, at least one shadow price is strictly positive in the only interesting case where no-control emissions violate at least one constraint on acid depositions.

From (7a) we can see that marginal abatement costs for a country in the optimal solution is equal to the sum of shadow prices multiplied with the respective atmospheric transport coefficients. Consequently, marginal abatement costs are largest for those countries that have large atmospheric transport coefficients to locations where the shadow prices on acidification are large. This is different from the CO2 abatement case where countries typically have equal marginal abatement costs in a cost-effective solution (see Tietenberg 1985 for further comparisons). Solving (7a) with respect on abatement yields

$$r_i = \left(\frac{\sum_j \lambda_j a_{ij}}{A_i b}\right)^{\frac{1}{b-1}}, \tag{8}$$

and substituting (8) into (2) gives

$$c_i = \left(\frac{\sum_j \lambda_j a_{ij}}{A_i^{\frac{1}{b}} b}\right)^{\frac{b}{b-1}}. \tag{9}$$

This is the abatement costs for a country *i* in the optimal solution. Both the abated amount and abatement costs are increasing functions of the sum of shadow prices times the atmospheric transport-coefficients. Also, *ceteris paribus,* a small technology parameter (A_i), which implies good abatement technology, gives relatively large abatement costs compared to other countries. Using (7a) and $c_i = A_i r_i^{b-1} r_i$, the abatement costs can also be written as

$$c_i(r_i) = \frac{\sum_j \lambda_j a_{ij}}{b} r_i . \tag{10}$$

If the sum of shadow prices multiplied with the respective atmospheric transport coefficient is large, then the average abatement costs is large too. Divide by r_i on both sides in (10) to see this.

The relationship between abatement costs and deposition reductions is found by solving (10) with respect on r_i and substituting this into (4). However, since we mainly are interested in the relationship between abatement costs and deposition reductions at domestic locations, a subset of locations for each country is defined. Let J_i be a subset of locations $(J_i \subset J)$ such that a location is a member of the subset if and only if the location belongs to country i.[5] The index j_i is an index for the members of the subset J_i such that $j_i \in J_i$. Substituting (10) into (4) for country $k \in I$ and location $j_k \in J_k$ gives

$$R_{j_k} = \sum_i a_{ij_k} r_i = a_{kj_k} \left(\frac{bc_k(r_k)}{\sum_j \lambda_j a_{kj}} \right) + \sum_{i \neq k} a_{ij_k} r_i \quad . \tag{11}$$

This equation shows deposition reduction in a domestic grid for country k as a function of country k's abatement costs in an optimal solution. However, both the coefficient in front of the parenthesis and the last sum can in general be different for all locations, and the denominator can be different for all countries. Consequently, it is not possible to establish any interesting relationship between abatement costs and deposition reduction in domestic grids unless we account for some of the structure of atmospheric transport coefficients.

Figures 3-5 shows the RAINS simulated acid depositions caused by German $SO2$ emissions, Dutch $NH3$ emissions and UK NOx emissions respectively.

(Figures 3-5 about here).

Clearly, the average of atmospheric transport coefficients to domestic grids is much larger than the average of coefficients to foreign grids. This feature is emphasised by the following assumption: all atmospheric transport coefficients to domestic grids are a^{in} and all coefficients to foreign grids are a^{out}, where $a^{in} > a^{out}$. Formally:

$$a_{ij} = \begin{Bmatrix} a^{in} & | j \in J_i \\ a^{out} & | j \notin J_i \end{Bmatrix} \quad \text{and } a^{in} > a^{out} > 0. \tag{12}$$

Now deposition reductions can be written as

$$R_{j_k} = \sum\nolimits_i a_{ij_k} r_i = a^{in} r_k + a^{out} \sum\nolimits_{i \neq k} r_i = \left(a^{in} - a^{out}\right) r_k + a^{out} \sum\nolimits_i r_i\ , \tag{13}$$

where the right hand side is the same for all locations within a given country, and the last term is equal for all countries. This implies that deposition reductions are equally large for all grids within a country and, more importantly, if a country abates more than another country then it also obtains larger reductions in acid depositions in domestic grids. This finding is a consequence of the simplifying assumption in (12). Still, it strongly suggests that the structure of atmospheric transport coefficients must be an important element when the Eco-Correlation is explained. This finding also have clear implications for countries willingness to trade emission permits in a hypothetical emission trading system, but this is typically neglected in contributions that discuss such trading systems. [6]

However, since countries have different abatement cost functions one can not *a priori* be sure that those countries that abate the largest amounts also have to carry the largest abatement costs. The cost functions and the features of optimal solutions must therefore be taken into account too.

Equation (13) implies that the reduced amounts of depositions are the same for all grids within a country. We can therefore simplify the notation and write R_k instead of R_{j_k}, where R_k is the deposition reduction in all domestic grids for country k. Solving (10) with respect on r_i for country $k \in I$ and substituting this into (13) gives

$$R_k = \left(a^{in} - a^{out}\right)\left(\frac{bc_k\left(r_k\right)}{\sum_j \lambda_j a_{kj}}\right) + a^{out}\sum_i r_i \,, \tag{14}$$

and this can be written as

$$c_k\left(r_k\right) = \sum_j \lambda_j a_{kj} \frac{R_k - a^{out}\sum_i r_i}{b\left(a^{in} - a^{out}\right)} = a_k \sum_j \lambda_j \frac{R_k - a^{out}\sum_i r_i}{b\left(a^{in} - a^{out}\right)} \tag{15}$$

where

$$\begin{aligned} a_k &\equiv \frac{\sum_j a_{kj}\lambda_j}{\sum_j \lambda_j} = \frac{a^{in}\sum_{j\in J_k}\lambda_j + a^{out}\sum_{j\notin J_k}\lambda_j}{\sum_j \lambda_j} \\ &= \left(a^{in} - a^{out}\right)\frac{\sum_{j\in J_k}\lambda_j}{\sum_j \lambda_j} + a^{out} \in \left[a^{out}, a^{in}\right] \end{aligned} \tag{16}$$

is the weighted average of country k's atmospheric transport coefficients to all grids and also to the binding grids. Equation (15) can also be written as

$$c_k = \alpha a_k \left(R_k - \beta\right) \tag{17}$$

where

$$\alpha = \frac{\sum_j \lambda_j}{b\left(a^{in} - a^{out}\right)} > 0 \quad \text{and} \quad R_k > \beta = a^{out}\sum_i r_i > 0\,. \tag{18}$$

Now we can easily compare costs and acid depositions for different types of countries. Hereafter a country is called non-binding if none of the binding constraints are associated with locations within the country, while the other countries are called binding countries. First we consider costs and acid depositions for the non-binding countries, and this will typically we the overwhelming majority of countries. From (16) we can see that $a_k = a^{out}$ for such countries, and from (17) the abatement costs are given by

$$c_k = \alpha a^{out}\left(R_k - \beta\right). \tag{19}$$

Clearly, deposition reductions and abatement costs for these countries can be plotted on the same increasing line. The relative positions on this line can therefore be found from the relative abatement costs. Since all binding grids are located outside the non-binding countries we know that $a_{ij} = a^{out}$ in all cases where i is a non-binding country and $\lambda_j > 0$. Consequently, from (9), the abatement costs for a non-binding country is

$$c_i = \left(\frac{a^{out}\sum_j \lambda_j}{A_i^{\frac{1}{b}} b}\right)^{\frac{b}{b-1}} \tag{20}$$

while the relative abatement costs for two non-binding countries i and j is

$$\frac{c_i}{c_j} = \left(\frac{A_j}{A_i}\right)^{\frac{1}{b-1}}. \tag{21}$$

The relative abatement costs is a decreasing function of the relative technology parameters. This implies that countries that have a large technology parameter $\left(A_i\right)$, have relatively small abatement costs in the optimal solution. Consequently, non-binding countries' relative position on the line that relates abatement costs and deposition reductions for such countries are determined entirely by their technology parameter.

Now consider abatement cost and deposition reductions for binding countries $\left(a_k > a^{out}\right)$.[7] The abatement costs for a binding country k is given by (17), so the cost for this country would be plotted $\alpha\left(a_k - a^{out}\right)\left(R_k - \beta\right) > 0$ above the line connecting deposition reductions and costs for all the non-binding countries.

Consequently, the binding countries have to pay more than the non-binding countries for a given deposition reduction in domestic grids. The binding countries also obtain additional deposition reductions for a given technology-parameter A_i. To see this substitute (8) into (13) for country $k \in I$:

$$\begin{aligned} R_k &= \left(a^{in} - a^{out}\right)\left(\frac{\sum_j \lambda_j a_{kj}}{A_k b}\right)^{\frac{1}{b-1}} + a^{out}\sum_i r_i \\ &= a_k^{\frac{1}{b-1}}\left(a^{in} - a^{out}\right)\left(\frac{\sum_j \lambda_j}{A_k b}\right)^{\frac{1}{b-1}} + a^{out}\sum_i r_i . \end{aligned} \tag{22}$$

From (22) we can see that deposition reductions in the optimal solution is given by a function that is increasing in the weighted average of atmospheric transport coefficients to binding grids (a_k) and decreasing in the technology parameter (A_k). Consequently, the binding countries obtain extra reductions in depositions for a given abatement technology, but at relatively large costs.

So far the analysis has shown how the model implies a close correlation between deposition reductions and abatement costs for countries in an optimal solution. However, the more ambitious purpose of the analysis in this paper is to provide an explanation for the Eco-Correlation, that is, for the pattern in figures 1 and 2 where two optimisation scenarios are compared. A second optimisation will therefore be considered in the next section.

3. Modified Targets

This section shows how countries' abatement costs and deposition reductions are changed if a new set of targets for acidification is used in the optimisation. The change in targets can for instance be caused by a general increase in the ambitious-level so that all constraints on depositions $\left(\overline{D}_j\right)$ are reduced. This is the case for the two RAINS optimisations that is compared in figure 2. Alternatively, a different targeting principle can be used. In that case, some of the upper constraints on acid depositions can be increased while others are decreased. This is the case in figure 1. However, in both cases all changes in the cost-effective solution are caused by the modification of targets for acid depositions.

Suppose that a new set of targets is used in (5). This will typically lead to changed values for all endogenous variables. Let the numbers 1 and 2 on top of variables indicate their values in the first and second optimisation respectively. First the *relative size* of change in countries' abatement costs and deposition reductions will be evaluated. Afterwards, the *signs* of change for individual countries will be considered.

First we consider we a case where the abatement costs is increased for country *i* while it is decreased for country *k*. Then, by assumption, country *i* have to carry a larger *net* increase abatement costs than country *k* (the net increase in costs is negative for country *k*).

$$c_i^2 - c_i^1 > c_k^2 - c_k^1 \tag{23}$$

Deposition reductions for a given country is given by (13), while the difference in deposition reductions for two countries *i* and *k* is given by

$$R_i - R_k = \left(a^{in} - a^{out}\right)\left(r_i - r_k\right). \tag{24}$$

Since the abatement costs is increased for country *i* and decreased for country *k*, and the parameters of the cost functions are assumed to be constant, we know that the abated amount is increased for country *i* and decreased for country *k*. Consequently, the net difference in (24) is larger in the second optimisation than in the first, and

$$R_i^2 - R_k^2 > R_i^1 - R_k^1 \quad \Rightarrow \quad R_i^2 - R_i^1 > R_k^2 - R_k^1 . \tag{25}$$

Proposition One. If the cost-effective solution for reduced acidification is changed as a result of modified targets, then the net increase in both abatement costs and deposition reductions are larger for all countries that have to carry larger abatement costs than for any of the other countries. (Proved by (23) and (25)).

In a graphical plot like those in figures 1 and 2 this means that all countries above the x-axis are further to the left than all countries below the x-axis.[8] That is also the case in figure 1, but there are some exceptions in figure 2. This is one of the most important findings in this paper, and it can be established for any set of monotone-convex cost functions, it does not depend on the specific formulation in (2). However, the most important findings in the rest of this paper cannot be established for all monotone-convex cost functions.

Proposition one does not give any information about the relative changes in costs and deposition reductions within the two groups of countries. For such comparisons, it is convenient to use the change-rates for existing differences in abatement costs and deposition reductions from the first to the second optimisation. The existing differences in abatement costs and deposition reductions for two countries *i* and *k* in the first optimisation are given by

$$c_i^1 - c_k^1 = \left(\frac{\sum_j \lambda_j^1}{b}\right)^{\frac{b}{b-1}} \left(\left(\frac{a_i^{1b}}{A_i}\right)^{\frac{1}{b-1}} - \left(\frac{a_k^{1b}}{A_k}\right)^{\frac{1}{b-1}}\right) \tag{26}$$

and

$$R_i^1 - R_k^1 = \left(\frac{\sum_j \lambda_j^1}{b}\right)^{\frac{1}{b-1}} \left(a^{in} - a^{out}\right) \left(\left(\frac{a_i^1}{A_i}\right)^{\frac{1}{b-1}} - \left(\frac{a_k^1}{A_k}\right)^{\frac{1}{b-1}}\right) \tag{27}$$

while the change-rates are defined by

$$\widehat{c_i - c_k} \equiv \frac{\left(c_i^2 - c_k^2\right) - \left(c_i^1 - c_k^1\right)}{\left(c_i^1 - c_k^1\right)} \quad \text{and} \quad \widehat{R_i - R_k} \equiv \frac{\left(R_i^2 - R_k^2\right) - \left(R_i^1 - R_k^1\right)}{\left(R_i^1 - R_k^1\right)} \tag{28}$$

and given by

$$\widehat{c_i - c_k} = \left(\frac{\sum_j \lambda_j^2}{\sum_j \lambda_j^1} \right)^{\frac{b}{b-1}} \frac{\left(\frac{a_i^{2b}}{A_i} \right)^{\frac{1}{b-1}} - \left(\frac{a_k^{2b}}{A_k} \right)^{\frac{1}{b-1}}}{\left(\frac{a_i^{1b}}{A_i} \right)^{\frac{1}{b-1}} - \left(\frac{a_k^{1b}}{A_k} \right)^{\frac{1}{b-1}}} - 1 \tag{29}$$

and

$$\widehat{R_i - R_k} = \left(\frac{\sum_j \lambda_j^2}{\sum_j \lambda_j^1} \right)^{\frac{1}{b-1}} \frac{\left(\frac{a_i^{2}}{A_i} \right)^{\frac{1}{b-1}} - \left(\frac{a_k^{2}}{A_k} \right)^{\frac{1}{b-1}}}{\left(\frac{a_i^{1}}{A_i} \right)^{\frac{1}{b-1}} - \left(\frac{a_k^{1}}{A_k} \right)^{\frac{1}{b-1}}} - 1. \tag{30}$$

Proposition Two. Independent of relative abatement costs and relative deposition reductions in the first optimisation, existing differences in abatement costs and deposition reductions (in the first optimisation) are increased if the change-rates rates for these differences, from the first to the second optimisation, are positive and *vice versa*. (Proof is offered in appendix A.)

However, even though the change-rates take the same sign, one cannot conclude that the net increase in abatement costs is largest for the country that obtains the largest net increase in deposition reductions. Suppose, for instance, that a binding country *i* have to carry larger abatement costs than another country *k* initially, even though country *i* obtain less deposition reductions in domestic grids than country *k*. Suppose also that the sum of shadow prices is increased from the first to the second optimisation and that the weighted averages of atmospheric transport coefficients are constant for these countries. In this case, proposition two implies that the net increase in costs will be largest for country *i* while the net increase in deposition reductions will be largest for country *k*. However, such cases are avoided if we consider two countries where both abatement costs and deposition reductions are largest for one of the countries in the first optimisation.

Proposition Three. If both abatement costs and deposition reductions are larger for country *i* than for country *k* (or inverse) in the first optimisation, and the change-rates of differences in abatement costs and deposition reductions take the same signs, then the net increase in abatement costs is largest for the country that obtains the largest net increase in deposition reductions. However, if the change-rates take different signs, the net increase in abatement costs is largest for the country that obtains the smallest net increase in deposition reductions. (Proof is offered in appendix A.)

Since the conditions for positive change-rates are similar in (29) and (30), the change-rates will take the same sign for many values on parameters and shadow prices. Still, the change-rates can in general take different signs.

Proposition Four. Even though the cost-effective solution for reduced acidification is changed as a result of modified targets, and a country *i* has larger abatement costs and larger deposition reductions than another country *k* in the first optimisation, the net increase in abatement costs can be smallest for that country that obtains the largest net increase in deposition reductions. (The proof is trivial by proposition three since (29) and (30) can take different signs.)

The intuition is as follows. Suppose that two countries *i* and *k* are non-binding in the first optimisation, such that $\left(a_i^1, a_k^1\right) = \left(a^{out}, a^{out}\right)$, and country *i* has a smaller technology parameter than country *k* $\left(A_i < A_k\right)$. Then, from (26) and (27), both abatement costs and deposition reductions are lager for country *i* than for country *k* in the first optimisation. Suppose now that the sum of shadow prices is increased from the first to the second optimisation. Suppose also that country *i* is non-binding in the second optimisation too while country *k* is binding. Since the sum of shadow prices is increased, existing differences in abatement costs and deposition reductions are increased for given weighted averages of atmospheric transport coefficients. However, since country *k* is binding in the second optimisation, we know that the weighted average of atmospheric transport coefficients for this country has increased $\left(a_k^2 > a^{out} = a_k^1\right)$. From (26) and (27) we can see that this gives a partial decrease in the existing differences. Since there are two opposing effects, existing differences can be increased or decreased. Suppose that the difference in deposition reductions has increased. However, from section 2 we know that the extra deposition reductions obtained by binding countries are relatively costly. The difference in abatement costs for countries *i* and *k* can therefore be decreased even though the difference in deposition reductions has increased, and this explains proposition four. However, if country *i* is binding in the second optimisation instead of country *k*, it is obvious from this discussion that the net increase in both abatement costs and deposition reductions will be larger for country *i* than for country *k*.

Proposition Five. If both abatement cost and deposition reductions in domestic grids are larger for country *i* than for country *k* in a cost-effective solution for reduced acidification, and the targets for acidification are changed, then the country that have to carry the largest net increase in abatement costs also obtain the largest net increase in deposition reductions if either

(a) the weighted average of atmospheric transport coefficients for country *i* is increased or constant while the opposite is true for country *k*'s coefficient and the sum of shadow prices is increased, or

(b) the weighted average of atmospheric transport coefficients for country *i* is reduced or constant while the opposite is true for country *k*'s coefficient and sum of shadow prices is reduced. (Proof is offered in appendix A).

Proposition five can be used to evaluate the relative changes among non-binding countries. From (16) we know that the weighted average of atmospheric transport coefficients are equal to a^{out} for such countries. Therefore, from (26) and (27), both abatement costs and deposition reductions in the first optimisation is larger for a non-binding country *i* than for another non-binding country *k* if $A_i < A_k$, and *vice versa*. The conditions under (a) in proposition five are therefore satisfied for any pair of non-binding countries if the sum of shadow prices is increased, while the conditions under (b) are satisfied for the same countries if the sum of shadow prices is reduced.

Proposition Six. If the cost-effective solution for reduced acidification is changed as a result of modified targets, then, for any pair of countries that are non-binding in both optimisations, the country that have to carry the largest net increase in abatement costs also obtains the largest net increase in deposition reductions. (Proof is offered in appendix A).

This is probably the most important finding in this paper since it implies an unambiguous negative correlation between changes in acid depositions and the corresponding changes in abatement costs for the bulk of countries.

Proposition five can also be used to evaluate relative changes for two countries where one of them or both are binding in at least one optimisation. Suppose for instance that the sum of shadow prices is increased, that both abatement costs and deposition reductions is larger for country *i* than for country *k* in the first optimisation, and that the weighted atmospheric transport coefficient is increased for country *i* (for instance because it is binding only in the second optimisation) while it is reduced or constant for country *k* (for instance because it is non-binding in both optimisations). In this case the net increase in both abatement costs and deposition reductions will be larger for country *i* than for country *k*. However, if

(a) the abatement costs are larger for country *i* than for country *k* in the first optimisation while country *k* obtain a larger deposition reduction in domestic grids than country *i*, or

(b) the difference between the atmospheric transport coefficients is smallest in the scenario where the sum of shadow prices is largest or

(c) the weighted averages of atmospheric transport coefficients are increased for both countries under consideration, or decreased for both countries,

then proposition five gives no information about the relative changes in abatements costs and deposition reductions.

We can, however, find unambiguous results as long as the *relative* weighted averages of atmospheric transport coefficients is largest in the optimisation where the sum of shadow prices is largest.

Proposition Seven. If both abatement cost and deposition reductions in domestic grids are larger for country *i* than for country *k*, in a cost-effective solution for reduced acidification, and the weighted average of atmospheric transport coefficients are increased or constant for both countries, and an eventually increase is relatively largest for country *i*'s coefficient, then the positive differences in abatement costs and deposition reductions are increased for any increase in the sum of shadow prices. If, on the other hand, the sum of shadow prices is reduced, and the weighted coefficients are reduced for both countries but relatively more for country *i*, then the positive difference in abatement costs and deposition reductions are reduced. (Proof is offered in appendix A.)

Now we consider the *signs* of change for individual countries. The changes in abatement costs and deposition reductions for a country *k* are given by

$$c_k^2 - c_k^1 = \frac{\left(a_k^2 \sum_j \lambda_j^{\,2}\right)^{\frac{b}{b-1}} - \left(a_k^1 \sum_j \lambda_j^{\,1}\right)^{\frac{b}{b-1}}}{\left(A_k^{\frac{1}{b}} b\right)^{\frac{b}{b-1}}} \tag{31}$$

and

$$
\begin{aligned}
R_k{}^2 - R_k{}^1 &= \left(a^{in} - a^{out}\right)\left(r_k^2 - r_k^1\right) + a^{out}\sum_i\left(r_i^2 - r_i^1\right) \\
&= \frac{a^{in} - a^{out}}{(A_k b)^{\frac{1}{b-1}}}\left(\left(a_k{}^2\sum_j \lambda_j{}^2\right)^{\frac{1}{b-1}} - \left(a_k{}^1\sum_j \lambda_j{}^1\right)^{\frac{1}{b-1}}\right) \\
&\quad + a^{out}\left(\left(\sum_j \lambda_j{}^2\right)^{\frac{1}{b-1}} - \left(\sum_j \lambda_j{}^1\right)^{\frac{1}{b-1}}\right)\sum_{i\in I^{nb}}\left(\frac{a^{out}}{(A_i b)}\right)^{\frac{1}{b-1}} \\
&\quad + a^{out}\sum_{i\notin I^{nb}}\left[\left(\sum_j \lambda_j{}^2\right)^{\frac{1}{b-1}}\left(\frac{a_i{}^2}{A_i b}\right)^{\frac{1}{b-1}} - \left(\sum_j \lambda_j{}^1\right)^{\frac{1}{b-1}}\left(\frac{a_i^1}{A_i b}\right)^{\frac{1}{b-1}}\right]
\end{aligned} \tag{32}
$$

where the set $I^{nb} \subset I$ is the set of countries that are non-binding in both optimisations. The shadow prices and the weighted average of atmospheric transport coefficients determine the signs in both (31) and (32) for given values on parameters. However, the conditions for positive changes are not identical.

Proposition Eight. If the cost-effective solution for reduced acidification is changed as a result of modified targets, the change in abatement costs can in general take the opposite sign as the change in deposition reductions for any country. (The proof is trivial from (31) and (32)).

For the non-binding countries $\left(k \in I^{nb}\right)$ the weighted averages of atmospheric transport coefficients are constant equal to a^{out}. For these countries the changes in abatement costs and deposition reductions are given by

$$
c_k^2 - c_k^1 = \left(\frac{a^{out}}{A_k^{\frac{1}{b}} b}\right)^{\frac{b}{b-1}}\left(\left(\sum_j \lambda_j{}^2\right)^{\frac{b}{b-1}} - \left(\sum_j \lambda_j{}^1\right)^{\frac{b}{b-1}}\right) \tag{33}
$$

and

$$
\begin{aligned}
R_k{}^2 - R_k{}^1 &= \left(a^{in} - a^{out}\right)\left(r_k^2 - r_k^1\right) + a^{out}\sum_i\left(r_i^2 - r_i^1\right) \\
&= \left(\left(\sum_j \lambda_j{}^2\right)^{\frac{1}{b-1}} - \left(\sum_j \lambda_j{}^1\right)^{\frac{1}{b-1}}\right)\left[\left(a^{in} - a^{out}\right)\left(\frac{a^{out}}{(A_k b)}\right)^{\frac{1}{b-1}} + a^{out}\sum_{i\in I^{nb}}\left(\frac{a^{out}}{(A_i b)}\right)^{\frac{1}{b-1}}\right] \\
&\quad + a^{out}\sum_{i\notin I^{nb}}\left[\left(\sum_j \lambda_j{}^2\right)^{\frac{1}{b-1}}\left(\frac{a_i{}^2}{A_i b}\right)^{\frac{1}{b-1}} - \left(\sum_j \lambda_j{}^1\right)^{\frac{1}{b-1}}\left(\frac{a_i^1}{A_i b}\right)^{\frac{1}{b-1}}\right].
\end{aligned} \tag{34}
$$

Proposition Nine. If the sum of shadow prices is increased (decreased) as a result of modified targets for acidification, abatement costs are increased (decreased) for countries that are non-binding in both optimisations. However, the change in acid depositions within these countries can in general take both signs. (The proof is trivial from (33) and (34).

An increase in the sum of shadow prices increases the abated amount for all non-binding countries, including country $k \in I^{nb}$. This gives a partial reduction in the deposited amount in domestic locations for country *k*. The increased sum of abatement in other non-binding countries gives additional deposition reductions for country $k \in I^{nb}$. All other countries $\left(i \notin I^{nb}\right)$ also abate a larger amount for given values on the weighted average of transport coefficients. Finally, some countries $\left(i \notin I^{nb}\right)$ increase their abatement additionally since their weighted averages of atmospheric transport coefficients have increased from the first to the second optimisation. All these effects give partial reductions in the amounts of acids deposited within country $k \in I^{nb}$. However, the weighted average of atmospheric transport coefficients will typically decrease for some countries. The signs in the last parenthesis in (34) are therefore ambiguous, and then the sign of equation (34) is ambiguous too. However, the positive elements in (34) will probably dominate in many cases when the sum of shadow prices is increased.

Proposition Ten. If the cost-effective solution for reduced acidification is changed as a result of modified targets and the sum of shadow prices is increased (decreased), and

(a) the share of non-binding countries is large enough, or

(b) the sum of abatement for the set of countries that are binding in at least one optimisation is increased (decreased) or the decrease (increase) is small enough, or

(c) the increase (decrease) in the sum of shadow prices is large enough, or

(d) the technology parameter $\left(A_k\right)$ for a non-binding country *k* is small enough, then the net changes in acid depositions and abatement costs for the non-binding country *k* will take the same signs. (Proof is offered in appendix A).

Since an increase in the sum of shadow prices gives a partial increase in abatement for all countries, we can expect that the abatement in many cases also will increase for the set of countries that are binding in at least one optimisation. For all such cases we know from (b) that the net change in acid depositions for any non-binding country will take the same sign as the net change in abatement costs the same country. Also, typically, there are only a few binding countries. Therefore, from (a), the reduction in acid depositions caused by increased abatement in non-binding countries will in many cases dominate an eventual reduction in abatement for the other countries. From (c) we also know that the positive effects on reduced depositions certainly will dominate if the sum of shadow prices increases enough. However, if the amount of acid depositions is increased for a non-binding country *k*, even though the sum of shadow prices has increased, we know from (d) that the technology parameter (A_k) is likely to be relatively large for this country. It is reasonable to associate large technology parameters with small countries since no-control emissions typically are small for these countries, and this reduces the amount of abatement that can be carried out by the cheapest abatement techniques.

Now we consider a country that has a larger weighted average of atmospheric transport coefficients in the second optimisation than in the first. If the sum of shadow prices is increased, this country will abate a larger amount. Therefore, based on the arguments for non-binding countries, the changes in costs and deposition reductions will typically take the same signs for these countries also.

This section has shown (a) under which conditions the net increase in abatement costs is largest for the countries that obtain the largest net increase in deposition reductions, and (b) under which conditions the net changes in abatement costs and deposition reductions take the same sign for individual countries. The most unambiguous results are found for non-binding countries. The conditions under (a) are always satisfied for these countries, while the conditions under (b) are satisfied for many cases.

4. Numerical Illustrations

This section illustrates analytical findings in a numerical example. Suppose that there is one country for each letter in the alphabet. Suppose also that $A_i = 1/e_i^{nc}$, $1000 = e_a^{nc} = e_b^{nc}\left(1.25\right)^{-1} = e_c^{nc}\left(1.25\right)^{-2} ... = e_z^{nc}\left(1.25\right)^{-25}$, $b = 1.75$, $a^{in} = 0.1$, $a^{out} = 0.01$ and $d_j = 100$. In addition we need two sets of targets for acid depositions. These targets can of course be assumed directly. However, the targets in the first optimisation are calculated as follows. Ecosystems have a certain buffer capacity for acid depositions, called *critical loads*.[9] If the amount of acid depositions is larger than the critical load for an ecosystem, then the difference is called an *exceedance*. The first set of targets requires a 60% reduction of all exceedances compared to no-control. Consequently, we also need a set of *critical loads* in order to calculate the targets. It is assumed that critical loads are equal to 150 for all ecosystems in countries *b, c* and *d*, while critical loads are equal to 2000 elsewhere. This is motivated by the small tolerance for acid depositions in the relatively small Scandinavian countries. Table 1 reports no-control numbers, critical loads and resulting targets, while optimisation-results are reported in table 2. GAMS codes are offered in appendix B.

(Tables 1-2 about here).

In the second optimisation, acid depositions are restricted by a common value, called *ceiling*, everywhere. The ceiling is calibrated to 9500 since this gives approximately the same total abatement costs in the two optimisations. Figure 6 shows how abatement costs and the amounts of reduced depositions are changed from the first to the second optimisation.

(Figure 6 about here).

The numerical example illustrates some of the findings stated in propositions.

(a) Net reductions in acid depositions are larger for countries that have to carry larger abatement costs (*v-z*) than for any of the other countries. This is stated in proposition one.

(b) Country *t* has larger abatement costs and larger deposition reductions than country *q* in the first optimisation. Still, the net changes in abatement costs and depositions (not deposition *reductions*) are largest for country *q*. This proves proposition four by an example. Another example is given by countries *u* and *m*.

(c) The weighted averages of atmospheric transport coefficients have been reduced for countries *b-d* while they are constant for countries *e-h*. Also, the sum of shadow prices has also been reduced, and both abatement costs and reductions in acid depositions are larger for countries *b-d* in the first optimisation than for countries *e-h*. Consequently, (b) in proposition five implies that the net change in abatement costs *and* deposition reductions are less for countries *b-d* than for countries *e-h*. Table 2 shows that this is satisfied.

(d) From figure 6 we can see that if a non-binding country (*a, e-r*) has a larger net increase in abatement costs than another non-binding country, then the former country obtains a smaller net increase in depositions. This is implied by proposition six.

(e) The net change in abatement costs take the same sign as the net change in reduced depositions for all countries (*a-z*), including the non-binding countries (*a, e-r*). Since the sum of shadow prices is reduced and total abatement in binding countries is increased less than the total decrease in abatement for non-binding countries, (b) in proposition ten is exemplified.

5. Summary and Conclusions

In the negotiations within LRTAP there have been some discussions about the consequences of using different targeting principles for acidification. However, some RAINS simulations for cost-effective abatement indicate that, if two scenarios are compared, countries typically obtain the largest reductions in acidification in the scenario where they have to carry the largest abatement costs. In addition, a country typically obtains larger reductions in mean acidification than another country if the former country have to carry larger abatement costs than the latter country.

This paper adds empirical evidence for this Eco-Correlation, and it is shown how the Eco-Correlation is implied by a simple model. In section 2, a formal model for cost-effective reductions of acidification in Europe was developed. The analysis showed that it is hard to establish any interesting relationship between countries' abatement costs and domestic reductions in acid depositions in the general case. However, based on RAINS calculated deposition maps, the atmospheric transport coefficients to domestic grids (locations) were assumed to be larger than the transport coefficients to foreign grids. Also, all coefficients were assumed to take one out of two values. Under this assumption it was possible to show that differences in the abated amount determine differences in domestic reductions in acid depositions. Also, abatement costs for non-binding countries are given by the same linear function of domestic reductions in acid depositions. Binding countries, however, obtain additional reductions in acid depositions, but at relatively large costs.

The main findings in this paper concern the *signs* and *relative sizes* of the changes in countries' abatement costs and deposition reductions that occur when the targets for acidification are modified. The most important findings are given in (a)-(c).

(a) The net increase in both abatement costs and deposition reductions are larger for all countries that have to carry larger abatement costs than for any of the other countries.

(b) If the net increase in abatement costs for a non-binding country is larger than the net cost increase for another non-binding country, then the former country also obtains the largest net increase in reduced depositions.

(c) If a non-binding country has to carry increased abatement costs when targets for acidification are changed, it typically obtains additional reductions in acid depositions at domestic locations also, and vice versa. However, there may be exceptions, in particular for small countries.

These findings can be explained as follows. The model suppresses the variation in the atmospheric transport coefficients to foreign locations. Relative differences in reduced depositions among countries are therefore given by the relative differences in the abated amounts, and (a) follows directly. Since the non-binding countries have identical average abatement costs in a *cost-effective* solution, the abated amount among the non-binding countries is largest for the country that have to carry largest abatement costs. Then, by (a), this country also obtains the largest reductions in depositions. If the sum of shadow prices is increased when the targets for acidification are modified, these differences are scaled up, and *vice* *versa*, and (b) follows. The explanations for (c) are basically that (1) domestic deposition reductions are influenced relatively a lot from countries' own abatement, (2) the abatement for all non-binding countries moves in the same direction, (3) the share of non-binding countries is typically relatively large and (4) an increase in the sum of shadow prices gives a partial increase in abatement also for countries that are binding in at least one optimisation. However, this finding is not is not so robust as (a) and (b).

The model and the findings in this paper will probably be relevant also for other environmental problems that are caused by transboundary emissions (disposals) that are non-uniformly dispersed. Some candidates are eurtrophication, ground-level ozone, particulate matter, poisons algae and accumulation of various chemicals in the food chain.

Notes

1. In Montgomery's analysis it is assumed that all environmental constraints can be stated in terms of concentrations. However, this is not trivial for acidification since nitrogen (NOx and NH3) contribute to acidification (together with SO2) only if the deposited amount is large enough. Consequently, there is not one unique linear *function* of nitrogen and sulphur, measured for instance in sulphur-equivalents, such that the values of the function give the level of acidification. A possible solution for this is to establish two permit markets for each region, which in combination secure protection against acidification for a certain ecosystem in each region. In the first market, permits for SO2 depositions are traded, and the amount of permits equals the critical load for SO2 in the selected ecosystem (under the assumption that nitrogen depositions are no larger than background values). In the second market, a permit is an allowance to deposit a certain combination of sulphur and nitrogen. The amount of permits is such that any possible combination of acid depositions, in accordance with this market, is exactly on the critical load function for the selected ecosystem if SO2 emissions are less than the critical load for SO2. An emitter must buy permits in both markets, and, taken together, the two markets ensure that acidification will be no larger than the intended level. Typically, at most one constraint (on sulphur or on all acids) will be binding in the optimal solution, implying excess supply and a price equal to zero in at least one market for each region. In theory it is therefore possible to establish a (combined) pollution permit market also for acidification.
2. Regional Acidification INformation and Simulation
3. See UN/ECE (1999) for the new protocol and Amann *et al*. (1998b, 1998d, 1999a,1999b) for recent RAINS optimisation scenarios prepared for the convention.
4. In general, the deposition of sulphur and nitrogen in 150x150 km EMEP[10] grids covering all Europe is calculated this way in the RAINS model (Alcamo and Hordijk 1990; Amann *et al*. 1998b, part a).
5. Many countries share EMEP grids (the locations in the RAINS model), but in order to avoid further complications this is not accounted for here.
6. Policy makers will certainly take into account acidification changes, in addition to cost changes, before they eventually choose to trade emission rights. This is typically not taken into account in the existing literature. See for instance Burtraw *et al*. (1998), Førsund and Nævdal (1998), Klaassen *et al.* (1994) or Rodríguez (1999). See Klaassen (1993) for an analysis of the differences in costs and ecosystem protection for European countries in some trading schemes, compared to a proposal for the second sulphur protocol. See Nentjes (1994) for an analysis of emission trading where

parties consider both abatement costs and environmental improvement before they eventually trade.

7. Actually $a_k \geq a^{out}$, but a_k for a binding country is equal to a^{out} only in the special case where all binding grids within country *k* are binding only on the margin so that all corresponding shadow prices are zero.
8. The label on the *x*-axis must however be changed from "Differences in mean accumulated excess … " to "Changed acid depositions in domestic grids". These concepts are similar but not identical since the latter concept doesn't account for differences in buffer capacities in ecosystems, but that is a relatively minor difference when differences between two optimisations are considered.
9. Critical loads for acidification is calculated for all Europe. See Posch *et al.* (1995) and (1997).
10. Co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe.

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Appendix A: Proofs

Proof for proposition two.

The change-rate for differences in abatement costs is given by

$$\overbrace{c_i - c_k}^{\wedge} \equiv \frac{\left(c_i^{\,2} - c_k^{\,2}\right) - \left(c_i^{\,1} - c_k^{\,1}\right)}{\left(c_i^{\,1} - c_k^{\,1}\right)}. \tag{A1}$$

If $c_i^{\,1} - c_k^{\,1} > 0$ and $\overbrace{c_i - c_k}^{\wedge} > 0$, then, from (A1), we know that $\left(c_i^{\,2} - c_i^{\,1}\right) > \left(c_k^{\,2} - c_k^{\,1}\right)$ so that the net increase in abatement costs is largest for the country that has largest abatement costs initially. If $c_i^{\,1} - c_k^{\,1} < 0$ and $\overbrace{c_i - c_k}^{\wedge} > 0$ then $\left(c_i^{\,2} - c_i^{\,1}\right) < \left(c_k^{\,2} - c_k^{\,1}\right)$ so that the net increase in abatement costs is largest for the country that has largest abatement costs initially. Existing differences in abatement costs are therefore increased if the change-rate for differences in abatement costs is positive. If, however, $c_i^{\,1} - c_k^{\,1} > 0$ and $\overbrace{c_i - c_k}^{\wedge} < 0$, then we know that $\left(c_i^{\,2} - c_i^{\,1}\right) < \left(c_k^{\,2} - c_k^{\,1}\right)$ so that the net increase in abatement costs is largest for the country that has smallest abatement costs initially. Also, if $c_i^{\,1} - c_k^{\,1} < 0$ and $\overbrace{c_i - c_k}^{\wedge} < 0$, then we know that $\left(c_i^{\,2} - c_i^{\,1}\right) > \left(c_k^{\,2} - c_k^{\,1}\right)$ so that the net increase in abatement costs is largest for the country that has smallest abatement costs initially. In total, the net increase in abatement costs is largest for the country that has largest abatement costs initially if the change-rate for differences in abatement costs is positive, and *vice versa*. The argument with respect to relative changes in reduced depositions is identical, except that (a) c_q^t $\left(t = 1{,}2\ q = i, k\right)$ is replaced by R_q^t and (b) the term *abatement costs* (or simply costs) is replaced by *amounts of reduced depositions*.

Proof for proposition three.

By assumption, both abatement costs and the amounts of reduced depositions is largest for one of the countries under consideration $\{i, k\}$ in the first optimisation. Let the costs and the amounts of reduced depositions by convention be largest for country *i*. Then $c_i^1 - c_k^1 > 0$ and $R_i^1 - R_k^1 > 0$. Consequently, from (A1), $\left(c_i^2 - c_i^1\right) > \left(c_k^2 - c_k^1\right)$ if and only if $\overbrace{c_i - c_k}^{\wedge} > 0$, while $\left(c_i^2 - c_i^1\right) < \left(c_k^2 - c_k^1\right)$ if and only if $\overbrace{c_i - c_k}^{\wedge} < 0$. In total, the net increase in abatement costs is largest for the country that has largest abatement costs initially if the change-rate for differences in abatement costs is positive, and *vice versa*. Also, since the same type of argument can be used for reduced depositions, the country the have to carry the largest net increase in abatement costs also obtain the largest net increase in reduced depositions if the change-rates take the same sign. If, however, the change-rates take different signs, then the net increase in costs is largest for the country that obtain the smallest net increase in reduced depositions.

Proof for proposition five

By assumption, both abatement costs and deposition reductions are largest for one of the countries under consideration $\{i, k\}$ in the first optimisation. Let costs and the amounts of reduced depositions by convention be largest for country *i*. Then $c_i^1 - c_k^1 > 0$ and $R_i^1 - R_k^1 > 0$. Since these assumptions satisfies the conditions in proposition three, we know that the net increase in abatement costs is largest for the country that obtains the largest net increase in deposition reductions if the change-rates in (29) and (30) take the same sign.

First we consider the case under (a) in proposition five so that $a_i^2 \geq a_i^1$, $a_k^2 \leq a_k^1$ and $\sum_j \lambda_j^2 > \sum_j \lambda_j^1$. Since $c_i^1 - c_k^1 > 0$ we know from (26) and (27) that the denominators in the second fractions in (29) and (30) are positive. Also, since $a_i^2 \geq a_i^1$ and $a_k^2 \leq a_k^1$ the corresponding nominators are equal to or larger than the denominators, and this implies that the fractions are at least 1. Since the sum of shadow prices by assumption in (a) is increased from the first to the second optimisation, the first fraction is larger than 1 too. Consequently, since the product of the numbers that are larger than 1 also is larger than 1, both change-rates are positive, and (a) in proposition five follows from proposition three.

Now we consider the case under (b) in proposition five, so that $a_i^2 \leq a_i^1$, $a_k^2 \geq a_k^1$ and $\sum_j \lambda_j^2 < \sum_j \lambda_j^1$. Since $c_i^{\,1} - c_k^{\,1} > 0$ we know from (26) and (27) that the second denominators in (29) and (30) are positive. Also, since $a_i^2 \leq a_i^1$ and $a_k^2 \geq a_k^1$ the corresponding nominators are less or equal to the denominators, and this implies that the fractions are equal to or less than 1. Since the sum of shadow prices is reduced from the first to the second optimisation, the first fraction is less than 1. Consequently, since the product of two numbers less than 1 also is less than 1, both change-rates are negative, and (b) in proposition five follows from proposition three.

<u>Proof for proposition six</u>

By assumption $a_i^1 = a_i^2 = a_k^1 = a_k^2 = a^{out}$. If $\sum_j \lambda_j^2 > \sum_j \lambda_j^1$ the conditions under (a) in proposition five are satisfied. These are: $a_i^2 \geq a_i^1$, $a_k^2 \leq a_k^1$ and $\sum_j \lambda_j^2 > \sum_j \lambda_j^1$. If $\sum_j \lambda_j^2 < \sum_j \lambda_j^1$ the conditions under (b) in proposition five are satisfied.

<u>Proof for proposition seven</u>

Since abatement costs and deposition reductions by assumption are larger for country *i* than for country *k* in the first optimisation, we know from (26) and (27) that

$$\left(\frac{{a_i^1}^b}{A_i}\right)^{\frac{1}{b-1}}-\left(\frac{{a_k^1}^b}{A_k}\right)^{\frac{1}{b-1}}>0 \tag{A2}$$

and

$$\left(\frac{a_i^1}{A_i}\right)^{\frac{1}{b-1}}-\left(\frac{a_k^1}{A_k}\right)^{\frac{1}{b-1}}>0\,, \tag{A3}$$

where (A2) and (A3) are <u>denominators</u> in (29) and (30) respectively. Let the relative weighted average of atmospheric transport coefficients be defined by

$$\theta^t \equiv \frac{a_i^t}{a_k^t} \quad t \in \{1,2\}\,, \tag{A4}$$

while the relative change in country *k*'s coefficient is defined by

$$\gamma \equiv \frac{a_k^2}{a_k^1}\,. \tag{A5}$$

If we substitute (A4) into (A2) and (A3) for t=1, we get

$${a_k^1}^{\frac{b}{b-1}}\left(\left(\frac{{\theta^1}^b}{A_i}\right)^{\frac{1}{b-1}}-\left(\frac{1}{A_k}\right)^{\frac{1}{b-1}}\right)>0 \tag{A6}$$

and

$${a_k^1}^{\frac{1}{b-1}}\left(\left(\frac{\theta^1}{A_i}\right)^{\frac{1}{b-1}}-\left(\frac{1}{A_k}\right)^{\frac{1}{b-1}}\right)>0\,. \tag{A7}$$

If we substitute (A4) and (A5) into the <u>numerators</u> in (29) and (30) we get

$$\left(\gamma a_k^1\right)^{\frac{b}{b-1}}\left(\left(\frac{{\theta^2}^b}{A_i}\right)^{\frac{1}{b-1}}-\left(\frac{1}{A_k}\right)^{\frac{1}{b-1}}\right) \tag{A8}$$

and

$$\left(\gamma a_k^1\right)^{\frac{1}{b-1}}\left(\left(\frac{\theta^2}{A_i}\right)^{\frac{1}{b-1}}-\left(\frac{1}{A_k}\right)^{\frac{1}{b-1}}\right). \tag{A9}$$

Equations (29) and (30) can therefore be written as

$$\overbrace{c_i - c_k}^{\wedge} = \left(\frac{\sum_j \lambda_j^2}{\sum_j \lambda_j^1} \right)^{\frac{b}{b-1}} \gamma^{\frac{b}{b-1}} \frac{\left(\frac{\theta^{2b}}{A_i} \right)^{\frac{1}{b-1}} - \left(\frac{1}{A_k} \right)^{\frac{1}{b-1}}}{\left(\frac{\theta^{1b}}{A_i} \right)^{\frac{1}{b-1}} - \left(\frac{1}{A_k} \right)^{\frac{1}{b-1}}} - 1 \tag{A10}$$

and

$$\overbrace{R_i - R_k}^{\wedge} = \left(\frac{\sum_j \lambda_j^2}{\sum_j \lambda_j^1} \right)^{\frac{1}{b-1}} \gamma^{\frac{1}{b-1}} \frac{\left(\frac{\theta^{2}}{A_i} \right)^{\frac{1}{b-1}} - \left(\frac{1}{A_k} \right)^{\frac{1}{b-1}}}{\left(\frac{\theta^{1}}{A_i} \right)^{\frac{1}{b-1}} - \left(\frac{1}{A_k} \right)^{\frac{1}{b-1}}} - 1. \tag{A11}$$

Since the denominators in (A10) and (A11) are positive by (A6) and (A7), it follows that both change-rates are positive if the sum of shadow prices has increased and $\gamma \geq 1$ and $\theta_2 > \theta_1$. Also, both change-rates are negative if the sum of shadow prices is reduced $0 < \gamma \leq 1$ and $\theta_2 < \theta_1$. Proposition seven follows.

Proof for proposition ten

From (33) it is trivial that the abatement costs for a non-binding country are increased if the sum of shadow prices is increased, and vice versa. Therefore, we only have to show that the net change in deposition reductions take the same sign as the net change in the sum of shadow prices if at least one of the conditions in (a)-(d) is satisfied.

Condition (a). Let the variable *n* with a top script be the number of countries in the set given by the top script. For instance, the number of countries in the set I^{nb} is given by $n^{I^{nb}}$. Then the share of countries that which are non-binding (θ) can be written as

$$\theta \equiv \frac{n^{I^{nb}}}{n} \in [0,1]. \tag{A12}$$

We also define some additional variables

$$\overline{\gamma}_{I^{nb}} \equiv \frac{\sum_{i \in I^{nb}} \left(\frac{a_i}{A_i b} \right)^{\frac{1}{b-1}}}{n^{I^{nb}}} > 0 \text{ and } \overline{\gamma}_{I/I^{nb}} \equiv \frac{\sum_{i \in I/I^{nb}} \left(\frac{a_i}{A_i b} \right)^{\frac{1}{b-1}}}{n^{I/I^{nb}}} > 0. \tag{A13}$$

Equation (34) can be written as

$$\begin{aligned} R_k^{\,2} - R_k^{\,1} = & \left(\left(\sum_j \lambda_j^{\,2} \right)^{\frac{1}{b-1}} - \left(\sum_j \lambda_j^{\,1} \right)^{\frac{1}{b-1}} \right) \left(a^{in} - a^{out} \right) \left(\frac{a^{out}}{(A_k b)} \right)^{\frac{1}{b-1}} \\ & + a^{out} n \cdot \left[\theta \overline{\gamma}_{I^{nb}} \left(\left(\sum_j \lambda_j^{\,2} \right)^{\frac{1}{b-1}} - \left(\sum_j \lambda_j^{\,1} \right)^{\frac{1}{b-1}} \right) \right. \\ & \left. + (1-\theta) \left(\overline{\gamma^2}_{I/I^{nb}} \left(\sum_j \lambda_j^{\,2} \right)^{\frac{1}{b-1}} - \overline{\gamma^1}_{I/I^{nb}} \left(\sum_j \lambda_j^{\,2} \right)^{\frac{1}{b-1}} \right) \right]. \end{aligned} \tag{A14}$$

From (A14) we can see that, for any increase (decrease) in the sum of shadow prices, and for any values on $\overline{\gamma}_{I^{nb}}$ and $\overline{\gamma}_{I/I^{nb}}$, the expression in (A14) will be positive (negative) if θ is large enough. This concludes the proof.

In an extreme case (A14) may be positive (negative) only if $\theta > n-1/n$ and this requires that $n^{nb} = n$. But then the sum of shadow prices is equal to zero in both optimisations so that deposition reductions and abatement costs are equal to zero. The net change in deposition reductions is positive (negative) in this case also, but not strictly positive (negative). Moreover, this is not an interesting case.

Condition (b). If the sum of shadow prices is increased (decreased), the abated amounts in all non-binding countries are increased (decreased). If, in addition, the sum of abatement in countries that are binding in at least one optimisation is increased (decreased), then total abatement is increased (decreased). Consequently, from (34), the net change in deposition reductions is positive (negative) for all non-binding countries. Also, if the abatement in countries that are binding in at least one optimisation is decreased (increased), and this decrease (increase) is less than the increase (decrease) in abatement in non-binding countries, then total abatement is increased (decreased). Consequently, from (34), the net change in deposition reductions for the non-binding country *k* is positive (negative).

Condition (c). Suppose that the sum of shadow prices is increased (decreased) a lot. Then, from (34), the net change in deposition reductions is positive (negative).

Condition (d). Equation (34) is monotonically decreasing in the technology parameter for the non-binding country *k*, A_k.

Appendix B: Gams Codes

```
SET
         i       countries
            /a,b,c,d,e,f,g,h,i,j,k,l,m,n,o,p,q,r,s,t,u,v,w,x,y,z/
         j       domestic grids for each country
                 /1,2,3/
         t       optimisations
                 /1,2/;
;

ALIAS(i,k)
ALIAS(j,jj)
;

VARIABLES
         e(i,t)          emissions
         r(i,t)          abatement
         c(i,t)          abatement costs
         D(i,j,t)        depositions
         R1(i,j,t)       deposition reductions
;

POSITIVE VARIABLES
         lambda(i,j,t)     shadow prices on acid depositions
;

PARAMETERS
         b               power in cost function              /1.75/
         a_in            coefficient to domestic grids       /0.1/
         a_out           coefficient to foreign grids        /0.01/
         d_back          background depositions             /100/
         e_nc(i)         no-control emissions
         A(i)            constant-term in cost function
         D_con(i,j,t)    constraints on acid depositions
         ceiling         a ceiling on depositions           /9500/
         c_loads(i)      critical loads
         D_nc(i,j)       definition of no-control depositions
;

e_nc(i)=1000*(1+0.25)**(ord(i)-1);
A(i)=1/e_nc(i);
```

```
c_loads(i) = 150$(ord (i)>1 and ord(i)<5)
             +2000$(ord(i)=1 or ord(i)>4);
D_nc(i,j) = d_back+(a_in-a_out)*e_nc(i)+sum(k,a_out*e_nc(k));


EQUATIONS
         qr_def(i,t)      definition of abatement
         qc_def(i,t)      definition of abatement costs
         qD_def(i,j,t)    definition of depositions
         qR1_def(i,j,t)   definition of deposition reductions
         qr(i,t)          f.o.c. for abatement
         qD(i,j,t)        constraints on acid depositions
;

qr_def(i,t)..     r(i,t)   =e= e_nc(i)-e(i,t);
qc_def(i,t)..     c(i,t)   =e= A(i)*r(i,t)**b;
qD_def(i,j,t)..   D(i,j,t) =e=
                   d_back+(a_in-a_out)*e(i,t)+sum(k,a_out*e(k,t));

qR1_def(i,j,t).. R1(i,j,t) =e=  D_nc(i,j)- D(i,j,t);
qr(i,t)..         A(i)*b*r(i,t)**(b-1) =e=
      sum(j,(a_in-
a_out)*lambda(i,j,t))+sum((k,j),a_out*lambda(k,j,t));
qD(i,j,t)..       D_con(i,j,t) =g= D(i,j,t);


* First targets: 60% reductions in exceedance depositions
D_con(i,j,'1')=[ d_back+(a_in-a_out)*e_nc(i)+sum(k,a_out*e_nc(k))
               - c_loads(i)]*0.4 + c_loads(i);

* Second targets: Depositions are ceiled by a common value
D_con(i,j,'2')=    ceiling;

model    eco
/qr_def.e,qc_def.c,qD_def.d,qR1_def.R1,qr.r,qD.lambda/;

solve eco using mcp;
```

Figure 1: Abatement costs and mean accumulated excess values in the Ceiling scenario minus those in the U.A. scenario.

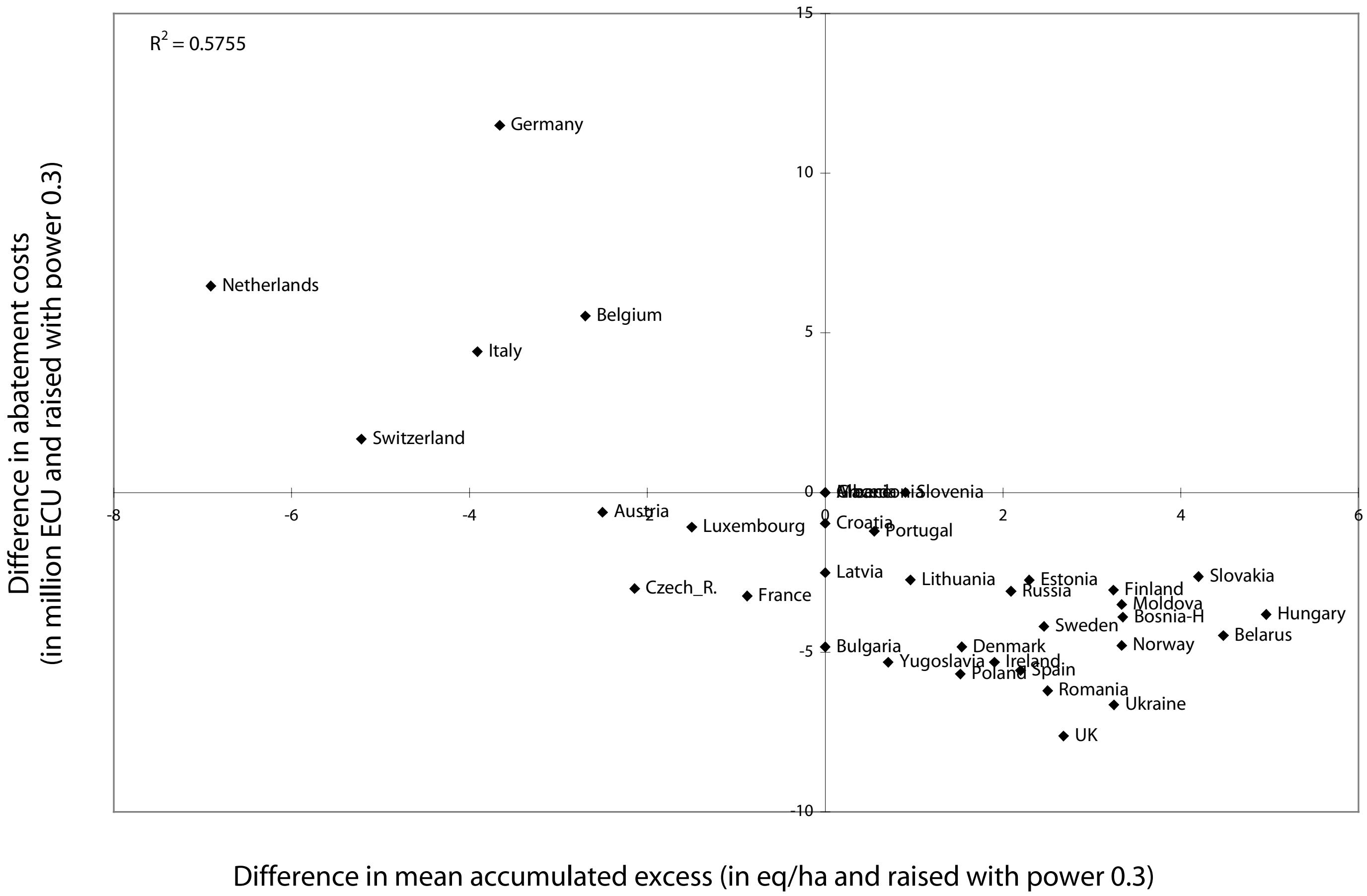

Figure 2: Abatement costs and mean accumulated excess values in the High ambition level acidification scenario minus those in the Central scenario.

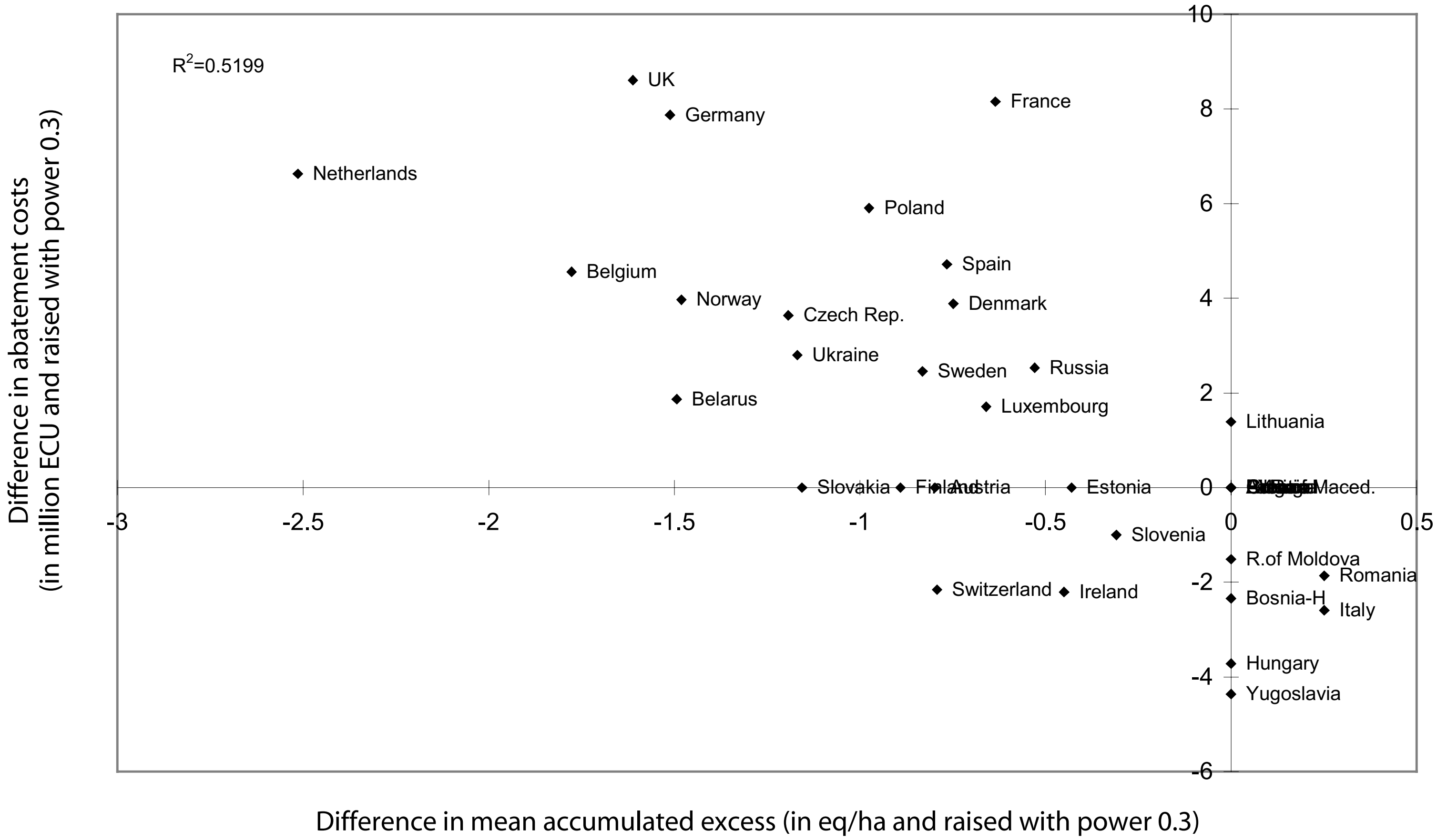

Figure 3: Depositions from German SO_2 emissions.

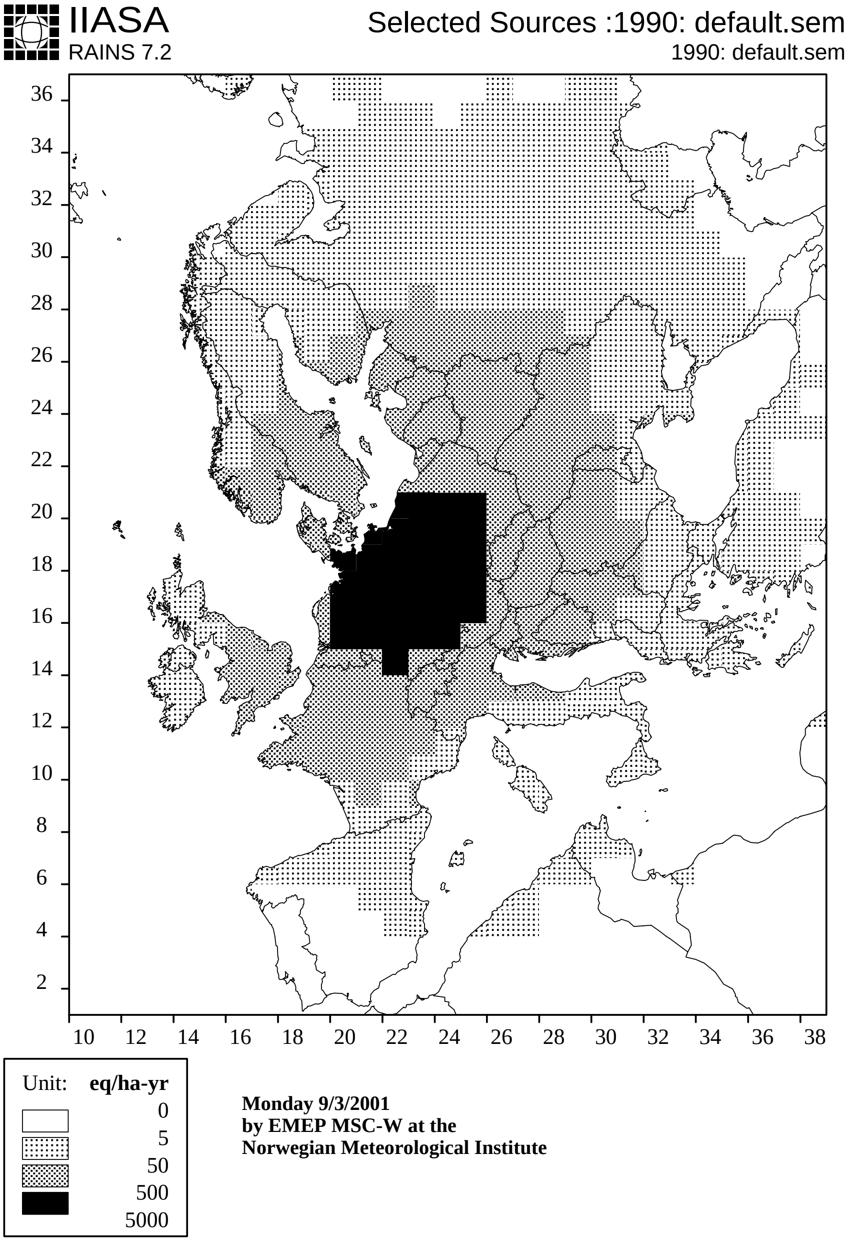

Figure 4: Depositions from Dutch NH3 emissions.

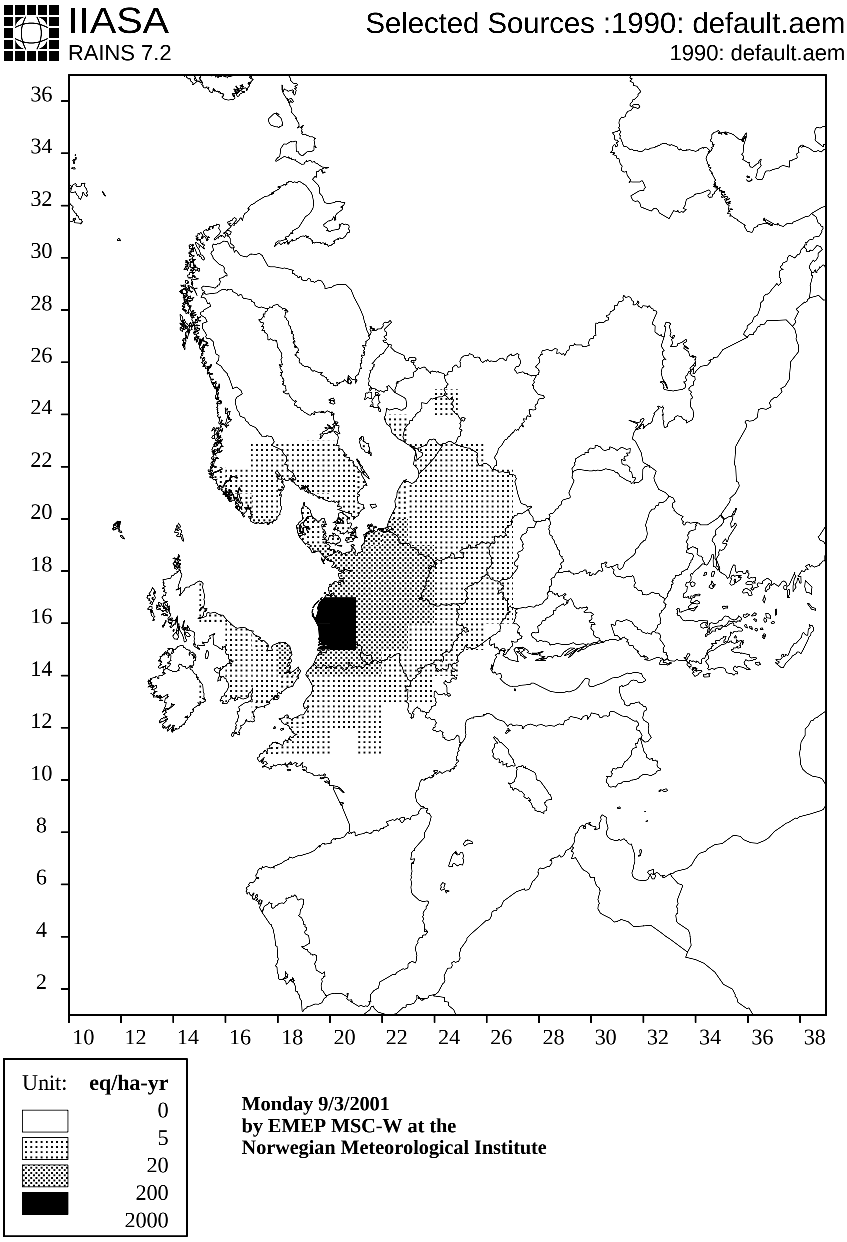

Figure 5: Depositions from UK NOx emissions.

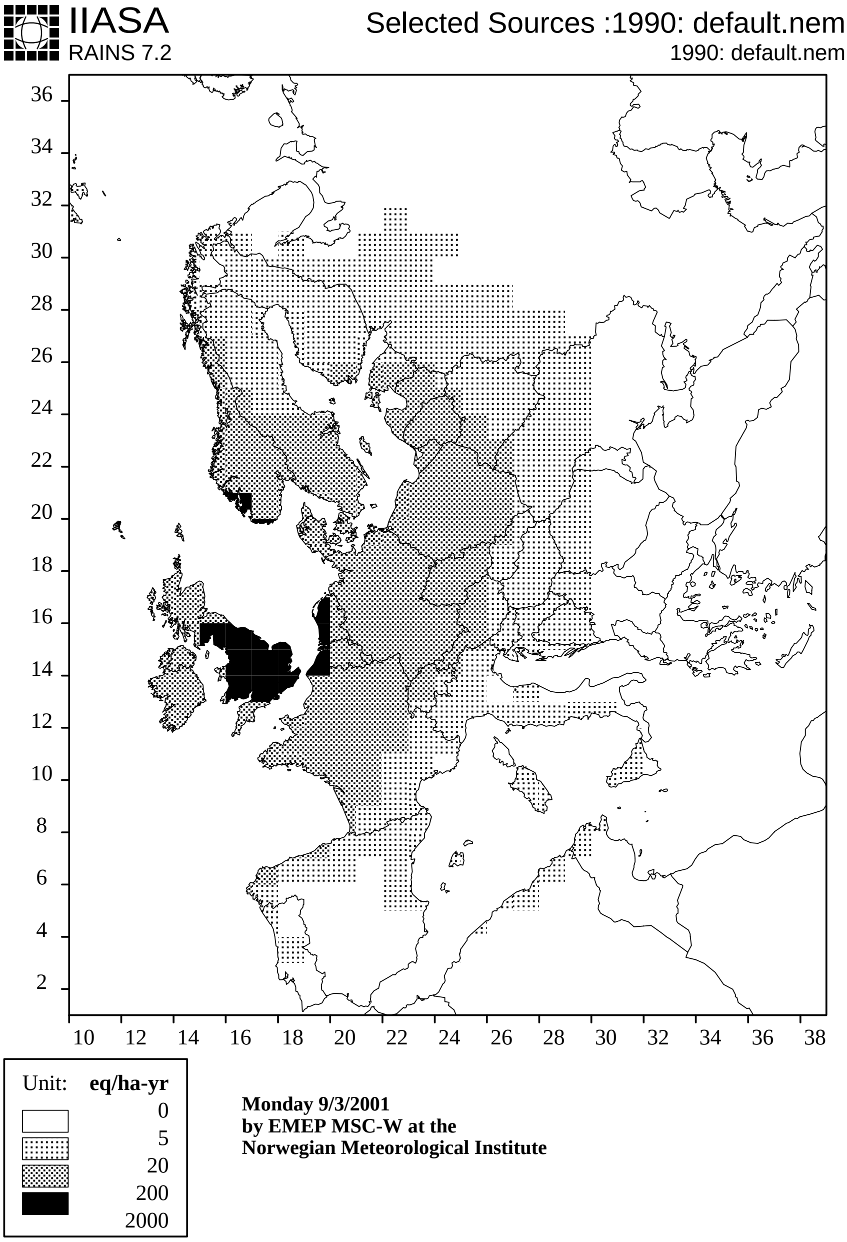

Figure 6: Cost and deposition changes from the first to the second optimisation.

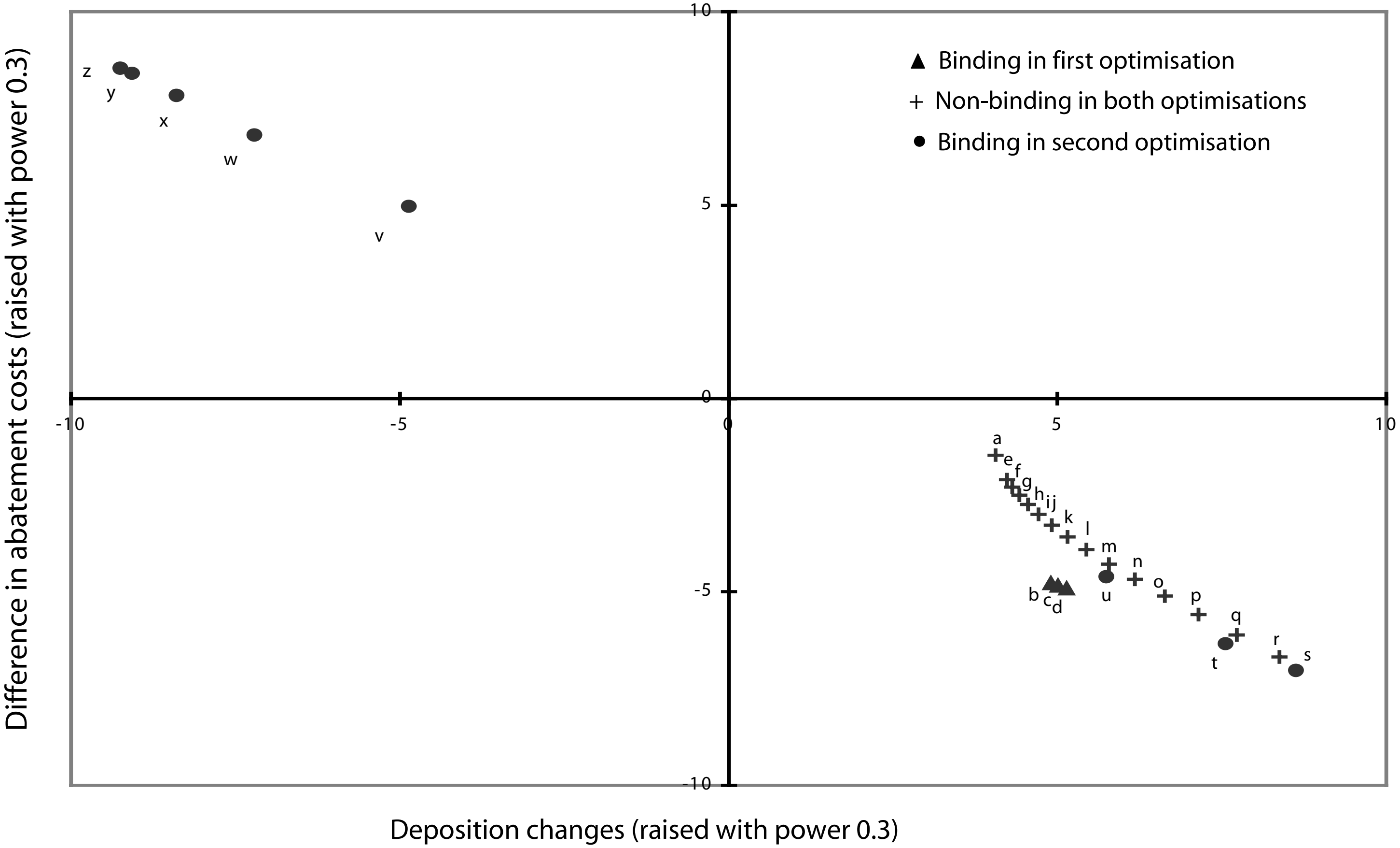

Table 1: No-control numbers, critical loads and targets.

Countries	*No-control emissions*	*No-control depositions*	*Critical loads*	*Exceedance in no-control*	*Target 1*	*Target 2*
a	1000	13385	150	13235	6554	9500
b	1250	13407	150	13257	5453	9500
c	1563	13436	2000	11436	5464	9500
d	1953	13471	2000	11471	5478	9500
e	2441	13515	2000	11515	6606	9500
f	3052	13570	2000	11570	6628	9500
g	3815	13638	2000	11638	6655	9500
h	4768	13724	2000	11724	6690	9500
i	5960	13831	2000	11831	6733	9500
j	7451	13965	2000	11965	6786	9500
k	9313	14133	2000	12133	6853	9500
l	11642	14343	2000	12343	6937	9500
m	14552	14605	2000	12605	7042	9500
n	18190	14932	2000	12932	7173	9500
o	22737	15341	2000	13341	7337	9500
p	28422	15853	2000	13853	7541	9500
q	35527	16492	2000	14492	7797	9500
r	44409	17292	2000	15292	8117	9500
s	55511	18291	2000	16291	8516	9500
t	69389	19540	2000	17540	9016	9500
u	86736	21101	2000	19101	9640	9500
v	108420	23053	2000	21053	10421	9500
w	135525	25492	2000	23492	11397	9500
x	169407	28541	2000	26541	12617	9500
y	211758	32353	2000	30353	14141	9500
z	264698	37118	2000	35118	16047	9500

Table 2: Optimisation results.

Countries	Lam-bda 1	Lam-bda 2	Mean atm. coeff 1	Mean atm. coeff 2	Costs 1	Costs 2	Cost change	Acid dep. red. 1	Acid dep. red. 2	Acid dep. change
a	-	-	0.01	0.01	4.2	0.7	-3.6	7860	7753	107
b	2.40	-	0.044	0.01	185.5	0.9	-184.6	7954	7755	200
c	2.08	-	0.040	0.01	192.7	1.2	-191.5	7971	7756	215
d	1.80	-	0.036	0.01	204.0	1.6	-202.4	7992	7759	234
e	-	-	0.01	0.01	14.0	2.2	-11.8	7885	7762	123
f	-	-	0.01	0.01	18.8	3.0	-15.8	7897	7766	131
g	-	-	0.01	0.01	25.3	4.0	-21.3	7913	7772	141
h	-	-	0.01	0.01	34.1	5.4	-28.7	7935	7780	156
i	-	-	0.01	0.01	45.9	7.2	-38.7	7965	7790	175
j	-	-	0.01	0.01	61.8	9.8	-52.1	8005	7804	201
k	-	-	0.01	0.01	83.3	13.1	-70.1	8058	7822	236
l	-	-	0.01	0.01	112.1	17.7	-94.4	8131	7848	283
m	-	-	0.01	0.01	151.0	23.8	-127.1	8228	7882	347
n	-	-	0.01	0.01	203.3	32.1	-171.2	8359	7927	432
o	-	-	0.01	0.01	273.7	43.2	-230.5	8536	7989	547
p	-	-	0.01	0.01	368.6	58.2	-310.4	8774	8072	702
q	-	-	0.01	0.01	496.3	78.3	-417.9	9094	8183	911
r	-	-	0.01	0.01	668.2	105.5	-562.8	9525	8333	1192
s	-	0.07	0.01	0.012	899.8	232.5	-667.4	10106	8791	1315
t	-	0.25	0.01	0.018	1211.6	738.8	-472.8	10888	10040	848
u	-	0.35	0.01	0.021	1631.5	1467.9	-163.5	11941	11601	340
v	-	0.41	0.01	0.023	2196.8	2406.3	209.5	13358	13553	-194
w	-	0.44	0.01	0.024	2958.0	3557.5	599.5	15267	15992	-725
x	-	0.45	0.01	0.024	3983.1	4937.2	954.1	17837	19041	-1204
y	-	0.44	0.01	0.024	5363.3	6570.8	1207.5	21298	22853	-1555
z	-	0.43	0.01	0.024	7221.8	8493.6	1271.9	25959	27618	-1659