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ABSTRACT

In the past, environmental decision making has been based on analysis of policy options with respect to emission reduction, deposition or concentration of pollutants and the design of preventive strategies using disparate single-model and discipline results. It was impossible to obtain optimal solution to environmnetal problems because it is difficult to conduct a coherent, systematic and sound analysis of environmental problems using a single disciplinary model. Thus, a need arises for an integrated approach in environmental policy making.

The trend in environmental management is a move from single pollutant/single-effect to multi-pollutant/multi-effect approach and to the inclusion of socioeconomic issues for the purposes of determining the interaction of the environment with the economy. Integrated assessment modeling (IAM) enables us to examine these kinds of issues by creating logical and scientific relationship between the functioning of various ecosystems and the manner in which they respond to external stimuli. Recognizing the crucial role that an integrative approach could play in the development of sound environmental decision making, Environment Canada and other government agencies have jointly participated in the development of IAM. Using data on emissions, depositions, source-receptor matrix, costs of emission abatement, models describing the functioning of aquatic and terrestrial ecosystems, IAM can be used to identify optimal emission reduction strategies that benefit both the economy and ecology.

The purpose of this paper is to demonstrate how economic aspects of emission abatement can be incorporated into IAM using acid rain as a case. The present study compared findings of optimal abatement strategies when economic abatement costs are included and when they are not. The findings indicate that i) a strong long-term commitment is required to provide 100% proetction and allow the rejuvenation of acidified lakes, ii) major reductions in emissions of SO_2 are still required from the USA, iii) inter-regional trading with the USA can play a major role in reducing emission of SO_2 , and iv) polluters, as well as the society, would be better-off when emission abatement strategies incorporate abatement costs than when not. This is particularly important in ensuring the integration of the economy with environment, and the attainment of sustainable development.

1. INTRODUCTION

Integrated Assessment Modeling (IAM) has become an important field of study over the past decade. Before discussing the contribution of the present study, it is important to clarify the meaning of the concept of IAM. The concept of IAM encompasses three elements: Integrated, Assessment and Modeling. IAM could mean a number of things to disciplinary thinkers, researchers, policy makers, etc. The scope of IAM can be as narrow as studying a single lake ecosystem or as complex as examining the global climate change.

The standard view of integration refers to the causal chain that joins human actions to valued consequences. Integration could mean incorporation of a single or chain of events into a specific framework that directly or indirectly impact a specific outcome. It could imply the consideration of the cultural elements of a specific target population in the formulation of a development project. At the other end of the spectrum, integration could imply the explicit consideration of social and economic factors that drive emissions, the biogeochemical cycles and atmospheric chemistry that determines the fate of emissions, and the resultant effect of emissions on the local and global environment, including the health and welfare of humans.[1,2,3,4,5]

Assessment can be defined as the presentation of and drawing casual inferences from knowledge or information derived from various disciplinary researches to help decision-makers evaluate possible actions or undertake an in-depth understanding of a problem.[1] Modeling is a framework or tool for organizing and assessing information.

Policy and basic sciences are the two essential ingredients of IAM. IAM establishes an interdisciplinary research so that effective communications can be established between basic and social scientists, and decision makers on the implications of changes in environmental health. Integrated assessment can be viewed as an interdisciplinary and participatory process that combines, interprets and communicates knowledge from disparate disciplines in order to facilitate greater appreciation and understanding of complex problems.[1,4]

An IAM is an important tool for a holistic analysis of environmental problems because several environmental problems have common causes, dynamics, and common impacts. IAM is able to examine the relationships between the causes (human activities), the mechanisms (changes in the functioning of the atmosphere, terrestrial and aquatic ecosystems), and the impacts (changes in environmental health). The present study describes and presents the role of IAM in environmnetal policy making in Canada.

2. EXPERIENCE WITH IAM

2.1. International Experience

IAM is not the only interdisciplinary or unifying research methodology or paradigm. The field of cybernetics in the 1950s, information theory of the 1960s, catastrophe and the world systems theories of the 1970s, chaos theory of the 1980s, and complexity theory of the 1990s are few examples of interdisciplinary or unifying paradigms.[3,6,7] However, emphasis is being given by policy makers to IAM as an important tool that would enable balancing economic growth with environmental protection.[2]

Research organizations in a number of countries have been involved in the development of IAM tools as well as in utilizing output from these tools. The Battelle Pacific Northwest Laboratories, Carnegie-Mellon University, Dutch National Institute for Public Health and Environmental Protection (RIVM), International Institute for Applied Systems Analysis (IIASA), Electric Power Research Institute (EPRI), Japanese National Institute for Environmental Studies, U.S. Environmental Protection Agency , and Environment Canada have been involved in the development of various forms of IAM tools.[8,9,10,11,12,13,14] In addition, organizations, such as Intergovernmental Panel on Climate Change (IPCC), U.N. Climate Convention, US Environmnetal Protection Agency (US-EPA), United Nations Economic Commission for Europe (UN-ECE), Environment Canada, etc. have utilized information supplied by IAM.[15]

Several IAM models have been developed over the past decade. These include Climatic Impact Assessment Program (CIAP) of the US Department of Energy (USDOE); RAINS Model for Europe and Asia (IIASA), Raison for Windows for Canada (Environment Canada), Tracking and Analysis Framework or TAF of the National Acid Precipitation Assessment Program (USEPA), IMAGE 2.0 (RIVM) and MiniCAM (USDOE) are few of the IAM platforms that combine both socioeconomic and environmental variables.[8,9,11,16] There are also models that examine only the physical environment such as General Circulation Models (GCMs) and MAGICC (National Center for Atmospheric Research-USA and University of East Anglia). Other IAM tools examine only the socioeconomic environment such as DICE (Yale University), CSERGE (Center for Social and Economic Research into the Global Environment) Model and the Energy Modeling Forum (Stanford University). [16,17,19,20,21]

Most IAM tools are international or national in application. However, regional sub-integrated assessments have also been undertaken. Regional IAM modeling may be able to provide valuable details about a specific policy outcome at a local or regional level.[22] The present study is geared toward demonstrating such an application.

2.2. Canadian experience

In Canada, an IAM platform evolved from a sub-basin or lake-ecosystem assessment tool called RAISON (Regional Analysis by Intelligent Systems ON a microcomputer) for windows.[12,13] RAISON for Windows is a powerful environmental information system tool used for data integration and management, and for data analysis, synthesis and display. Unlike the policy driven IAM platforms such as RAINS, the Canadian version of IAM attempts to balance the economy with the environment or policy with science.[12,13,14]

The Canadian version of IAM can be divided into three major components: Biological or aquatic sciences, atmospheric sciences, natural resource sciences, and socioeconomic sciences. The biological or aquatic sciences include models such as waterfowl acidification response modeling system (WARMS), Cation Denudation rate (CDRM),Trickle down (TD), CDRLTH, and TDBO. The Atmospheric sciences include source-receptor relationship matrix for SO_2 and NOx from long-range atmospheric transport model. The natural sciences module is still in development but currently has forestry impact model. The socioeconomic sciences currently has cost of emission reduction and functional specifications between costs and emission removal. These modules are interconnected through linear and non-linear optimization algorithms. Furthermore, the Canadian IAM platform includes emissions and deposition data, and critical deposition loadings for sensitive aquatic ecosystems. The IAM platform also employs neural network approach to recognize patterns and fill gaps in monitoring data. Optimization procedures including linear programming and genetic algorithms are also included in the platform. Moreover, uncertainty and error propagation in models, using causal probability network and fuzzy expert system, are introduced to the platform. [12,13,14]

The optimization scheme contains an objective function and constraints to be satisfied. That is it maximizes emissions reductions subject to the satisfaction of constraints such as non-exceedance of maximum deposition at sensitive receptors, maximum allowable reductions form source regions as well as the numbers of sources that would be examined simultaneously. The results of the non-linear optimization runs would identify a strategy that is least cost and yet enable the attainment of environmnetal goals.

The Canadian IAM platform has been used as a decision-support framework for basin management strategies on nutrient abatement, effluent limits, waste disposal, dredging and other cleanup options in the Great Lakes 2000 program. Information on hydrology, water quality, geology, fisheries, forestry, transportation, urban development, socio-economics and health has been integrated in support of watershed ecosystem research studies such as the Grand River Eco-Research Project. Decision-support framework using expert system technologies to link simulation models on hydrological runoff, water quality, groundwater and river ecology for watershed management and planning have been developed (e.g., a study on the Duffins Creek Watershed).[12,13,14]

Moreover, analysis of lake ecosystem (e.g., lake Erie) response to climate change scenarios has been undertaken. Integrated assessment of ecological impacts due to sulfur and nitrogen oxides for evaluation of policy options of emission control for selected sites in Canada and the United States has been conducted. In addition, modeling industrial effluent transport and fate in the Athabasca River, and pathway and fate of contaminants for the Great Lakes-St. Lawrence Mixed Woods Plain have been carried out. Internationally, the RAISON system has been used for watershed modeling and lake hydrodynamics for the Lerma-Chapala basin (Mexico) and the Lake Caohu basin (P.R. China).[12,13,14]

3. AN EXAMPLE FROM ACIDIFICATION STUDY

3.1. Introduction

Sulphur dioxide (SO_2) and nitrogen oxides (NO_x) can be classified as acidifying pollutants since they become acids upon contact with moisture. These gases are also transformed in the atmosphere to their corresponding acid species, sulphuric (H_2SO_4) and nitric (HNO_3) acid. These and other air pollutants can be deposited on vegetation, soils, surface or ground waters, etc. in wet and dry forms. In addition, one of the constituents of NO_x, nitrogen dioxide (NO_2) is converted to ground-level ozone (O_3) and peroxyacetyl nitrate (PAN).

Several gaseous sulphur compounds are emitted into the atmosphere through man-made or natural processes. Of these sulphur compounds, SO_2 and hydrogen sulphide (H_2S) are the most important species of environmental concern. Emission of SO_2 and its depositions as sulphate is the major anthropogenic causes of acidification of lakes, stream and terrestrial ecosystems. Man-made sources contribute to more than half of total sulphur emissions in the northern hemisphere.[22] In Canada, the major sources of SO_2 emissions are industrial processes (62%), fuel combustion (33%) and transportation (4%).[24]

Effective control of atmospheric deposition of acidifying pollutants that would enable the attainment of critical deposition loadings in Canada requires collaborative efforts among provinces and with the USA. Critical deposition loadings is define as "the highest deposition of acidifying compounds that will not cause chemical changes leading to long term harmful effects on ecosystem structure and function."[25] To attain critical deposition loadings or reduce acidic deposition, the Canada-US Acid Rain Control Accord was signed in 1991. According to this

Accord, Canada has committed to keep the total annual emission of SO_2 to 3.2 million tons per year by the year 2000. Of this national cap, 2.3 million tons have been set to be achieved by the provinces in Eastern Canada. This cap represents a 40% reduction from the 1980 level. There is no formal commitment to extend this cap beyond the year 2000. Many acidified ecosystems require longer time period to recover. Therefore, there is a need to develop a strategy for further reduction of SO_2 in North America.

Emission inventories of SO_2 and NO_x from point sources indicate that the ratio of emissions of NO_x from the USA 16 times that of Canadian emissions (see Table 1). In aggregate, however, U.S. emissions of SO_2 and NO_x are at least four fold that of Canadian emissions (Table 1). The ratio of SO_2 emissions to the NO_x emissions in Canada is about 1 while that of U.S.A. is 1.5. Without a firm commitment plan to reduce emissions of SO_2 and NO_x in the U.S.A., transboundary flow of acidifying pollutants to Canada may increase.[26] Canada may require to implement additional control measures and instruments to minimize the acidification and other effects of NO_x and SO_2.

In the present study a model that inherently incorporates inter-regional trading is employed. The present study is intended to demonstrate the use of IAM in determining optimal policy scenario in a situation when only environmental goals are perceived compared to a situation when both environmental and economic concerns are integrated in the decision making process.

3.2. Inputs into the Model

Inputs to the IAM platform include gridded emissions and deposition data, critical deposition loadings for sensitive receptors, cost functions, cost and deposition optimization algorithms, source-receptor relationship matrix, lake chemistry and data on aquatic ecosystems of lakes in the receptor sites. The purpose of the present study is to examine the cost implications of only deposition optimization strategy that takes into account percentage of lakes protected from acidification, and cost and deposition optimizations routine that incorporates cost and environmental goals would be carried out.

The 1990 Canadian long-range transport of air pollutants and acid deposition report divided North America into 40 sources of emission and 15 sensitive receptors sites (Figures 1 and 2).[24] For the purpose of national policy making and international negotiation, the use of these large sources and few receptors may prove adequate.

3.3. Analysis of optimization results

The analysis is divided into two parts: ecological or deposition optimization, and an ecologic-economic or deposition-cost optimization models. The results are demonstrated for three sensitive Canadian receptors: Algoma (Ontario), Monmorency (Quebec) and Kejimkujik (Nova Scotia); and one USA receptor: Adirondack (New York). Selected features of these receptor sites are provided in Table 2. The results of the Optimization routine are presented in Tables 3 to 6. The percentage emission reductions presented in the discussions below are in comparison with the 1990 emissions. Unless indicated, the maximum reduction specified in all optimization routine is 75% of 1990 emissions.

3.3.1. Results for Algoma (Ontario)

The results of deposition optimization algorithm indicated that in order to protect 90% of lakes from being acidified (Ph<=6) in the Algoma region (southeastern Ontario), the estimated deposition has to be 10.8kg/ha/yr of SO_4. This objective assumes a background deposition of 3.6 kg/ha/yr of SO_4. To achieve this ecosystem objective, Canadian emissions of SO_2 have to be reduced by 732kt (24%). The cost to achieve this level of reduction is 345 million US$. At the same time, USA emissions of SO_2 has to be reduced by 4277kt (22%) at a cost of 3.5 billion US$. In total, emission of SO_2 from North America has to be reduced by 5009kt (22%) at a cost of 3.8 billion US$ (Table 3).

The same ecosystem objective was optimized using both cost and environmental goals. That is the optimization scheme was performed to identify a strategy that satisfies the environmnetal goal and yet attainable at a minimum cost. The results show that Canadian emissions of SO_2 can be reduced by 1168kt (38%) at a cost of 357million US$. To achieve the same environmental goal at a minimum cost, USA has to reduce its emissions of SO_2 by 5805kt (29%) at a cost of 3.5 billion US$ (Table 3).

The above results indicate that it cost more for Canada to reduce emissions to achieve 90% protection of aquatic ecosystems in the Algoma region. Aggregating reductions in both Canada and USA, deposition optimization results shows a reduction of 5009kt at a cost of 3.8 billion US$. However, cost optimization with environmental objective resulted in a reduction of 6972kt at a cost of 3.8 billion US$. Introducing inter-regional trading that takes into account both costs and environmental goals, therefore, resulted in 39% more emissions reduction at a cost of about 1% less than those incurred when the optimization routine considers only environmental goals.

3.3.2. Results for Monmorency (Quebec)

To attain a 90% aquatic ecosystem protection, Canada has to reduce emissions of SO_2 by 1172kt (38%) at a cost of 1.2 billion US$. To achieve the same environmnetal goal, USA has to reduce its emissions of SO_2 by 2601kt at a cost of 3.4 billion US$. On the other hand, cost optimization routine showed that Canada need to reduce emissions by 1440kt(47%) at a cost of 1.1 billion US$. At the same time, the results from the cost optimization routine indicated that USA has to reduce emissions by 5588kt (28%) at a cost of 3.3 billion US$. Thus, a strategy that involves cost and deposition optimization proves to be extremely attractive since it allows a reduction of 7027kt at a cost of 4.3 billion US$. It means that about 86% more emission reduction at about 5% less cost can be attained when the development of an acid rain strategy involves costs and environmental goals than when it relies only on environmental goals (Table 4).

3.3.3. Results for Kejimkujik (Nova Scotia)

Protection of more than 80% of the aquatic ecosystems at this receptor site with a maximum emission reduction of 75% was found to be unattainable. Therefore, a protection level of 80% was chosen as an environmental goal. The result of deposition optimization showed that Canada need to reduce emissions by 747kt (24%) at a cost of 835 million US$ (Table 5). Similarly, USA has to reduce emissions SO_2 by 3672kt (18%)at a cost of 5.1 billion US$. On the other hand, cost and deposition optimization routine showed that Canada should reduce emissions by 1382kt (45%) at a cost of 857 million US$. At the same time USA should reduce emissions by 6507kt (33%) at a cost of 4.5 billion US$. In total, emissions have to be reduced by 4418 (19%) from north America at a cost of 5.9 billion US$ under deposition only scenario. However, when both costs and environmental objectives are incorporated in strategy development, emissions would have to be reduced by 7889kt (34%) at a cost of 5.3 billion US$ (Table 5). Thus, it would be beneficial to both ecosystems and the economy to adopt cost and deposition optimization strategy.

3.3.4. Results for Adirondack (USA)

To protect 85% of aquatic ecosystem in the Adirondack, Canada has to reduce emissions of SO_2 by 738Kt (24%) at a cost of 356 million US$. At the same time, USA should reduce emissions of SO_2 by 5415kt (27%) at a cost of 8.3 billion US$ (Table 6). However, when cost and environmental goals are incorporated in the development of an acid rain strategy, emission reduction from Canada increased to 1412kt (46%) at a cost of 732 million US$. At the same time, reduction from USA increased to 8694Kt (45%) at a cost of 10.6 billion US$. In the USA, where most reduction are expected, deposition minimization seem to be relatively cheaper (about 30% less) (Table 6).

Increasing the maximum reduction as well as reducing the percentage of lakes protected from being acidified showed that deposition optimization remains relatively cheap. For example, increasing emission reduction to 85% and reducing protection level to 80% show about a 5% increase in cost under cost optimization compared with deposition optimization scheme. Increasing the emission reduction level to 90% show that the amount of emissions reduced was larger under a routine that incorporate both costs and environmental goals, but the cost of emission reductions were approximately equal in both routines. This finding may suggest that reducing the size of trading regions or a re-evaluation of the cost structure and the manner in which costs were aggregated for the USA emission regions may probably show a different result. Alternatively, the findings may imply that when the major polluters and the area affected most are in the same country, inter-regional trading may not always be cheaper.

For all receptors examined in this study, 100% protection form acidification was not possible. Furthermore, for some receptors while environmental goals were attainable, economic goals of minimum cost were not feasible and vice versa. Gradual approach to emission reduction with inclusion of both costs and environmnetal goals seem to be a feasible strategy.

4. CONCLUSIONS

Environmnetal decision making used to rely on evidence derived from single and disparate empirical models. However, the causes of and solutions to most environmental problems tend to be interconnected. Consequently, policies that depend on disciplinary research may be not be optimal with respect to balancing economic growth with environmental proetction. As a result several countries, including Canada, are moving toward the use of integrated assessment modeling to bring together knowledge from various disciplines to get an in-depth understanding of environmental problems and make sound decisions.

Several organization and institutions around the world are making use of IAM in environmental decision making. However, some IAM tools tend to be either mostly policy or science driven. Identification of trade-off between economic growth and environmnetal proetction is crucial to attain sustainable development. In this respect, the Canadian version of IAM is well suited to give due consideration to economy and environment so that the decisions would not jeopardize the delicate balance between economy and environment.

The Canadian version of IAM incorporates several ecosystem models, economic component and scientific and socioeconomic databases. The platform was used to demonstrate the implications of environmental decision making that are based on only basic sciences and those based on both basic and social (economic) sciences. Optimal strategies were examined taking into account acid rain and inter- and intra- country emissions trading.

The findings of the analysis with respect to minimizing the impact of acidification indicates that it requires long-term commitment to provide 100% protection aquatic ecosystem or lakes without hurting the economy. That is, gradually- phased emissions reduction would be required to reduce deposition in order to allow recovery and perpetuation of aquatic and other ecosystems affected by acid rain.

The incorporation of multiple objectives, that is economic and environmental goals, in developing environmental policies may contribute to faster recovery of acidified lakes compared to strategies that consider only environmental goals because the former approach allows the removal of a large percentage of current emissions. Furthermore, the study indicated that these large reductions can be achieved at costs that are less than or equal to those incurred when policy development tools take into account only environmental goals. It means that strategies the incorporate economic and environmental goals would make the polluters, society and the environment better-off. Furthermore, the analysis indicated attainment of environmental goals in Canadian sensitive receptors require major emissions reductions from the USA.

The principle of sustainable development requires that there must be a balance between economy and the environment. Sustainability can be achieved only through policies that protect the environment while at the same time minimizing impacts on economic growth. Future studies in this area can be directed towards incorporating goals such as employment and indicators of carrying capacity of ecosystems.

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5. REFERENCES

1. Morgan, M.G. and H. Dowlatabadi. Climatic Change, 1996, 34, 3-4, 337-368.
2. Parson, E.A. and K. Fisher-Vanden, Searching for Integrated Assessment: A Preliminary Investigation of Methods, Models, and Projects in the Integrated Assessment of Global Climatic Change. Consortium for International Earth Science Information Network (CIESIN).University Center, Mich. 1995.
3. Risbey, J., M. Kandlikar, and A. Patwardhan. Climatic Change, 1996, 34, 3-4, 369-395.
4. Rotmans, J., Van Asselt, M. Climate change, 1996, 34, 3-4, 327-336.
5. Rotmans, J., M. Hulme, and T.E. Downing. Global Environmental Change, 1994, 4 (2): 97-124.
6. Forrester, J.W., 1971. World Dynamics.Wright-Allen Press, Cambridge, Mass.
7. Brunner, R.D. 1996. Climate Change, 32:121-147.
8. Alcamo, J., G.J.J. Kreileman, M. S. Krol, and G. Zuidema. 1994. "Modeling the Global Society-biosphere-climate System: Part 1: Model Description and Testing." In IMAGE 2.0: Integrated Modeling of Global Climate Change, ed. J. Alcamo. Dordrecht, The Netherlands: Kluwer Academic Publishers.
9. Alcamo, J., R. Shaw, and L. Hordijk, eds. 1990. The RAINS Model of Acidification: Science and Strategies in Europe. Dordrecht, The Netherlands: Kluwer Academic Publishers.
10. Ball, M., and H. Dowlatabadi. 1995. "The Role of Aerosols in Climate Change: Results from an Integrated Assessment Model (ICAM 2.0)." Pittsburgh, Pa.: Carnegie Mellon University, Department of Engineering and Public Policy.
11. Consortium for International Earth Science Information Network (CIESIN). 1995. Thematic Guide to Integrated Assessment Modeling of Climate Change. University Center, Mich.
12. Lam, D.C.L., C.W. Mayfield, D.A. Swayne and K. Hopkins. 1994. J. Biol. Systems 2:499-517.
13. Lam, D.C.L., W.G. Booty, W.G., Wong,I., Kay, D., and Kerby, J. The RAISON decision support system: examples of applications. National Water Research Institute, Environment Canada, Burlington, Ontario, Contribution No. 95-151, 1995
14. Lam, D.C.L., Puckett, K.J., Wong, I., Moran, M.D., Fenech, G., Jeffries, D.S., Olson, M.P., Whelpdale, D.M., McNicol, D., Mariam, Y.K.G., and Minns, C.K., Water Quality Res. J. Canada. 33, 1, 1-17.

15. IPCC 1996. Integrated assessment of climate change: An overview and comparison of approaches and results. In Intergovernmental Panel of Climate Change: Working Group III Report. In press.

16. Rubin, E.S. 1991. J.of the Air and Waste Management Association, 1991, 41: 914-21.

17. Edmonds, J.A., M.A. Wise, and C. MacCracken. 1994. Advanced Energy Technologies and Climate Change: An Analysis Using the Global Change Assessment Model (GCAM). PNL-9798, UC-402. Richland, Wash.: Pacific Northwest Laboratory.

18. Maddison, D. 1994b. "A Cost-Benefit Analysis of Slowing Climate Change." Center for Social and Economic Research on the Global Environment (CSERGE). London: University College London.

19. Hulme, M., S.C.B. Raper, and T.M.L. Wigley. 1994."An Integrated Framework to Address Climate Change (ESCAPE) and Further Development of the Global and Regional Climate Modules (MAGICC)." In Integrative Assessment of Mitigation, Impacts, and Adaptation to Climate Change, ed. N. Nakicenovic, W.D. Nordhaus, R. Richels, and F.L. Toth. International Institute for Applied Systems Analysis (IIASA) Collaborative Paper, CP-94-9. Laxenburg, Austria: IIASA.

20. Nordhaus, W.D., and Z. Yang. 1995. RICE: A Regional Dynamic General Equilibrium Model of Optimal Climate-Change Policy. New Haven, Conn.: Yale University and Massachusetts Institute of Technology.

21. Energy Modeling Forum. 1995. Second Round Study Design for EMF 14: Integrated Assessment for Climate Change. Palo Alto, Calif.: Stanford University.

22. Cohen, S.J. 1995. An interdisciplinary assessment of climate change on northern ecosystems: The Mackenzie Basin Impact Study. In Human Ecology and Climate Change: People and Resources in the Far North, eds. D.L. Peterson and D.R. Johnson, 301-316.Washington, D.C.:Taylor and Francis.

23. Legge, A.H., and Krupa, S.V. (eds). 1990. Acidic Deposition: Sulphur and Nitrogen Oxides. Lewis Publishers, Inc. Michigan, U.S.A.

24. Environment Canada, 1995. Air Emissions: Baseline Forecast, 1990-2010, Pollution Data Branch. March.

25. Environment Canada, 1990. The 1990 Canadian Long-Range Transport of Air Pollutants & Acid Deposition Assessment report: Part 1, Executive Summary; & Part 4, Aquatic Effects.

26. Mariam, Y. 1994. Trend analysis of energy use and emission of NOx for eastern Canada. Mimeo. Economic Analysis Branch, Environment Canada. December.

Table 1. Comparison of Annual (1990) Canadian and U.S.A. SO_2 and NO_x Emissions from Point and Area Sources (in Tons/year)

	Canadian Emissions		U.S.A. Emissions		Ratio of U.S.A. to Canadian Emissions	
Source/Categories	SO_2	NO_x	SO_2	NO_x	$US_{(SO2)}$:$CCAN_{(SO2)}$	$US_{(NOx)}$: $CCAN_{(NOx)}$
Point Sources	2996199.3	665177.3	20739516.2	10326178.9	7	16
Area Sources	486434.2	2868910.9	1307800.7	4998436.7	3	2
All Sources	3482633.5	3534088.2	22047317	15324616	6	4

Table 2. Background, actual, total, and critical deposition loadings (kg SO_4/ha/yr)

Receptors	Background Deposition	Actual Deposition 1990	Total Deposition 1990	Critical Deposition Loadings	Location
Algoma	3.6	13.887	17.447	16	Ontario
Monmorency	4.8	14.001	18.831	9	Quebec
Kejimkujik	5.6	8.375	13.965	8	N.S.
Adirondack	3.3	14.514	17.794		New York

Table 3. Results of IAM for Algoma Receptor

Receptor	Algoma						
Excess percent of lakes with PH<=6	10.0%						
Objective function	10.8 kg/ha/yr						
Background	3.6kg/ha/yr						
Region Name	Deposition Optimized				Cost and Deposition Optimized		
	SO_2 Emission Before (kT)	Emission Reduction (kT)	% Emission Reduction	Costdep (US$M)	Emission Reduction (kt)	%Emission Reduction	Cost (US$M)
11	12.00	9.00	75.00	14.99	0.16	1.00	0.27
12	10.00	7.50	75.00	25.10	5.93	59.00	19.83
13	50.00	37.50	75.00	61.47	8.49	17.00	13.92
14	688.00	516.00	75.00	119.41	516.00	75.00	119.41
15	216.00	162.00	75.00	123.53	162.00	75.00	123.53
16	30.00	0.00	0.00	0.00	6.26	21.00	1.30
17	184.00	0.00	0.00	0.00	5.95	3.00	1.00
18	162.00	0.00	0.00	0.00	121.35	75.00	12.36
19	46.00	0.00	0.00	0.00	30.74	67.00	2.54
20	176.00	0.00	0.00	0.00	0.00	0.00	-0.36
21	182.00	0.00	0.00	0.00	0.00	0.00	1.37
22	72.00	0.00	0.00	0.00	0.17	0.00	0.42
23	610.00	0.00	0.00	0.00	171.73	28.00	30.04
24	110.00	0.00	0.00	0.00	2.72	2.00	0.69
Canada Total	**3078.00**	**732.00**		**344.49**	**1167.63**		**357.37**
50	2318.00	1738.50	75.00	732.55	1262.71	54.00	532.07
51	1124.00	843.00	75.00	486.87	706.09	63.00	407.80
52	1274.00	0.00	0.00	0.00	393.74	31.00	122.03
53	1658.00	802.70	48.40	410.58	712.69	43.00	364.54
54	952.00	0.00	0.00	0.00	237.84	25.00	149.97
55	454.00	340.50	75.00	891.08	233.17	51.00	610.21
56	938.00	0.00	0.00	0.00	97.89	10.00	37.93
57	796.00	0.00	0.00	0.00	453.52	57.00	131.21
58	1024.00	0.00	0.00	0.00	259.78	25.00	113.74
59	536.00	0.00	0.00	0.00	5.84	1.00	1.17
60	688.00	0.00	0.00	0.00	217.10	32.00	16.23
61	612.00	459.00	75.00	800.05	459.00	75.00	800.05
62	124.00	93.00	75.00	177.04	63.29	51.00	120.49
63	790.00	0.00	0.00	0.00	0.00	0.00	0.00
64	744.00	0.00	0.00	0.00	147.29	20.00	2.49
65	1088.00	0.00	0.00	0.00	349.50	32.00	28.25
66	584.00	0.00	0.00	0.00	75.97	13.00	-1.99
67	710.00	0.00	0.00	0.00	44.92	6.00	2.92
68	314.00	0.00	0.00	0.00	0.00	0.00	4.21
69	70.00	0.00	0.00	0.00	0.54	1.00	2.82
70	70.00	0.00	0.00	0.00	14.09	20.00	2.52
71	470.00	0.00	0.00	0.00	34.72	7.00	3.87
72	1698.00	0.00	0.00	0.00	34.81	2.00	-1.37
73	216.00	0.00	0.00	0.00	0.23	0.00	-0.01
74	658.00	0.00	0.00		0.00	0.00	0.00
US total	**19910.00**	**4276.70**		**3498.17**	**5804.76**		**3451.14**
Grand Total	**22988.00**	**5008.70**		**3842.66**	**6972.38**		**3808.52**

Table 4. Results of IAM for Monmorency Receptor

Receptor	Monmorency
Excess percent of lakes with PH<=6	10.0%
Objective function	11.9kg/ha/yr
Background	4.8kg/ha/yr

Region Name	Deposition Optimized				Cost and Deposition Optimized		
	SO_2 Emission Before (kT)	Emission Reduction (kT)	Emission Reduction (%)	Costdep (US$M)	Emission Reduction (kT)	%Emission Reduction	Cost (US$M)
10.00	530.00	0.00	0.00	0.00	136.12	26.00	31.05
11.00	12.00	0.00	0.00	0.00	0.10	1.00	0.13
12.00	10.00	7.50	75.00	22.73	4.54	45.00	13.75
13.00	50.00	37.50	75.00	48.81	7.95	16.00	10.35
14.00	688.00	516.00	75.00	119.41	516.00	75.00	119.41
15.00	216.00	162.00	75.00	123.53	162.00	75.00	123.53
16.00	30.00	22.50	75.00	35.31	9.26	31.00	14.53
17.00	184.00	138.00	75.00	637.67	95.27	52.00	440.23
18.00	162.00	121.50	75.00	12.44	121.50	75.00	12.44
19.00	46.00	34.50	75.00	4.01	34.50	75.00	4.01
20.00	176.00	132.00	75.00	177.97	131.72	75.00	177.58
21.00	182.00	0.00	0.00	0.00	117.93	65.00	99.25
22.00	72.00	0.00	0.00	0.00	3.01	4.00	1.26
23.00	610.00	0.00	0.00	0.00	96.86	16.00	11.94
24.00	110.00	0.00	0.00	0.00	2.72	2.00	0.69
Canada total	**3078.00**	**1171.50**		**1181.88**	**1439.47**		**1060.17**
50.00	2318.00	562.90	24.30	257.57	1289.54	56.00	590.07
51.00	1124.00	0.00	0.00	0.00	511.06	45.00	130.54
52.00	1274.00	955.50	75.00	913.82	715.56	56.00	684.34
53.00	1658.00	0.00	0.00	0.00	600.17	36.00	206.08
54.00	952.00	0.00	0.00	0.00	153.49	16.00	68.69
55.00	454.00	340.50	75.00	902.72	237.79	52.00	630.42
56.00	938.00	0.00	0.00	0.00	45.99	5.00	12.89
57.00	796.00	0.00	0.00	0.00	211.28	27.00	42.48
58.00	1024.00	0.00	0.00	0.00	277.36	27.00	140.91
59.00	536.00	402.00	75.00	647.14	225.60	42.00	363.17
60.00	688.00	0.00	0.00	0.00	182.07	26.00	6.66
61.00	612.00	0.00	0.00	0.00	228.40	37.00	121.53
62.00	124.00	0.00	0.00	0.00	20.14	16.00	23.77
63.00	790.00	0.00	0.00	0.00	38.58	5.00	25.10
64.00	744.00	0.00	0.00	0.00	109.46	15.00	0.33
65.00	1088.00	0.00	0.00	0.00	397.62	37.00	39.63
66.00	584.00	0.00	0.00	0.00	144.40	25.00	40.11
67.00	710.00	0.00	0.00	0.00	38.65	5.00	1.92
68.00	314.00	235.50	75.00	319.94	64.29	20.00	87.34
69.00	70.00	52.50	75.00	271.96	0.54	1.00	2.82
70.00	70.00	52.50	75.00	54.73	31.76	45.00	33.11
71.00	470.00	0.00	0.00	0.00	36.09	8.00	4.19
72.00	1698.00	0.00	0.00	0.00	27.63	2.00	-1.81
73.00	216.00	0.00	0.00	0.00	0.29	0.00	-6.94
74.00	658.00	0.00	0.00	0.00	0.00	0.00	0.00
US total	**19910.00**	**2601.40**		**3367.88**	**5587.76**		**3254.27**
Grand total	**22988.00**	**3772.90**		**4549.77**	**7027.22**		**4314.44**

Table 5. Results of IAM for Kejimkujik Receptor

Receptor	Kejimkujik					
Excess percent of lakes with PH<=6	21.0					
Objective function	9.9 kg/ha/yr					
background	5.6 kg/ha/yr					

Region Name	Deposition Optimized				Cost and Deposition Optimized		
	Total SO_2 Emissions (kt)	Emission Reduction (kt)	% Emission Reduction	Costdep (US$M)	Emission Reduction (kt)	% Emission Reduction	Cost (US$M)
11.00	12.00	0.00	0.00	0.00	0.00	0.00	0.03
12.00	10.00	0.00	0.00	0.00	4.50	45.00	13.75
13.00	50.00	0.00	0.00	0.00	6.30	13.00	4.13
14.00	688.00	0.00	0.00	0.00	516.00	75.00	119.41
15.00	216.00	162.00	75.00	123.53	162.00	75.00	123.53
16.00	30.00	22.50	75.00	25.79	8.80	29.00	10.09
17.00	184.00	138.00	75.00	294.80	72.50	39.00	154.88
18.00	162.00	121.50	75.00	12.44	121.50	75.00	12.44
19.00	46.00	34.50	75.00	4.01	34.50	75.00	4.01
20.00	176.00	132.00	75.00	178.19	132.00	75.00	178.19
21.00	182.00	136.50	75.00	196.54	136.50	75.00	196.54
22.00	72.00	0.00	0.00	0.00	7.00	10.00	3.41
23.00	610.00	0.00	0.00	0.00	41.20	7.00	4.66
24.00	110.00	0.00	0.00	0.00	2.70	2.00	0.69
Canada total	**3078.00**	**747.00**		**835.29**	**1381.60**		**856.82**
50.00	2318.00	427.30	18.40	211.87	1315.50	57.00	652.28
51.00	1124.00	0.00	0.00	0.00	582.90	52.00	198.60
52.00	1274.00	955.50	75.00	1153.24	816.70	64.00	985.72
53.00	1658.00	0.00	0.00	0.00	627.20	38.00	236.33
54.00	952.00	0.00	0.00	0.00	221.00	23.00	128.38
55.00	454.00	340.50	75.00	640.27	133.60	29.00	251.22
56.00	938.00	0.00	0.00	0.00	127.00	14.00	56.85
57.00	796.00	0.00	0.00	0.00	413.50	52.00	113.58
58.00	1024.00	768.00	75.00	735.17	381.60	37.00	365.29
59.00	536.00	402.00	75.00	619.48	221.50	41.00	341.33
60.00	688.00	0.00	0.00	0.00	201.50	29.00	9.63
61.00	612.00	0.00	0.00	0.00	227.50	37.00	120.26
62.00	124.00	0.00	0.00	0.00	0.00	0.00	0.00
63.00	790.00	0.00	0.00	0.00	145.90	18.00	161.39
64.00	744.00	0.00	0.00	0.00	128.40	17.00	0.97
65.00	1088.00	0.00	0.00	0.00	453.40	42.00	84.46
66.00	584.00	438.00	75.00	704.56	294.80	50.00	474.21
67.00	710.00	0.00	0.00	0.00	35.80	5.00	1.70
68.00	314.00	235.50	75.00	655.00	85.50	27.00	237.80
69.00	70.00	52.50	75.00	295.40	0.70	1.00	3.94
70.00	70.00	52.50	75.00	54.66	31.80	45.00	33.11
71.00	470.00	0.00	0.00	0.00	37.10	8.00	4.44
72.00	1698.00	0.00	0.00	0.00	24.20	1.00	-1.89
73.00	216.00	0.00	0.00	0.00	0.20	0.00	-0.01
74.00	658.00	0.00	0.00	0.00	0.00	0.00	0.00
US Total	**19910.00**	**3671.80**		**5069.67**	**6507.30**		**4459.59**
Grand total	**22988.00**	**4418.80**		**5904.97**	**7888.90**		**5316.41**

Table 6. Results of IAM for Adirondack Receptor

Receptor	Adirondack
Excess percent of lakes with PH<=6	15.0%
Objective function	9.3 kg/ha/yr
Background	3.3 kg/ha/yr

Region Name	Deposition Optimized				Cost and Deposition Optimized		
	Total SO_2 Emissions (kt)	Emission Reduction (kt)	% Emission Reduction	Costdep (US$M)	Emission Reduction	% Emission Reduction	Cost (US$M)
10.00	530.00	0.00	0.00	0.00	136.10	26.00	31.05
11.00	12.00	0.00	0.00	0.00	0.40	3.00	0.94
12.00	10.00	0.00	0.00	0.00	7.50	75.00	27.75
13.00	50.00	37.50	75.00	55.38	8.20	16.00	12.11
14.00	688.00	516.00	75.00	119.41	516.00	75.00	119.41
15.00	216.00	162.00	75.00	123.53	162.00	75.00	123.53
16.00	30.00	22.50	75.00	57.87	10.00	33.00	25.72
17.00	184.00	0.00	0.00	0.00	72.20	39.00	153.72
18.00	162.00	0.00	0.00	0.00	121.50	75.00	12.44
19.00	46.00	0.00	0.00	0.00	34.50	75.00	4.00
20.00	176.00	0.00	0.00	0.00	132.00	75.00	178.19
21.00	182.00	0.00	0.00	0.00	29.10	16.00	8.58
22.00	72.00	0.00	0.00	0.00	7.70	11.00	3.93
23.00	610.00	0.00	0.00	0.00	172.30	28.00	30.22
24.00	110.00	0.00	0.00	0.00	3.10	3.00	0.76
Canada total	**3078.00**	**738.00**		**356.19**	**1412.60**		**732.36**
50.00	2318.00	1738.50	75.00	2042.72	1588.00	69.00	1865.88
51.00	1124.00	0.00	0.00	0.00	774.50	69.00	608.15
52.00	1274.00	955.50	75.00	1153.27	816.70	64.00	985.74
53.00	1658.00	484.70	29.20	625.20	952.30	57.00	1228.35
54.00	952.00	0.00	0.00	0.00	336.40	35.00	373.32
55.00	454.00	340.50	75.00	1108.27	288.00	63.00	937.39
56.00	938.00	0.00	0.00	0.00	249.20	27.00	185.96
57.00	796.00	0.00	0.00	0.00	537.00	67.00	245.79
58.00	1024.00	768.00	75.00	1232.85	521.80	51.00	837.63
59.00	536.00	402.00	75.00	818.26	249.50	47.00	507.85
60.00	688.00	0.00	0.00	0.00	227.40	33.00	22.66
61.00	612.00	0.00	0.00	0.00	458.70	75.00	798.57
62.00	124.00	0.00	0.00	0.00	66.60	54.00	134.17
63.00	790.00	0.00	0.00	0.00	453.70	57.00	1095.75
64.00	744.00	0.00	0.00	0.00	151.70	20.00	3.04
65.00	1088.00	0.00	0.00	0.00	442.40	41.00	71.70
66.00	584.00	438.00	75.00	704.75	294.90	50.00	474.50
67.00	710.00	0.00	0.00	0.00	66.00	9.00	11.58
68.00	314.00	235.50	75.00	537.68	79.90	25.00	182.42
69.00	70.00	0.00	0.00	0.00	0.50	1.00	2.82
70.00	70.00	52.50	75.00	54.66	31.80	45.00	33.11
71.00	470.00	0.00	0.00	0.00	57.30	12.00	14.59
72.00	1698.00	0.00	0.00	0.00	48.90	3.00	0.58
73.00	216.00	0.00	0.00	0.00	0.50	0.00	0.00
74.00	658.00	0.00	0.00		0.00	0.00	0.00
US total	**19910.00**	**5415.20**		**8277.66**	**8693.70**		**10621.56**
Grand total	**22988.00**	**6153.20**		**8633.85**	**10106.30**		**11353.92**

Fig.1. Map of Forty Emission Regions Used for Acid Rain Assessment

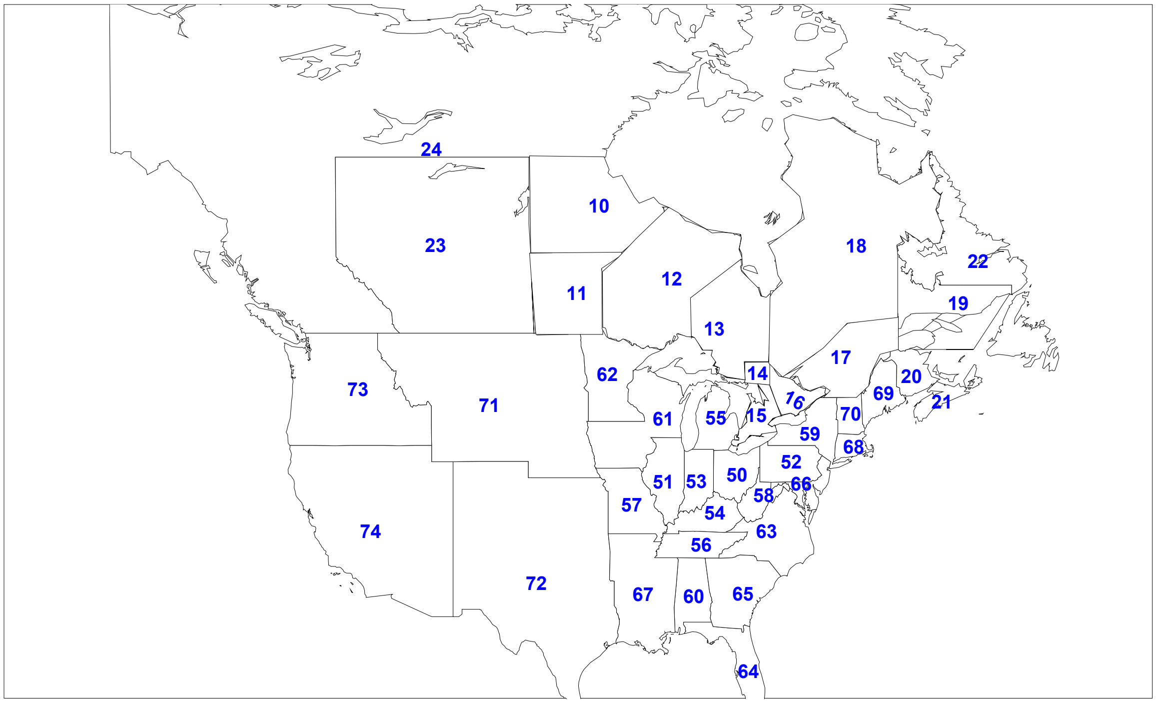
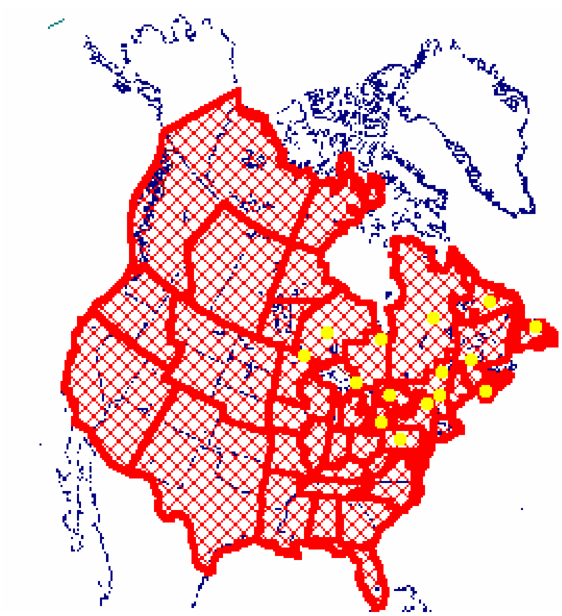


Fig. 2. Map of Forty Source Regions and Fifteen Receptor Sites in North America



Note: Points identified with yellow circles are receptor sites while the emission regions delineated with red lines are similar to those in fig.1.