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Cost-effectiveness Analysis of Reducing the Emission of Nitrogen Oxides in Asia

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Abstract The purpose of this study is to evaluate cost-effective reduction strategies for nitrogen oxides (NO_x) in the Asian region. The source-receptor relationships of the Lagrangian "puff" model of long-range transportation, ATMOS-N, were used to calculate the wet/dry deposition of the nitrogen (N) in Asia. Critical loads of N deposition in Asia were calculated from the relationships between the critical load of sulfur (S) and balance of N in and out using the data of S critical load of RAINS-ASIA. The cost functions of N reduction of Asian countries were derived by the regression analysis with the data of cost functions of European countries used in RAINS. In order to assess the environmental impact, the gaps between N deposition and critical load of N were calculated. The emission of NO_x was reduced in some cases of this model, and the changes of gaps between N deposition and critical load were observed as well as the changes of the reduction cost. It is shown that a uniform reduction of NO_x emissions by countries in Asia is not cost-effective strategy.

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1 Introduction

Recently increasing emissions of sulfur dioxides (SO_2) and nitrogen oxides (NO_x) due to great economic growth in Asia are a major concern for serious damage to ecosystems caused by acid deposition. In the 1990s in Europe, the integrated assessment model, the Regional Air pollution INformation and Simulation (RAINS) model, was developed to provide the scientific basis to reduce cost-effectively the emission of SO_2 as a precursor of acid deposition (Alcamo, Shaw, & Hordijk, 1990; Cofala et al., 2003; Cofala & Syri, 1998b). RAINS was the useful tool in the process of concluding protocol of Convention on Long-Range Transboundary Air Pollution (CLRTAP). Considering overall ecosystem effects by nitric acid deposition, eutrophication and ground-level ozone, RAINS has subsequently become an important tool for protocols of CLRTAP to reduce the emission of NO_x, ammonia (NH_3) and volatile organic compounds (VOCs) (Amann, Cofala, Heyes, Klimont, & Schopp, 1999).

In Asia the assessment model for acid deposition, RAINS-ASIA, was developed in the late 1990s for cost-effective control of SO_2 emissions in this region (Downing, Ramankutty, & Shah, 1997). To date, however, official versions of RAINS-ASIA do not contain NO_x, NH_3 or VOCs. Here we create a new module for calculating the reduction cost of the NO_x emissions and examine the options for reduction utilizing the methodology of RAINS and RAINS-ASIA.

2 Acid Deposition Problems and Regional Cooperation in Europe, North America and Asia

Acidification throughout Europe and North America has been an important research focus for environmental scientists since the 1960s. The Cooperative Programme for the Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP) was initiated in 1977 and led to the 1979 signing of CLRTAP by the most countries of Eastern and Western Europe, the United States and Canada.

In North America, it was warned in the early 1970s that the acidification damage to lakes, streams and forests was observed in the northeastern US and Canada (Howard & Perley, 1980). Canada and the US established the Canadian Network for Sampling Precipitation (CANSAP) in 1976 and the National Atmospheric Deposition Program (NADP) in 1978, respectively (Carmichael, Peters, & Saylor, 1990; EPA, 2000).

The Acid Deposition Monitoring Network in East Asia (EANET[1]) started its activities in 1998 considering the rapid economic growth and consequent increasing emission of air pollutants in the East Asian region (EANET, 2000). EANET, which includes 12 countries as of June 2005, has been carrying out cooperative activities such as reliable monitoring of wet and dry deposition and effects on ecosystems as the first step to assess the acid deposition problems in East Asia. In South Asia, the regional cooperative program on air pollution, the Malé Declaration,[2] was initiated in 1998 and has commenced its activities.

3 The Integrated Assessment Models: Reduction of Emission and Its Cost

Integrated assessment models may be employed to help understand complicated acid deposition problems. An atmospheric model simulates the long-range transportation, chemical transformation and the amount of deposition of air pollutants, and an economic model provides the vision of the cause and the reduction cost of emission of SO_2, NO_x, NH_3 and VOCs. This type of multi-disciplinary model aids scientists and policy makers in considering different abatement options. The RAINS integrated assessment framework includes five components; (a) emission inventory, (b) atmospheric transport and transformation, (c) environmental effects, (d) abatement and mitigation options, and (e) monetary evaluation (Amann, 2001; Amann et al., 1999; Hordijk & Kroeze, 1997).

4 Development of the Model of Reducing NO_x Emission and Estimation of its Cost in Asia

Our study follows the RAINS methodology to assess N controls in Asia. We follow five steps in the evaluation process: (a) calculation of N deposition from the emission inventory of NO_x using the transportation/deposition model, (b) derivation of critical load of N from the critical load value used in RAINS-ASIA, (c) estimation of the national cost function of the NO_x emission, (d) evaluation of change of adverse effects on ecosystem using critical load of N in some cases of NO_x emission reduction, (e) case simulation of reduction cost of each country of NO_x emission control (Amann & Klaasen, 1995).

4.1 Emission Inventory

The NO_x emission inventory of the University of Iowa's Center for Global and Regional Environmental Research (CGRER)[3] was used in this study since it was the most recent estimate (Aardenne van, Carmichael,

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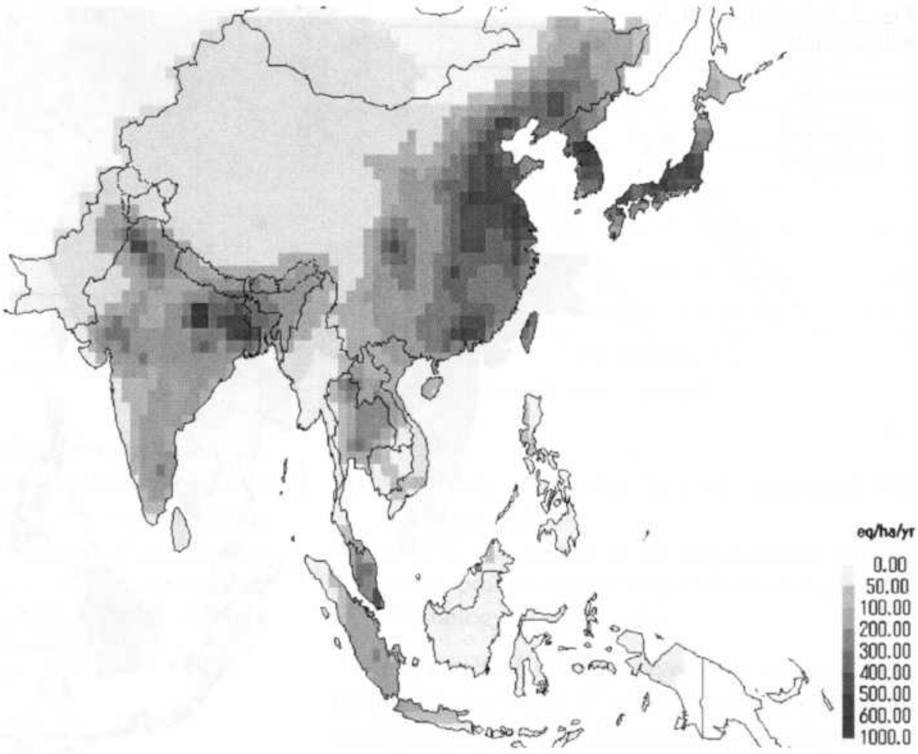
[1] http://www.eanet.cc/

[2] http://www.rrcap.unep.org/issues/air/Maledec/

[3] http://atmos.cgrer.uiowa.edu/EMISSION_DATA/index_16.htm#

Fig. 1 Deposition of N



Levy, Streets, & Hordijk, 1999; Klimont, 2001; Yienger & Levy, 1995), developed in support of the Aerosol Characterization Experiments (ACE)-Asia and Transport and Chemical Evolution over the Pacific (TRACE-P) experiments (Woo et al., 2002). The domain covers 13°S~53°N latitude and 60°E~157°E longitude, and the resolution is 1°×1°, including 22 Asian countries and 60 sub-regions for the year 2000. The total amount of NO_x emission in Asia was estimated 26.77 Tg-NO_2/year.

4.2 Model of Transportation and Deposition

This study estimated N deposition through the use of annual source-receptor relationships (SRRs) calculated with the regional transport and chemistry model, ATMOS-N[4] (Holloway, Levy, & Carmichael, 2002). Although the original SRRs calculations used other emission inventories, these values were scaled to the CGRER estimate, assuming a linear relationship between emissions and deposition. As illustrated in Fig. 1, deposition is highest in the eastern part of China, the eastern part of India, the northern part of R. of Korea and the middle part of Japan. ATMOS-N is a Lagrangian "puff" model in which emissions are modeled as non-interacting puffs advected horizontally and split in three vertical layers. Data of winds and precipitation used in ATMOS-N are National Centers for Environmental Prediction (NCEP) reanalysis data in 1990.

4.3 Critical Load of N

Critical loads are the threshold value of the amount of acid deposition above which adverse effects can be observed on ecosystems, and below which ecosystems are protected. Critical load levels are derived from site-specific topography, soil and ecosystem of the area. Although no such precise level exists in nature, critical loads have been a useful method for assessing protection levels for environmental decision-making (Posch, de Smet, Hettelingh, & Downing, 2001).

Critical loads of S in Asia were calculated (Hettelingh, Sverdrup, & Zhao, 1995) with Steady-State Mass Balance (SSMB) methodology and used in RAINS-ASIA (Shindo & Hettelingh, 2000), but critical loads of N in whole Asian region have not yet been calculated. Critical loads of N were

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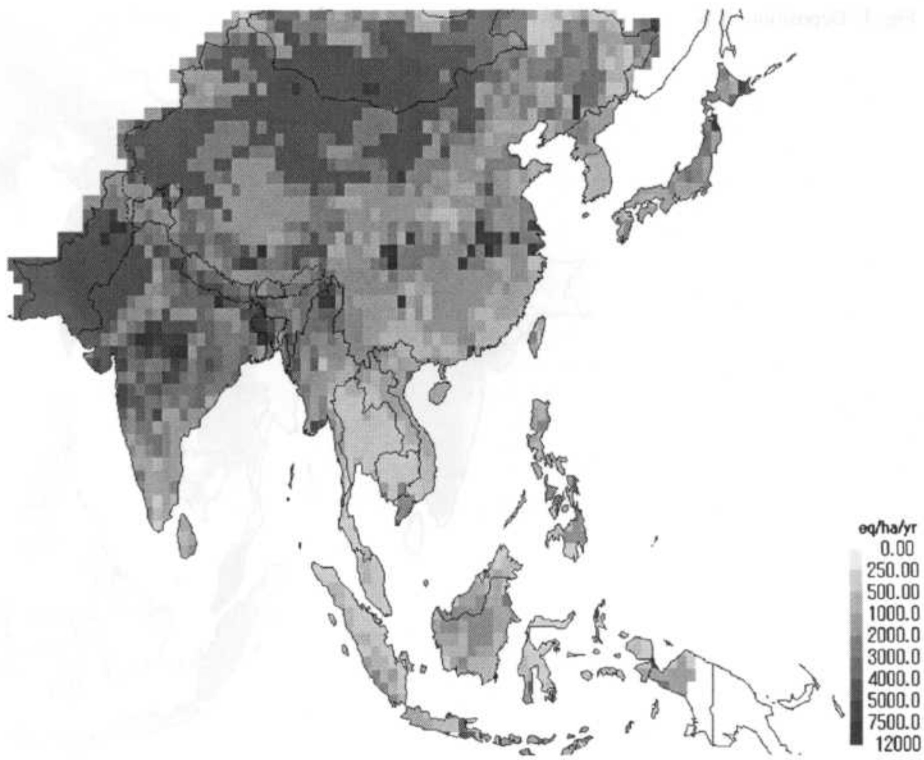
[4] ATMOS-N was the only model that published annual SRRs of NO_x in Asia as of 2004.

Fig. 2 Critical load of N ($CL_{max}(N)$-25%)



calculated in this study using the relationships between critical loads of S[5] and N. In order to avoid the uncertainty of SSMB, 25-percentile critical load (protecting 75% of the ecosystems) were used instead of using the lower percentile such as 5-percentile critical load.

The critical loads of N are expressed by means of mass balances for S and N as following equations (Posch, De Vries, & Hettelingh, 1995):

$$CL_{max}(N) = CL_{min}(N) + CL_{max}(S)/(1 - f_{de}) \qquad (1)$$

$$CL_{min}(N) = Nu + Ni \qquad (2)$$

$$CL_{nut}(N) = Nu + Ni + N_{le(crit)}/(1 - f_{de}) \qquad (3)$$

Where $CL_{max}(S)$ is the maximum critical load for sulfate, $CL_{max}(N)$ is the maximum critical load for nitrate, $CL_{min}(N)$ is the minimum critical load for nitrate, $CL_{nut}(N)$ is the critical load for nutrient nitrate, f_{de} is the denitrification fraction, Nu is the net growth uptake, Ni is the long-term immobilization, and $N_{le(crit)}$ is the critical leaching of nitrate.

In this study Nu is assumed zero because uptake and release of nutrients can be considered to be balanced in a natural forest with stable amount of plants. The constant value of f_{de} corresponds to a soil type is adopted in many studies in Europe (e.g. Posch, Hettelingh, Slootweg, & Downing, 2003; Posch et al., 1995). Regarding value of f_{de}, 0.1 was applied to all grid cells here as a simple estimation. Though there are few studies on f_{de} in Asia, a study used 0.1 or 0.5 as the value of f_{de} corresponding to wet of a soil type of

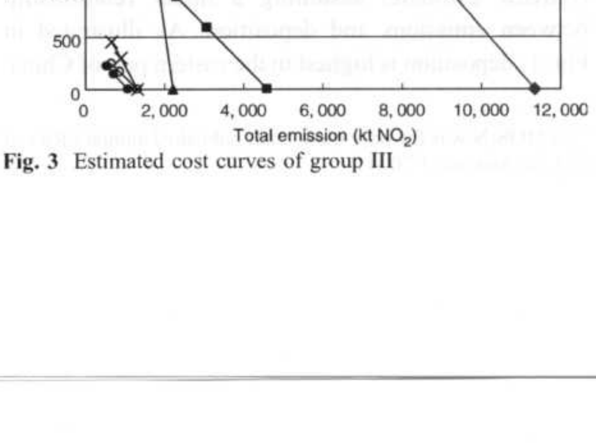


Fig. 3 Estimated cost curves of group III

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[5] The critical load values calculated in RAINS-ASIA phase II were used here.

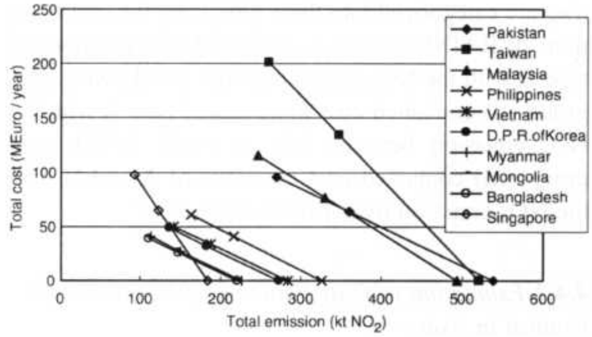

Fig. 4 Estimated cost curves of group II

Japan (Hayashi & Ozaki, 2001). The value of 0.1 will avoid underestimation of adverse effects on ecosystems. The critical load of N for eutrophication ($CL_{nut}(N)$) is not used. Only the aspect of acidification of N is considered in this study since the information on critical leaching of N is not sufficient in Asia. Figure 2 shows $CL_{max}(N)$ of 25-percentile.

4.4 Estimation of the Cost Function

In this section the cost functions of reducing anthropogenic NO_x emission of countries in Asia are estimated from those in Europe used in RAINS.

4.4.1 Regression Analysis for Cost Function of NO_x Emission Control of RAINS

In RAINS model the cost function of the reduction of NO_x emission were created for each country and year (Cofala & Syri, 1998a). It is assumed that the most cost-effective option of NO_x reduction is preferentially used, so controls are implemented in order of descending cost-effectiveness. Control options are applied to both stationary and mobile sources, with cost functions[6] of 27 countries in Europe for 2000 used to derive the cost functions of 22 countries in Asia.

For the regression analysis, it was assumed that the total cost of NO_x emission reduction was the function of the NO_x emission, Gross Domestic Product (GDP) and GDP per capita (GDP/C). The reasons of the assumption were following points;

(a) The total cost of NO_x reduction was proportional to the amount of NOx emission reduction,

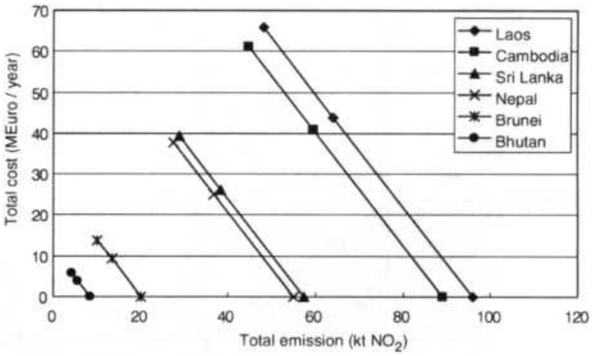

Fig. 5 Estimated cost curves of group I

(b) GDP was relative to the total amount of NO_x emission, and

(c) GDP/C was related to the shape of cost function as the proxy variable, which showed the level of technology of the country.

As a result of multiple regression analysis, logarithmic equations had R^2 value less than 0.4 (R^2 is the coefficient of multiple determination), and quadratic equations had the problem of the inconsistent shape of curve with the original curves though some equations had R^2 more than 0.9. Consequently the regression line (4) was the more appropriate estimated function ($R^2>0.8$).

$$\begin{aligned}\text{Total cost} = {} & \alpha + \beta\ \text{GDP} + \gamma\ \text{emission} \\ & + \delta\ \text{GDP/C} + \zeta\ \text{emission GDP} \\ & + \eta\ \text{emission GDP/C} + \varepsilon \qquad (4)\end{aligned}$$

Where the α, β, γ, δ, ζ and η are coefficients, and ε is disturbance term.

The total cost functions of European countries in RAINS were categorized by their shapes of curve into three types (A, B, and C). The cost curve of type A[7] is concave upward, the cost curve of type B[8] is linear, and the cost curve of type C[9] is other shape. The type C was, therefore, considered to be excluded from the

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[6] The data was downloaded from the web site of IIASA (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/) in September 2004.

[7] England, Italy, Poland, Netherlands, Belgium, Greece, Portugal, Czech, Norway, Finland, Denmark, Austria, Hungary, Ireland, Slovakia.

[8] Germany, France, Spain, Sweden, Switzerland, Slovenia, Lithuania, Estonia, Luxemburg, Cyprus, Marta.

[9] Latvia.

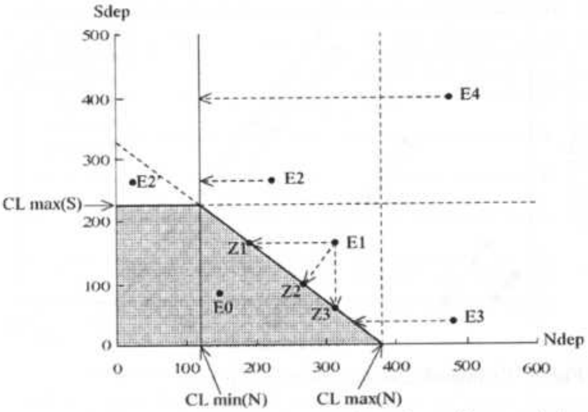

Fig. 6 Relationship between N and S deposition and the critical load of sulfur and nitrogen (Source: Posch et al., 1995, modified by Yamashita)

analysis as the outlier. The estimated regression equations by the multiple regression analysis are as follows (figures in parentheses are *t*-values);

Type A:

$$\begin{aligned}\text{Total cost} = {} & \underset{(4.08)}{56.58} + \underset{(26.34)}{0.001935} \times \text{GDP} - \underset{(-10.15)}{0.3395} \\ & \times \text{emission} - \underset{(-1.99)}{6.654 \times 10^{-8}} \\ & \times (\text{emission} \cdot \text{GDP}) - \underset{(-15.36)}{3.140 \times 10^{-5}} \\ & \times (\text{emission} \cdot \text{GDP/C})\end{aligned}$$

$$R^2 = 0.6824 \tag{5}$$

Type B:

$$\begin{aligned}\text{Total cost} = {} & \underset{(1.82)}{107.6} + \underset{(27.44)}{0.003327} \times \text{GDP} - \underset{(-14.24)}{1.370} \\ & \times \text{emission} - \underset{(-5.78)}{2.893 \times 10^{-7}} \\ & \times (\text{emission} \cdot \text{GDP}) - \underset{(-4.43)}{0.009412} \\ & \times \text{GDP/C}\end{aligned}$$

$$R^2 = 0.8026 \tag{6}$$

It is noted with the obtained regression lines that the cost is over-estimated for the point of no-reduction (full emission) to half-reduction (half of emission) of the total emission, and under-estimation for over half-reduction of the total emission since the gap between obtained cost line and the cost curve of RAINS is growing when the reduction goes over the half of emission.

It is assumed by the relation between the NO_x emission and the type of cost function that the countries are categorized into three groups by the cost functions of RAINS: group (I) contained cost functions of type B with the NO_x emission under 100 kt-NO_2/year, group (II) contained cost functions of type A with the NO_x emission between 100 to 1,000 kt-NO_2/year, group (III) contained cost functions of A and B with the NO_x emission over 1,000 kt-NO_2/year.

4.4.2 Estimation of Cost Function of NO_x Emission Control in Asia

The estimated cost functions of type A and type B (Eqs. 5 and 6) were used to derive the cost functions of countries in Asia since the equations are thought to be available also for Asian countries in spite of differences of economic condition between Europe and Asia. The cost functions of 22 Asian countries were estimated sorting the countries by NO_x emission based on the same criteria that were employed in defining cost curves for European countries. Among countries of group III only Japan was categorized as type B since Japan has many options to reduce the emission of NO_x from the stationary and mobile sources, similar to Germany. The estimated cost curves of the group III,[10] the group II[11] and the group I[12] are shown in Figs. 3, 4 and 5, respectively. The constant terms are adjusted so that the total cost equals zero at the point of no-reduction in Figs. 3, 4 and 5.

4.5 Reduction Cost of NO_x Emission

4.5.1 Deposition and Critical Load of S and N

The relationship between deposition of S and N exceeding the critical load (Ex) is expressed as follows;

$$\mathrm{Ex(S+N)} = \mathrm{S_{dep}} + \mathrm{N_{dep}} - \mathrm{CL(S+N)} \tag{7}$$

Where Ex(S+N) is the deposition of S and N exceeding the critical load, S_{dep} and N_{dep} are deposition of S and N respectively, and CL(S+N) is the critical load of S and N (Posch et al., 1995). The Fig. 6 shows its relationship.

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[10] China, India, Japan, R. of Korea, Indonesia, Thailand.

[11] Pakistan, Taiwan, Malaysia, Philippines, Vietnam, D.P.R. of Korea, Myanmar, Mongolia, Bangladesh, Singapore.

[12] Lao, Cambodia, Sri Lanka, Nepal, Brunei, Bhutan.

Fig. 7 The cells of $Ex(S+N) \geqq 0$ in the area of $S_{dep} \leqq CL_{max}(S)$

Fig. 8 The cells of $Ex(S + N \times 2/3) \geqq 0$ in the area of $S_{dep} \leqq CL_{max}(S)$

Fig. 9 The cells of $Ex(S+N/2) \geqq 0$ in the area of $S_{dep} \leqq CL_{max}(S)$

Fig. 10 The cells of $N_{dep}-CL_{min}(N)$ with no reduction of NO_x emission

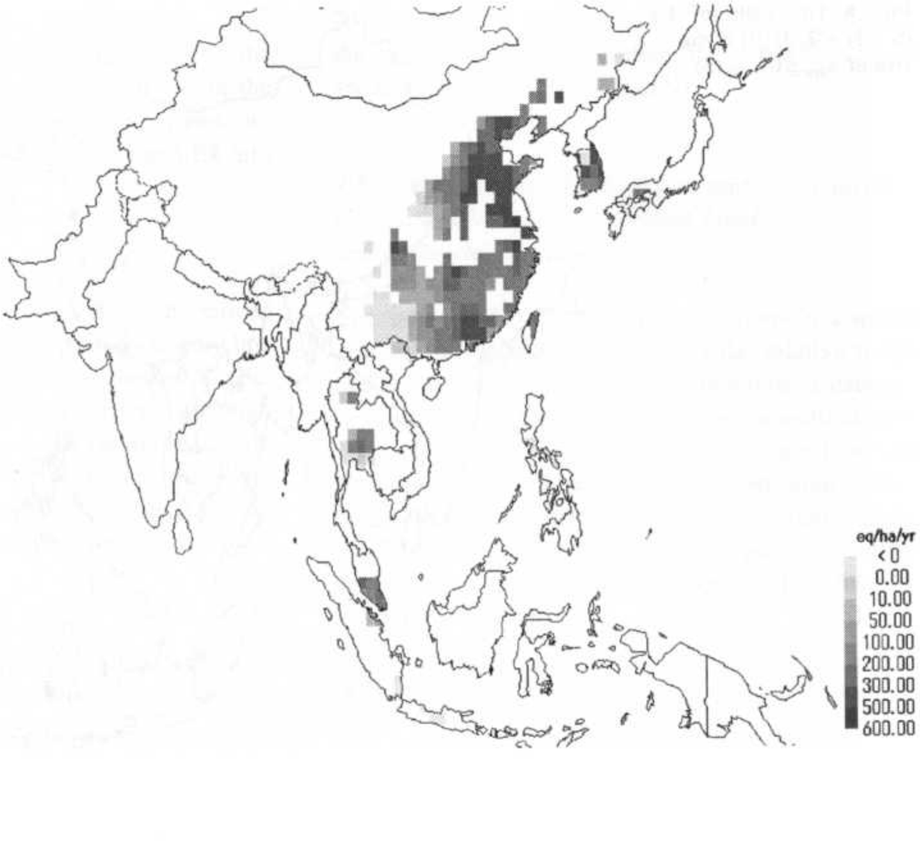


Fig. 11 The cells of $N_{dep}-CL_{min}(N)$ with 33% reduction of NO_x emission

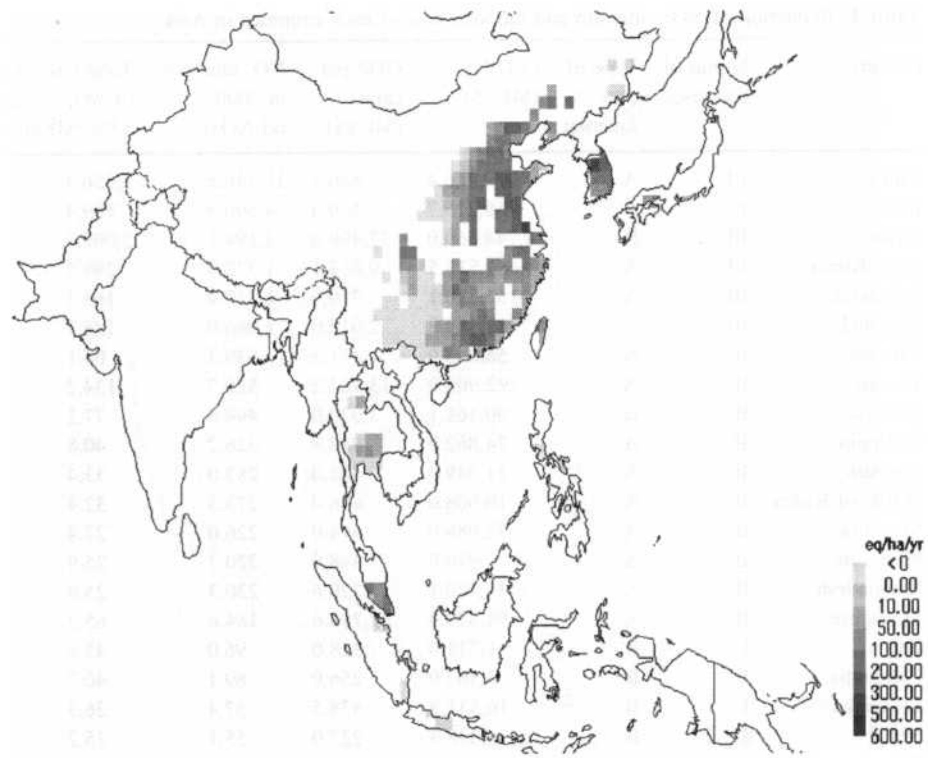


Fig. 12 The cells of $N_{dep}-CL_{min}(N)$ with 50% reduction of NO_x emission

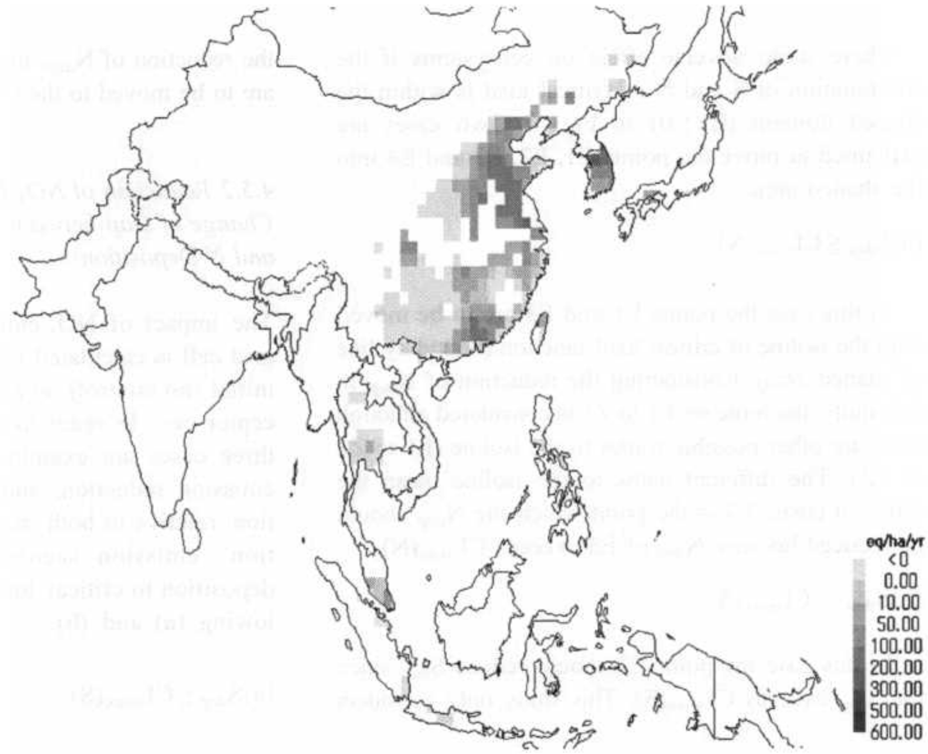


Table 1 Reduction of NO_x emission and the total cost of each countries in Asia

Country	Group of countries	Type of cost function	G D P (MUS$)	GDP per capita (MUS$)	NO_x emission in 2000 (kt NO_2)	Total cost of reduction of NO_x emission at 33% (MEuro/year)	Total cost of reduction of NO_x emission at 50% (MEuro/year)
China	III	A	1,079,386.4	846.4	11,346.8	1,656.4	2,484.6
India	III	A	468,225.7	460.4	4,590.9	589.4	884.1
Japan	III	B	4,744,660.0	37,408.0	2,198.1	2,009.7	3,014.6
R. of Korea	III	A	461,518.5	9,853.1	1,322.0	299.5	449.2
Indonesia	III	A	152,226.1	719.5	1,317.4	163.5	245.2
Thailand	III	A	122,569.3	2,012.0	1,086.0	148.7	223.1
Pakistan	II	A	58,663.9	411.2	539.3	64.1	96.1
Taiwan	II	A	292,900.9	13,184.2	520.7	134.2	201.2
Malaysia	II	A	90,161.1	3,920.0	494.0	77.2	115.8
Philippines	II	A	74,862.0	988.8	326.2	40.8	61.2
Vietnam	II	A	31,349.0	401.0	283.0	33.4	50.1
D.P.R. of Korea	II	A	10,608.0	476.0	273.3	32.4	48.5
Myanmar	II	A	32,988.0	694.0	226.0	27.4	41.1
Mongolia	II	A	970.0	388.0	220.7	25.9	38.8
Bangladesh	II	A	45,470.1	329.6	220.3	25.9	38.9
Singapore	II	A	91,473.3	22,754.6	184.6	65.2	97.8
Rao	I	B	1,733.0	328.0	96.0	43.9	65.8
Cambodia	I	B	3,367.0	256.0	89.1	40.7	61.1
Sri Lanka	I	B	16,331.8	878.5	57.4	26.3	39.5
Nepal	I	B	5,338.3	227.0	55.1	25.2	37.8
Brunei	I	B	4,316.0	12,922.0	20.2	9.2	13.9
Bhutan	I	B	483.0	234.0	8.4	3.9	5.8
Total			7,789,601.4	109,692.5	25,475.5	5,542.7	8,314.1

There is no adverse effect on ecosystems if the combination of S and N of critical load is within the shaded domain ($Ex \leqq 0$) in Fig. 6. Two cases are explained to move the points E1, E2, E3 and E4 into the shaded area.

$(a) S_{dep} \leqq CL_{max}(S)$:

In this case the points E1 and E3 are to be moved onto the isoline of critical load function (boundary line of shaded area). Considering the reduction of N_{dep} in this study, the route on E1 to Z1 is considered although there are other possible routes to the isoline (E1 to Z2 or Z3). The different paths to the isoline mean the different costs. E3 is the point which the N_{dep} should be reduced because N_{dep} of E3 exceeds $CL_{max}(N)$.

$(b) S_{dep} > CL_{max}(S)$:

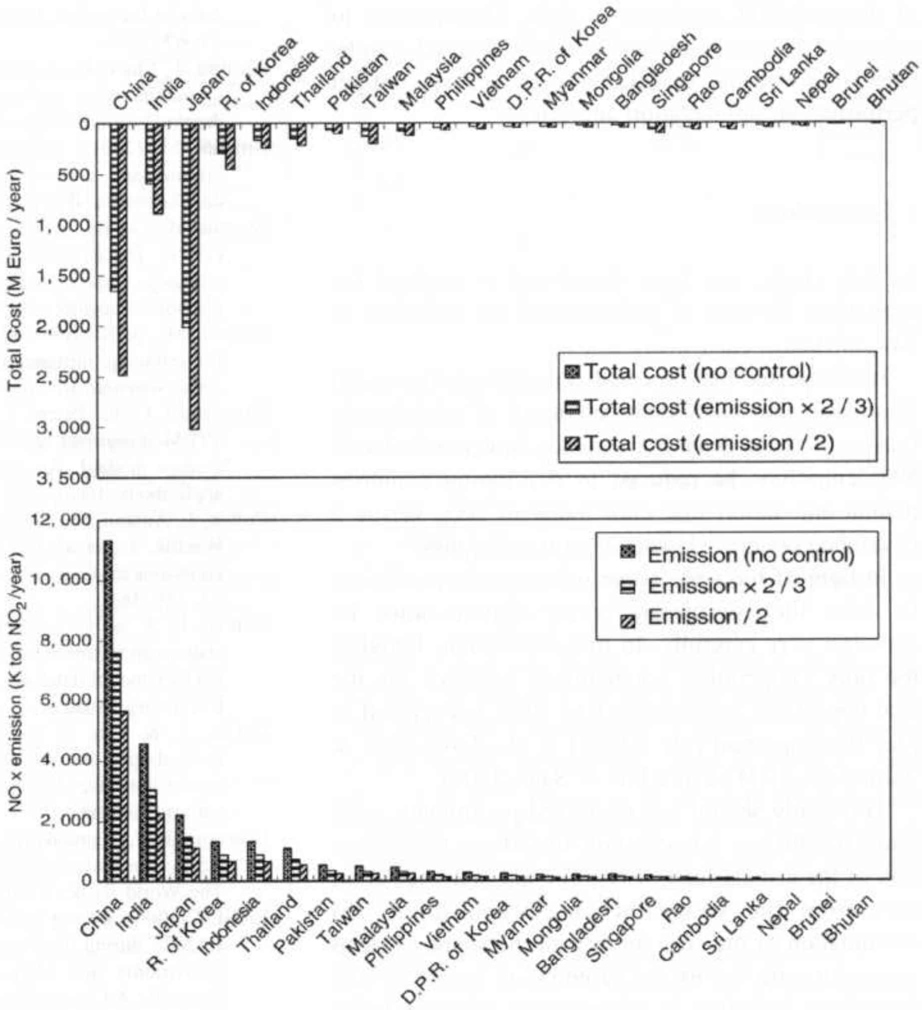
In this case the point E2 should reduce S_{dep} since the S_{dep} exceeds $CL_{max}(S)$. This study only considers the reduction of N_{dep}, therefore, the points E2 and E4 are to be moved to the $CL_{min}(N)$.

4.5.2 Reduction of NO_x Emission and Consequent Change of Gap between Critical Load and N Deposition

The impact of NO_x emission reductions in a source grid cell is calculated with the SRRs, relative to the initial (no control) level of N deposition in each receptor cell. In order to shorten the calculation time three cases are examined here: no control, a half emission reduction, and one third emission reduction, relative to both 'baseline" and "current legislation" emission scenarios. Two cases of sulfur deposition to critical load are examined in the following (a) and (b).

$(a) S_{dep} \leqq CL_{max}(S)$:

Fig. 13 Reduction of NO_x emission and total cost



Ex with the reduction of NO_x emission at 0, 33 and 50% are shown in Figs. 7, 8 and 9,[13] respectively. The shaded grid cells have the deposition exceeded critical load, the blank grid cells mean the area of $S_{dep}>CL_{max}(S)$, and the area (Ex<0) is also shown in the figures (the most lightly shaded).

$(b) S_{dep} > CL_{max}(S)$:

The results of $N_{dep}-CL_{min}(N)$ with the reduction of NO_x emission in the proportion of 0, 33 and 50% are shown in Figs. 10, 11 and 12. The blank grids mean the area of $S_{dep} \leqq CL_{max}(S)$, and the area ($N_{dep}-CL_{min}(N)<0$) is also shown in the figures (the most lightly shaded).

4.5.3 *Reduction of NO_x Emission and its Cost*

Using the national cost functions estimated in 4.4.2, the two cases of total cost of NO_x emission reduction were calculated. The uniform reduction of NO_x emission is not cost-effective as illustrated by Table 1 and Fig. 13. For instance in the case of reduction at 33%, though the amount of reduction of NO_x emission of Japan is one-fifth (732 kt/year) as much as that of China, the cost of Japan is 1.2 times (3,014 MEuro/year) as much as that of China. The NO_x emission of top six countries (China, India, Japan, R. of Korea, Indonesia and Thailand) is 85.8%

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[13] Mapping program of RAINS-ASIA is used to show the result of calculation.

of the total NO_x emission in Asia. Optimization to minimize the cost of reduction of NO_x and SO_2 can be calculated with our model, although we have not yet performed an optimization analysis.

5 Conclusions

In this study, we have developed a method for estimating the cost of reduction of the emission of NO_x in Asia.

It is expected that this study can provide the useful information for cost-effective control of acid deposition problems in Asia. For instance, how much should NO_x emissions be reduced in developing countries (China and India) that emit much of NO_x versus a developed country (Japan) in terms of equity?

In light of the wide range of economic conditions in Asia, the appropriate policy options must be explored very carefully. In this connection, EANET, the only cooperative international initiative for the acid deposition problems in East Asia, is expected to play the important role (Otoshi et al., 2001; Sato & Yamashita, 2004; Yamashita & Sato, 2005).

This study should be considered preliminary, with room for further investigation including: (a) derivation of the critical load of N from soil and vegetation data from the viewpoint of eutrophication, (b) examination of the cost curve with the shape of steep increasing rate, (c) using the emission inventory and deposition including N of ammonia, (d) cumulative estimation of the cost function from the emission inventory in the future. Furthermore, the optimization calculation to minimize the reduction cost of S and N simultaneously is necessary for integrated cost-effective analysis of adverse effects on ecosystem by acid substances. Ozone problems related to acid deposition should also be taken into account from the viewpoint of cost-effectiveness as well as multi-effect and multi-pollutant approach.

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