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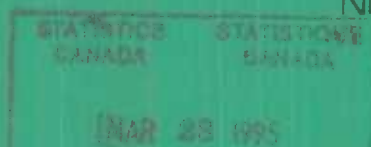
The Linkage of Greenhouse Gas Emissions to Economic Activity Using an Augmented Input/Output Model

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This paper is one in a series of internal discussion papers produced in Statistics Canada's National Accounts and Environment Division. These papers address topics related to environmental statistics and the National Accounts components which are currently under development.

Ce document fait partie d'une série de documents internes produits dans la Division des comptes nationaux et de l'environnement de Statistique Canada. Ces documents traitent de sujets reliés aux statistiques de l'environnement et composantes des comptes nationaux au stade de la recherche.

Discussion papers in this series are made available in the official languages in which they were written. Translated versions are not available in most cases.

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1 Introduction

1.1 Statistics Canada's Green Plan Initiative

Statistics Canada is in the early stages of several new projects centred on the integration and analysis of a variety of socio-economic and environmental data relevant to the study of environmental issues. These projects form the basis of Statistics Canada's Green Plan initiative to develop an environmental component for its System of National Accounts. This component will comprise four "satellite accounts"[1] linked to the main national accounts:

1. Natural Resource Stock Account;
2. Natural Resource Use Account;
3. Waste and Pollutant Output Account;
4. Environmental Expenditures Account.

It is the third account with which this proposal is concerned. The Waste and Pollutant Output Account will integrate available data on the output of unwanted by-products from Canadian production and consumption activities. The basis for this account will be Statistics Canada's national input/output system,[2] which will be augmented with waste output data.

The proposal here is for a pilot version of this account limited to the output of one class of pollutants: greenhouse gases (GHGs). Greenhouse gas emissions have been chosen for two reasons. First, there exists at this time a good deal of the data necessary to complete a pilot study on greenhouse gases (see section 4). Thus, the development of the pilot account can proceed without a lot of time consuming preliminary data development. Second, greenhouse gas emissions and their role in global climate change are an environmental issue of global importance today, including, as discussed next, in Canada.

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[1] Satellite accounts lie outside of the main System of National Accounts but employ essentially the same terminology and accounting procedures. Thus, they can be used to link data specific to a certain subject area, the environment for instance, to the national accounts without the need for direct modification of the latter.

[2] In this proposal the term "input/output system" is used to refer to an input/output framework and the accompanying input/output model. Those unfamiliar with input/output systems are referred to Miller and Blair, 1985 for a thorough discussion.

1.2 Greenhouse Gases in Canada's Green Plan

Canada's Green Plan (Government of Canada, 1990) identifies the increase in average global temperature that is likely to result from the increased atmospheric concentrations of so-called greenhouse gases as a threat to global environmental security.[34] The Green Plan goes beyond merely identifying the threat of global warming however, and commits the Canadian Government to action aimed at reducing Canada's GHG emissions. As a first step toward this, the Green Plan sets a target of the stabilisation of GHG emissions at 1990 levels by the year 2000 (ibid.: 100).

Clearly, there are significant information requirements that will have to be met if Canada is to achieve this reduction target. Most obviously, the Government will require an estimate of gross 1990 GHG emissions in order to assess progress toward meeting the target for 2000. Although such an estimate does not exist at this time, work is currently under way at Environment Canada on the development of an estimate for publication in 1992 (Jacques, Personal Communication). The study proposed below is in no way meant as a substitute for this work. Rather, it is hoped that Statistics Canada can complement Environment Canada's work through the linkage of the latter's environmental data with the detailed economic data to which Statistics Canada has access.

Beyond gross 1990 emission levels, the Government will require knowledge of the relation of these emissions to sectoral economic activity. That is, it will be necessary to understand the extent to which each sector of the economy contributes to GHG emissions and how this contribution is related to the level of activity in each sector. Such knowledge is essential for the development and assessment of policies that can most effectively and efficiently meet the proposed emissions stabilisation target. It is also essential if we are to evaluate the constraints on reduction scenarios imposed by the structure of the Canadian economy and vice versa.

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[3] Five gases or groups of gases have been identified as being of primary concern for their role in global warming: carbon dioxide (CO_2), methane (CH_4), dinitrogen oxide (N_2O), chlorofluorocarbons (CFCs), and ozone (O_3). Four of these are directly emitted from anthropogenic sources: CO_2, CH_4, N_2O, and CFCs. Ozone (O_3) is not directly emitted by human activities, but is produced in the atmosphere as a result of chemical reactions involving precursor molecules such as nitrogen oxides (NO_x), carbon monoxide (CO) and volatile organic carbon compounds (VOCs) (OECD/IEA, 1991). Therefore, the following seven gases or groups of gases form the list that will be considered in this study: CO_2, CH_4, N_2O, CFCs, NO_x, CO and VOCs.

[4] GHG emissions can be expressed for individual gases or by converting the emission of each gas to its CO_2 equivalent and aggregating all emissions into a single value. The latter is perhaps more desirable for policy development because of its greater simplicity and ease of interpretation, while the former is required if the emissions estimates are to be used in detailed research.

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1.3 Goals of this Study

As implied in the foregoing, the major goal of this study is the linkage, at a highly disaggregated level, of GHG emissions with Canadian production and consumption activity. As the agency entrusted with the collection of socio-economic data in Canada, Statistics Canada is in the best position to make this linkage. It should be made clear, however, that it is not a goal of this study to be a major data development exercise. Rather, the hope is that this study can make use of existing GHG emissions data from various sources, mainly Environment Canada, without having to resort to estimating emissions based on primary data. Of course, it is realised that some data estimation is unavoidable. However, for those areas in which data collection proves to be too time consuming the most that this project will do is identify these as gaps to be filled by later data collection exercises.

While the goal of linking GHG emissions to economic activity is important, it should not be an end in itself; data, however organised, are of little value unless they can be used for analytical purposes. Thus, the larger goal of this study is the linkage of GHG emissions with economic activity in the way that is most useful for those engaged in economic/environmental research. In what follows a method for meeting this goal using an augmented version of Statistics Canada's national input/output system is presented. The reasons for employing an input/output system in this study will, hopefully, be made clear in the presentation.

The presentation is organised as follows: positive and negative aspects of input/output systems for environmental analysis are considered in section 2; several applications of the proposed system are discussed in section 3; section 4 is devoted to data sources; technical considerations, for those interested, are left for section 5; and a brief summary comprises the concluding section 6.

2 Input/Output Systems and Environmental Analysis

2.1 Positive Aspects

There was a considerable amount of work done in environmental economics during the 1960's. One of the results of this work was the adoption from the physical sciences by some researchers of the materials-balance concept as a theoretical framework for the analysis of environment/economy linkages. The materials-balance approach stresses the importance of the law of conservation of mass for such analysis. This law states that the flow of materials into a system during a given time period must equal exactly the flow out plus any material accumulated within the system during the period. When applied

to environmental/economic systems, this law reveals that for a given time period there must be an output of materials from an economy to the environment equal to the input of materials in the opposite direction, allowing for temporary material accumulation within the economic system (Victor, 1972: 17-47). The case of air emissions from the combustion of fossil fuels is an excellent means of illustrating the materials-balance approach. In their natural state, oil, natural gas and coal exist as underground deposits. As they are exploited, these materials are extracted from the ground and enter the economic system where they are combusted and transformed into useable energy and gaseous by-products. The latter are immediately emitted to the atmosphere as unwanted by-products. For a given economic system during a specific time period, the mass of gases emitted to the atmosphere from the combustion of fossil fuels is exactly equal to the mass of fuel consumed within the system, less any fuel temporarily stockpiled for later consumption.

If one accepts that the materials-balance concept represents a valid and useful approach to studying environment/economy linkages, and that is the perspective taken here, then input/output systems appear as a very effective analytical framework. The reason for this is the fact that they combine in one system the complete, integrated picture of an economy that is necessary for materials-balance analysis. Second, input/output systems have at their heart the fundamental relationship between material inputs and outputs embodied in the law of conservation of mass and energy. That is, the basic relationship in any input/output system is that material inputs into a given industry must equal exactly the material outputs from that industry, plus any materials temporarily stored as inventoried goods. Thus, when augmented to include the input and output of materials to and from the environment, input/output systems are an excellent framework for facilitating a materials-balance analysis of economic/environmental systems.

To avoid confusion, it should be noted here that this pilot study will consider only the output side of the economy/environment materials-balance, and this only partially. Other accounts to be developed for the environment component of the national accounts will deal with other aspect of this balance.

Another important quality of input/output systems in the context of this study is their very high degree of sectoral detail. In fact, at the worksheet level of aggregation, which is to be used as the basis for the system developed in this study, Statistics Canada's national input/output system represents the most detailed picture of the economy available. The sectoral breakdown of the economy to be used in this study contains 216 industries, 602 commodities and 136 final demand categories. Since it is economic activity that drives anthropogenic GHG emissions, this fine resolution will allow the sources and emissions of GHGs to be analysed in substantial detail. In the case of fossil fuels for example, the input/output system contains detail on the consumption of seven different fossil fuels by as many as 216 different

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industries and 132 different categories of final demand. Once the augmentations to the input/output system proposed in this study are implemented, it will be possible to analyse GHG emissions resulting from fossil fuel consumption at this same level of detail. Moreover, the level of economic detail that is available within Statistics Canada is not available to other researchers, as many of the data contained in the input/output framework at the lowest level of aggregation are confidential.[5]

A third important quality of input/output systems is the fact that they allow the determination of both the direct and indirect impacts of a given change in commodity final demand. This can be made clearer with an example. Consider a change in the final demand for automobiles. Such a change will obviously result in a change in GHG emissions from the automobile industry. A slightly deeper view of the inter-related structure of economic systems reveals that the GHG emissions of all industries that provide inputs for the automobile industry must also change, as must those of the next industrial level down, and so on. The change in emissions from the automobile industry is considered a direct impact of the change in demand for cars, while all other changes are referred to as indirect impacts. The GHG emissions model presented below has the capacity to capture both of these changes and estimate new emissions across all industries based on this one change in final demand.

2.2 Negative Aspects

While the beneficial qualities of input/output systems are well known, there are also features that limit their usefulness for economic and environmental analysis. The most often discussed limitation of input/output systems is their static nature with respect to the technological structure of the economy.[6] In contrast to real economic systems, in which technological structures are ever-changing, input/output systems represent economic systems as though their technological structures were constant. Because of this abstraction from reality, any projections of economic activity made using input/output systems will be in error to the extent that the technological structure of the economy changes during the period of study. This limitation may be particularly significant for the application of input/output analysis that is suggested in this proposal, since the technology employed in reducing air emissions from industrial sources has changed quickly, and will likely continue to do so, in the in the face of increasing regulatory control.

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[5]   Within Statistics Canada it will be possible to use the model in its most disaggregated form. Any results published outside the agency, however, must be aggregated to the medium level of the input/output system in order to meet confidentiality restrictions imposed by the Statistics Act. There are 63 industries, 28 final demand categories and 100 commodities at the medium level.

[6]   The technological structure of an economy, as it is represented in input/output models, refers to the array of inputs required by industries to produce their outputs.

Of course, the constant technology problem of can be overcome by specifying technological change exogenously, but this requires assumptions about the nature and rate of technological change that are difficult to make. There is an extensive literature on the subject of technological change and input/output systems (Miller and Blair, 1985). Many of the researchers who have considered this question have found that the assumption of constant technology is reasonable, at least in the short term.

Another limitation on input/output systems is the linear production functions that they assume for industries. This assumption requires that industrial outputs be exactly proportional to inputs. Linear production functions contradict the reality of increasing returns to scale, or increases in outputs more than exactly proportional to increases in inputs, that can be observed in many industries (Miller and Blair, 1985: 267). To the extent that industries are able to reduce their inputs of materials that ultimately result in GHG emissions (fossil fuels are the obvious example) while maintaining production at a given level from one time period to the next, then GHG emissions estimates made using the above model will be too high. The seriousness of this problem is an open question at this point.

A third drawback is the fact that input/output systems have no capacity to deal endogenously with behavioral changes that can result from changes in relative input prices. For example, if fuel oil prices were to rise rapidly and suddenly for whatever reason, industrial consumers would, to the extent possible, substitute other fuel products for oil in their input structure. Input/output systems, however, are unable to internally correct for the change in input structure that would result from this type of price-induced behavioral shift. As a consequence, input/output systems are not sufficient in themselves for modelling the changes in GHG emissions that might result, for example, from the application of a fuel tax based on carbon content. However, when combined with behavioral models that can supply the appropriate parameter changes, as is often the case in macroeconomic modelling systems, input/output systems play an integral part in the impact analysis of price-induced shifts in purchasing habits.

It is worth noting that the criticism that input/output systems, especially at the national level, are unable to capture the spatial quality of economic activity does not have much significance for the system proposed here. It is true that this system will not capture the spatial dimension of GHG emissions any more than any national input/output system captures the sub-national dimension of economic activity. Yet the nature of GHG emissions and climate change are such that a sub-national analysis of these emissions is of little interest, as air emissions quickly disperse and the impacts of climate change are of national and global rather than regional importance.

There can be no doubt that there are tradeoffs associated with the use of input/output systems. On the one hand are the high resolution and the direct/indirect impact analysis capabilities afforded by the

systems, and on the other the simplifications necessary to make them workable. These tradeoffs indicate the importance of not expecting more from input/output systems than they are able to deliver. For example, one ought to be cautious in the interpretation of activity projections made with an input/output model any further than four or five years from its base-year. Similarly, one ought to be somewhat suspect of regional analyses done using a national model. These caveats notwithstanding, the GHG emissions model proposed here has a number of valid uses, some of which are described in the next section.

3 Applications of the GHG Emissions System

One of the stated goals of this study is the linkage of GHG emissions to economic activity in a way that is useful to researchers and policy-makers. It is felt that the augmented input/output system proposed here meets this goal. A few examples of applications to which the system might be applied will, hopefully, convince the reader as well.

3.1 Development of Indicators

There is a great deal of interest today in the development of indicators that will allow people to gage progress in achieving desired environmental goals. In the case of GHG emissions it would be interesting to know, for example, how Canada's GHG emissions per unit of output change over time. The input/output system proposed here can be used to estimate this indicator, for the economy as a whole, for individual sectors within the economy, or even for individual commodities. Such an indicator could prove valuable in tracking the effect of a reduction scenario in achieving its goal.

3.2 Impact Analysis Using the Model

It will be possible once the GHG emissions model has been implemented to use it for sectoral impact analysis of emission reduction scenarios. That is, given the appropriate changes to the system parameters resulting from a specific emission reduction scenario, the system can be used to determine the impact, in terms of changes in sectoral GHG emissions, resulting from that scenario. This type of analysis will be very useful in determining the efficiency and effectiveness of different emissions reduction scenarios. There are two approaches that can be taken to analyses of this sort.

First, it will be possible to analyse the impact of emission reduction measures that change the technological structure of the economy. This is very easily done by comparing, for a given set of final demands, the total emissions resulting from the status quo technological structure in the economy and from

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the structure imposed by the reduction measures. Technological structure can be altered in two ways to effect GHG emission reductions: changes can be made directly to industrial processes themselves, or the fossil fuel inputs into the processes can be changed. In either case, since input/output systems are incapable of endogenously determining technological change, new emission coefficients must be supplied to the system exogenously.

The second category of emission reduction scenarios that can be analysed using the system are those which affect commodity final demands. A carbon tax placed on fossil fuels is the most obvious example. Such a tax would have the effect of reducing the consumption of fossil fuels and/or shifting consumption patterns among them. To assess the impact of a carbon tax, it is necessary to supply the system with a new matrix of final demands reflecting the shift in purchasing habits induced by the tax. The GHG emission estimate resulting from the pre-tax final demand matrix can then be compared to that resulting from the post-tax final demand matrix.

Of course, it is quite possible to perform impact analyses of emission reduction scenarios that combine elements of technological change as well as changes to final demand. No matter what reduction scenario is being modelled, however, the new emission coefficients and/or final demands must be supplied to the input/output system from an exogenous source.

3.3 GHG Emissions Content of Imports and Exports

The nature of atmospheric emissions is such that GHG emissions from individual nations will ultimately contribute to climate change on a global scale. One consequence of this is that to be truly effective at slowing change, any GHG reduction strategy will require the commitment of most world nations, and certainly all of the major GHG emitters. For such a strategy to be equitable, the portion of the total reduction that is assigned to each nation ought to reflect its share in global emissions. Given this, a valid concern that is likely to be expressed by many nations is the extent to which an individual nation is able to "export" its GHG emissions to other nations by importing emissions-intensive goods. If it can be shown that nation X has low domestic GHG emissions, but "exports" substantial emissions in the form of emissions-intensive imports, then the basis for negotiating X's share of total reductions is greater than it might appear at first glance. The extent to which Canada is effectively "exporting" GHG emissions in this way can be determined using the proposed GHG emissions model. This can be done by determining the increase in Canadian GHG emissions that would result if all of our imports for which domestic production capacity exists were produced at home rather than abroad.

Of course it is not just the emissions-intensity of imports that is of interest in the negotiation of international accords. Particularly for a country that is economically dependent on energy-intensive primary exports, as is Canada, it is also important to understand the contribution of exports to total emissions. If it can be shown that the nature of Canada's economic structure is such that the production of exported goods contributes significantly to our total emissions, this would place us it a different light vis a vis other nations at the negotiation table. Again, the GHG emissions system can be used to determine the extent to which the production of goods for export contributes to total Canadian emissions.

4 Data Sources

One of the difficulties with implementing input/output systems is their very large data requirement. This problem is particularly acute for environmental input/output systems, since environmental data are more scarce and often not as reliable as economic data. As many of the environmental data that are necessary for the GHG emissions system are not collected routinely by Statistics Canada, other sources must be sought for these data. In some cases, though, Statistics Canada does have the necessary primary data to estimate certain GHG emissions. The sub-sections below outline the status of data availability for each GHG.

A point that ought to be stressed before discussing data availability is that not all sources of GHG emissions can be included in the input/output system. The nature of such systems dictates that only those sources directly linkable with market activity can be incorporated in the data framework. Thus, important sources of GHG emissions such as forest fires, landfill sites, and wetlands, cannot be included in the system.

4.1 Carbon Monoxide (CO), Nitrogen Oxides (NO$_x$) and Volatile Organic Carbon Compounds (VOCs)

Through on-going data collection efforts at Environment Canada in recent years, there now exists a relatively comprehensive and accurate inventory of Canadian emissions of the following common air contaminants: CO, VOCs, NO$_x$, SO$_x$, total hydrocarbon (THC), and particulate matter (Kosteltz and Deslauriers, 1990). This inventory, which covers the year 1985[7] in its most recent edition, includes

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[7] As the inventory of common air contaminants represents the largest single data source for this study, 1985 will be used as the base-year for all economic and environmental data.

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emissions from the majority of industries, certainly all of the major industrial emitters, and from a good number of non-industrial sources as well (transportation, municipal incineration, and recreation, for example). As three of the six contaminants included in this inventory have been identified as GHGs (CO, NO_x and VOCs) and CH_4 emissions can be derived indirectly from the inventory, it represents a good portion of the data necessary to implement the system proposed here.

4.2 Carbon Dioxide (CO_2)

As well as the inventory of common air contaminants, Environment Canada has recently released an inventory of Canadian emissions of CO_2 (Jacques, 1990). This inventory covers 1987 CO_2 emissions from industrial processes, fuel consumption by stationary and mobile sources, waste incineration and slash burning.

In its current state the inventory will require some modification for use in this study. First of all, the data collected in the inventory are for 1987, whereas 1985 has been chosen as the base-year for data in this study. Second, the data are too highly aggregated to be used in a very highly disaggregated input/output system. Thus, the CO_2 emissions data will have to be re-estimated for 1985, using source data aggregated for use at the worksheet level of Statistic's Canada's input/output system. This re-estimation should not prove unreasonably difficult, for two reasons. First, CO_2 emission factors are reported in Environment Canada's CO_2 inventory and in OECD/IEA (1991), so there is no need for primary research to estimate these factors. Second, CO_2 emissions from economic activity are largely driven by the consumption of fossil fuels.[8] The most detailed data available on the supply and disposition of fossil fuels in Canada are accessible within Statistics Canada. These data will allow the determination of both the type and quantity of fossil fuel used by each of the industrial and final demand sectors at the worksheet level.[9] This, in turn, will allow the estimation of CO_2 emissions associated with fossil fuel consumption for each sector.

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[8] Only a few industries release CO_2 as a direct result of chemical or physical reaction in their production processes. The vast majority of CO_2 emissions from industrial sources are indirectly related to commodity outputs through the consumption of fossil fuels to meet energy requirements.

[9] The production of a detailed fossil fuel supply and disposition table is planned as a parallel study within Statistics Canada.

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4.3 Methane (CH$_4$)

There exists at this time no inventory of Canadian CH$_4$ emissions. This means that these emissions will have to be estimated for this study.

The major anthropogenic bacteriological sources of CH$_4$ have been identified as rice fields, ruminants and landfills, and the non-bacteriological sources as leakages from the production and transportation of natural gas, coal and oil; and, to a lesser extent, emissions from fuel combustion in automobiles and biomass burning (Wahlen et al., 1989; OECD/IEA, 1991). Emissions from commercial rice fields are likely to be minor in Canada, as there is very little rice farming. CH$_4$ emissions from ruminants may represent a significant portion of total Canadian emissions, as we keep a good deal of livestock in this country. Natural gas, coal and oil production, automobiles and biomass burning will all contribute, in varying degrees, to total Canadian emissions.

As noted above, the inventory of common air contaminants contains data on the emissions of VOCs and THCs. The difference between THC and VOC emissions can be attributed to CH$_4$ (Jacques, Personal Communication). Thus, for those sectors in the inventory for which both THC and VOC estimates are supplied, CH$_4$ emissions can be determined via this indirect route. In the case of sectors to which this method cannot be applied, it may be possible to use CH$_4$ emission factors from OECD/IEA (1991), coupled with appropriate Statistics Canada data to estimate emissions. More research on the possibilities for estimating CH$_4$ emissions is needed at this time.

4.4 Dinitrogen Oxide (N$_2$O)

At this stage of the study very little is known about N$_2$O emission sources or emission factors. One industrial source of N$_2$O that has been identified is nylon production (Jacques, Personal Communication); others will be identified from the literature. N$_2$O is also a product of chemical reactions between NO$_x$ and SO$_x$ during the combustion of fossil fuels. Obviously, more research is needed to identify sources and emission factors for N$_2$O.

4.5 Chlorofluorocarbons (CFC)

As with N$_2$O, little research has been done for this study on sources and emission factors for CFCs. Estimation of the emissions of this particular GHG promises to be the most difficult of all the gases, because, unlike other GHGs, CFC emissions are not a function of fossil fuel consumption, nor can their emission from industrial processes be based on simple stoichiometric relationships.

CFCs have two major uses that lead to atmospheric emissions. These are as blowing agents in the production of a wide variety of blown foam products (polyurethane foam, for example), and as heat transfer gases in many different types of refrigeration units.[10] The first use lends itself reasonably well to emission estimation, as it is at least theoretically possible to come up with an average factor relating the emission of CFCs from a given foam manufacturing process to the quantity of foam produced by that process. Whether or not the data, both technical and economic, that are necessary to put such an estimation procedure into practice exist is unclear. The second use of CFCs does not lend itself well at all to emission estimation, as the emission of coolant gases from refrigeration units is a function of a number of variables, including age and type of cooling unit, level of maintenance, degree of use and disposal method.

At this point it is not possible to state how CFC emissions will be estimated for this study. It may turn out that this is simply too difficult, both because of technical difficulties in developing emission factors and because of the lack of appropriate economic data. This would be unfortunate, as the heat capturing capacity of CFCs is on average 5 400 times that of CO_2, making them a significant contributor to global warming despite their very low atmospheric concentrations (OECD/IEA, 1991: 14).

In sum, while a good deal of the data necessary to develop the GHG emissions model proposed here are extant, there are still substantial portions of the data that remain to be collected. Some of these will no doubt prove easier to gather than others, and some will certainly remain uncollected at the end of this study. If, however, one of the outputs of this study is a list of data gaps, this will in itself be a useful contribution to the development of climate change policy in Canada.

5 Proposal for Augmenting Statistics Canada's Input/Output System

As stated above, Statistics Canada's national input/output system forms the basis for the GHG emissions system. The augmentations to Statistics Canada's system proposed here are based on work done in the early 1970's by Victor (1972). Victor's study supplemented Canadian input/output data for the year 1961 with data on the input and output of "ecologic commodities"[11] in the economy. Victor combined

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[10]   The use of CFCs as propellants in aerosol cans has been illegal in Canada for some years now.

[11]   Victor defines ecologic commodity inputs as materials taken from the environment for use in the economic system, whether the materials are privately owned as in the case of coal or common property as in the case of air. Materials in the environment become ecologic commodity inputs at their point of entry into the economy. Similarly, ecologic commodity outputs are defined as waste materials emitted to the environment from the economic system; waste

this environmental data with the existing economic input/output data to estimate an augmented input/output model that linked ecologic commodity inputs and outputs directly to the final demand for goods and services. In essence, this is exactly what is proposed for this study. However, as it deals solely with GHG emissions, this study will focus only on the output side of the ecologic commodity input/output balance. The reasons for limiting the scope of this study to only one side of this balance are twofold.

First, this study represents only one of a number of studies proposed by Statistics Canada under its Green Plan initiative. Other studies will analyse the second half of the ecologic commodities input/output balance. Ultimately the construction of a input/output system representing the complete Canadian economy-environment system is planned. Second, by limiting the scope of this study to GHG emissions, which is a well-defined issue of significant importance for Canadian environmental policy and for which there already exist many good data, it is hoped that the usefulness of input/output techniques for environmental analysis can be demonstrated in a reasonable period, without the need for a great deal of extra data collection.

5.1 Augmented Accounting Framework

The augmented accounting framework to be used in the study is shown in Figure 1.

The shaded columns in Figure 1 are recognisable as the standard accounting framework of the Canadian input/output tables (Statistics Canada, 1987: 18).[12] The augmentations required for this study, as defined below,[13] are found in the unshaded columns:

matrix GHGI (n x z) - an element, $\mathbf{ghgi}_{j\gamma}$, in this matrix represents annual emissions[14] of GHG γ ($\gamma = 1$ to z) from industry j (j = 1 to n);

vector h (n x 1) - an element, $\mathbf{h}_j$, of this vector represents total annual GHG emissions of industry j (j = 1 to n). Elements in this vector are formed from row sums of matrix GHGI;

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materials become ecologic commodity outputs upon their exit from the economic system (Victor, 1972: 54-55). This taxonomy reflects the materials-balance approach that Victor used in his study. See section 2 above.

[12] For those unfamiliar with Statistics Canada's input/output framework a brief description is presented in Appendix I.

[13] The definitions given here for the various matrices and vectors are intended to be as general as possible, in recognition of the fact that this framework can be used equally well at different levels of aggregation. A value of 7 is used for z in this study, as this is the number of gases that have been implicated in global warming.

[14] In this study all GHG emissions will be expressed in tonnes and all economic activity will be expressed in dollars.

matrices $\textbf{GHGF}_\gamma$ (z x [m x f]) - a set of z matrices, one for each GHG, in which an element, $\textbf{ghgf}_{ij\gamma}$, represents annual emissions of GHG γ ($\gamma = 1$ to z) associated with the consumption of commodity i (i = 1 to m) by final demand category j (j = 1 to f);[15]

vectors $\textbf{k}_\gamma$ (z x [m x 1]) - a set of z vectors, one for each GHG, in which an element, $\textbf{k}_{i\gamma}$, represents annual emissions of GHG γ ($\gamma = 1$ to z) associated with the consumption of commodity i (i = 1 to m) across all categories of final demand. Elements in these vectors are formed from row sums of matrices $\textbf{GHGF}_\gamma$;

Figure 1 - Augmented Input/Output Framework

	Commodities 1...m	Industries 1...n	Final Demand 1...f		Total	GHG 1...z	Total	
Commodities 1...m		U	F	$GHGF_\gamma$	q		k_γ	l
		u_{ij}	f_{ij}	$ghgf_{ij\gamma}$	q_i		$k_{i\gamma}$	l_i
Industries 1...n	V				g	GHGI	h	
	v_{ji}				g_j	$ghgi_{j\gamma}$	h_j	
Primary Inputs 1...p		YI	YF		n			
		yi_{ij}	yf_{ij}		n_i			
	q'	g'	e'	s_γ	t		r	
	q'_i	g'_j	e'_j	$s_{j\gamma}$	t_j		r_i	

Notes: Labels in upper case indicate matrices, while those in lower case indicate vectors and scalars;
                             Primed labels indicate transposition of the matrix or vector;
                             Greek subscripts refer to environmental variables, while latin subscripts refer to economic variables.

vector l (m x 1) - an element, l_i, of this vector represents total annual GHG emissions associated with the consumption of commodity i (i = 1 to m) across all categories of final demand. Elements in this matrix are calculated as $l_i = \sum\limits_{\gamma=1}^{z} k_{i\gamma}$;

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[15]   While the data requirements to complete seven 602 x 136 matrices may appear to be overwhelming, in fact the task is not unreasonably data-intensive. This is because most elements of these matrices will be zero, as the consumption of the majority of commodities by the majority of final demand categories results in no direct GHG emissions.

vector r (1 x z) - an element, r_i, of this vector represents total annual industrial emissions of GHG γ (γ = 1 to z). Elements in this vector are formed from the column sums of matrix GHGI;

vectors s_γ (z x [1 x f]) - a set of z vectors, one for each GHG, in which an element, $s_{\gamma j}$, represents annual emissions of GHG γ (γ = 1 to z) associated with the consumption of all economic commodities by final demand category j (j = 1 to f). Elements in these vectors are formed from the column sums of matrices $GHGF_\gamma$;

vector t (1 x f) - an element, t_j, of this vector represents total annual GHG emissions associated with the consumption of all economic commodities by final demand category j (j = 1 to f). Elements in this vector are calculated as $t_j = \sum\limits_{\gamma=1}^{z} s_{\gamma j}$.

5.2 GHG Emissions Model

Using the augmented accounting framework presented above it is possible to develop a model to estimate GHG emissions for any given year after the model's base-year (1985 in the present case). This model will consist of the sum of two terms: a term estimating GHG emissions resulting from the production of goods and services by industries, and a term estimating the emissions resulting from the consumption of goods and services by the various categories of final demand. Each of these is outlined below, starting with the industrial emissions term.

5.2.1 **Industrial Emissions** - Before developing the industrial GHG emissions term, it is useful to present, in unaugmented form, Statistics Canada's Open Output Determination Input/Output Model (Statistics Canada, 1987: 74), since this is the model on which this term is based:[16]

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[16]   For the sake of brevity no derivation of this model is presented here.

$$g = [(I - DB)^{-1}D][Fi].\qquad(1)$$

The elements of (1)[17] are defined as follows:

vector g (n x 1) - an element, g_j, of this vector represents total annual output of industry j (j = 1 to n);

matrix I (n x n) - an identity matrix;

matrix D (n x m) - an element, d_{ji}, of this matrix represents the jth industry's share (j = 1 to n) of the total marketed output of commodity i (i = 1 to m). Elements in this matrix, referred to as market share coefficients, are calculated from base-year data as $d_{ji} = v_{ji}/q_j$[18];

matrix B (m x n) - an element, b_{ij}, of this matrix represents the input of commodity i (i = 1 to m) used per unit of output of industry j (j = 1 to n). Elements in this matrix, referred to as direct input coefficients or technical coefficients, are calculated as $b_{ij} = u_{ij}/g_j$;

matrix F (m x f) - an element, f_{ij}, in this matrix represents the annual demand for commodity i (i = 1 to m) by final demand category j (j = 1 to f);

vector i (f x 1) - a unity column vector.[19]

The elements of matrices D and B can be calculated from industrial input/output relationships for a base-year. Once these coefficients have been determined, and assuming that they remain constant over time, it is possible to estimate the levels of industry output (vector g) required to satisfy an exogenously

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[17]   The version of the output determination model shown here does not include allowances for leakages from domestic industrial output to competing imports, government production and/or withdrawals from inventoried goods. For the illustrative purposes of this proposal, the simplified version of the model presented here is quite sufficient.

[18]   Vector q (m x 1) contains elements, q_j, that represent the total annual use of commodity j (j = 1 to m) by industries and final demand categories.

[19]   An italic i in this study indicates a unity column (i) or row (i') vector, of appropriate dimension, used to generate matrix column sums (premultiplication) and row sums (postmultiplication).

specified set of future commodity final demands (matrix F) using (1). With the basic Statistics Canada input/output model presented, the relatively simple augmentations required to develop it into the GHG industrial emissions term can now be presented. Before presenting these augmentations, however, it is useful first to clarify the nature of industrial GHG emissions.

There are two types of industrial GHG emissions: those associated directly with the consumption of fossil fuels by industries, and those associated directly with the production processes used by industries. An example of the latter type is CO_2 emissions resulting from the calcination of limestone in the production of cement. Assuming that both types of industrial GHG emissions are linearly related to levels of production, the following relationship can be stated:

$$GHGI' = [\Phi B_{ff} + \Omega]\bar{g}. \tag{2}$$

The elements of (2) are defined as follows:

matrix $\bar{g}$ (n x n) - a diagonal matrix[20] of total industry output, formed from the diagonalisation of vector g;

matrix GHGI' (z x n) - the transpose of matrix GHGI;

matrix Ω (z x n) - elements, $\omega_{\gamma j}$, in this matrix, referred to in this study as direct industrial emission coefficients, represent direct emissions of GHG γ (γ = 1 to z) per unit of output of industry j (j = 1 to n). These coefficients are calculated from base-year data as $\omega_{\gamma j} = ghgi_{ij} / \bar{g}_{jj}$.

matrix Φ (z x m_{ff})[21] - elements, $\phi_{\gamma j}$, in this matrix, referred to in this study as fossil fuel emission coefficients, represent emissions of GHG γ (γ = 1 to z) per unit of consumption of fossil fuel j (j = 1 to m_{ff}). These coefficients will be drawn from the scientific literature;

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[20]   A barred label is used to indicate a diagonal matrix in this study.

[21] m_{ff} is the number of fossil fuel commodities in the input/output system.

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matrix B_{ff} (m_{ff} x n) - elements, $b_{ff,ij}$, in this matrix, referred to in this study as fossil fuel direct input coefficients, represent the use of fossil fuel i (i = 1 to m_{ff}) per unit of output of industry j (j = 1 to n). This matrix is equivalent to the rows in matrix B that show the direct input coefficients for fossil fuels.[22]

Given the relationship between GHG emissions and industrial activity stated in (2), all that is necessary to augment (1) into the industrial emissions term is to diagonalise g in (1) and to substitute into (2) for $\bar{g}$:

$$GHGI' = [\Phi B_{ff} + \Omega] \overline{[(I-DB)^{-1}D][Fi]}. \tag{3}$$

Once matrices B (and therefore, B_{ff}), D, Ω and Φ have been determined from base-year data, (3) can be used to estimate the industrial GHG emissions resulting from any exogenously specified matrix of commodity final demands.

5.2.2 **Final Demand Emissions** - It is proposed for this study that a unique GHG emission coefficient will be estimated for the consumption of each commodity by each final demand category. This recognises that the consumption of the same commodity by different categories of final demand can result in different GHG emissions. For example, the consumption of heating fuel by households may not result in the same unit GHG emissions as does the consumption of the same commodity for institutional heating purposes. While it is in theory possible that a unique emission coefficient can be calculated for the consumption of each commodity by each final demand category, it

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[22]   The method employed here differs somewhat from that used in Victor's study. In the latter all ecologic outputs are assumed to be directly related to commodity outputs, whereas the method employed here allows for GHG emissions to be linked to either commodity outputs or inputs. While the two approaches yield the same results, the method used here has the advantage that it allows changes in GHG emissions resulting from input structure changes (eg. a change from coal to natural gas by the electricity generation industry) to be dealt with in a more explicit manner.

remains to be seen whether the necessary data are available.[23] Given that it is possible to estimate these unique emissions coefficients, and assuming that final demand GHG emissions are linear functions of consumption levels, the following simple relationship can be stated:

$$GHGF_\gamma = \Lambda_\gamma \otimes F. \tag{4}$$

The elements of (4) are defined as follows:

matrices GHGF$_\gamma$ and F - as above;

matrices Λ_γ [z x (m x f)] - elements in these z matrices, $\lambda_{ij\gamma}$, referred to in this study as final demand emission coefficients, represent emissions of GHG γ (γ = 1 to z) per unit of consumption of commodity j (j = 1 to m) by final demand category i (i = 1 to f). These coefficients will be taken from the scientific literature.

The $\otimes$ indicates that matrices Λ_γ and F are to be multiplied element-wise, rather than row-by-column as in standard matrix multiplication.

Once the coefficients in Λ_γ have been determined, it is possible to estimate the GHG emissions associated with any exogenously specified set of commodity final demands using (4).

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[23] The treatment of emissions from final demand is another area in which the method proposed for this study differs from that used in Victor's study. In the latter it was assumed that the consumption of a given commodity results in the same ecologic commodity outputs no matter what the consuming category of final demand is.

Having presented both terms of the GHG emissions model they can now be combined, in slightly modified form,[24] as follows:

$$ghg_{total} = \left[[\Phi B_{ff} + \Omega] \overline{[(I-DB)^{-1}D][Fi]} \right] i + \sum_{\gamma=1}^{z} a_{\gamma} \left[i'(\Lambda_{\gamma} \otimes F)i \right] \tag{5}$$

All elements in (5) have been defined above, except for:

vector ghg$_{total}$ (z x 1) - elements in this vector, **ghg**$_{total\,\gamma}$ represent total annual emissions of GHG γ (γ = 1 to z) associated with all production and consumption activities in the Canadian economy for a given set of commodity final demands;

vectors a$_{\gamma}$ [z x (z x 1)] - a set of z vectors in which z-1 elements are equal to zero and a single element is equal to one. The position of the single unity element is determined by the value of γ.

With appropriate base-year economic and environmental data, the coefficients in matrices D, B (and B$_{ff}$), Ω, Φ, and Λ_{γ} can be estimated. Assuming that these coefficients remain stable over time, (5) can be used to estimate economy-wide GHG emissions given any exogenously specified set of commodity final demands.

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[24]   The slight modifications to (3) and (4) are necessary to convert them from matrices into vectors of dimension (z x 1). Postmultiplication of (3) by i performs a simple row summation on matrix GHGI'. Pre and postmultiplication of (4) by i produces a set of z scalars equal to the element-wise summations of matrices GHGF$_{\gamma}$. Premultiplication of these scalars by a$_{\gamma}$ and the summation of these products yields the appropriate vector form for this term.

6 Summary

In summary, the following relationships useful for estimating GHG emissions have been presented above:

$$GHGI' = [\Phi B_{ff} + \Omega]\overline{[(I-DB)^{-1}D][Fi]}; \qquad (3)$$

$$GHGF_\gamma = \Lambda_\gamma \otimes F; \qquad (4)$$

$$ghg_{total} = \left[[\Phi B_{ff} + \Omega]\overline{[(I-DB)^{-1}D][Fi]}\right]i + \sum_{\gamma=1}^{z} a_\gamma \left[i'(\Lambda_\gamma \otimes F)i\right] \qquad (5)$$

Matrices D, B (and B_{ff}), Ω, Φ and Λ_γ can all be estimated from base-year data. Once these five matrices are complete, and a final demand matrix, F, has been supplied to the model, the above relationships can be used in the following ways:

(3) can be used to estimate a matrix of annual GHG emissions, GHGI, resulting from industrial production activities;

(4) may be used to estimate z matrices, $GHGF_\gamma$, each showing the annual emissions of a different GHG resulting from the consumption of goods and services by final demand categories; and

(5), the GHG emissions model, can be used to estimate a vector of total annual emissions of each of the z GHGs, ghg_{total}, from economy-wide production and consumption activities.

Many of the data necessary to implement the GHG emissions model are available at the national level for the year 1985. There is still the need, however, to develop disaggregated figures for the consumption of fossil fuels to allow for detailed CO_2 emissions to be estimated. Disaggregated fossil fuel

supply and disposition data are to be developed within Statistics Canada as a parallel study to the one presented here. Data on the emissions of N_2O, CFCs and CH_4 will require further research.

Appendix I - Statistics Canada's Input/Output Framework

The standard framework of Statistics Canada's national input/output system is presented in Figure I-A:

Figure I-A - Statistics Canada Input/Output Framework

	Commodities 1...m	Industries 1...n	Final Demand 1...f	Total
Commodities 1...m		U u_{ij}	F f_{ij}	q q_i
Industries 1...n	V v_{ji}			g g_j
Primary Inputs 1...p		YI yi_{ij}	YF yf_{ij}	n n_i
	q' q'_i	g' g'_j	e' e'_j	

Notes: Labels in upper case indicate matrices, while those in lower case indicate vectors and scalars; Primed labels indicate transposition of the matrix or vector.

Source: Statistics Canada, 1987: 18.

The elements of this framework are defined as follows:

matrix V (n x m) - an element, v_{ji}, in this matrix represents the dollar value of the annual production of commodity i (i = 1 to m) by industry j (j = 1 to n). This matrix is commonly referred to as the make matrix;

matrix U (m x n) - an element, u_{ij}, in this matrix represent the dollar value of the annual use of commodity i (i = 1 to m) by industry j (j = 1 to n). This matrix is commonly referred to as the use matrix;

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matrix F (m x f) - an element, f_{ij}, in this matrix represents the dollar value of annual purchases of commodity i (i = 1 to m) by final demand sector j (j = 1 to f).[25] This matrix is commonly referred to as the final demand matrix;

vector q (m x 1) - an element, q_i, in this vector represents the dollar value of the total annual use of commodity i (i = 1 to m) by industries and final demand sectors. Elements in this vector are formed from the row sums of matrices U and F;

vector q' (1 x m) - the transpose of vector q above;

vector g (n x 1) - an element, g_j, in this vector represents the dollar value of the total annual production of industry j (j = 1 to n). Elements in this vector are formed from the row sums of matrix V;

vector g' (1 x n) - the transpose of vector g above;

matrix YI (p x n) - an element, yi_{ij}, in this matrix represents the dollar value of the annual use of primary input i (i = 1 to p) by industry j (j = 1 to n);[26]

matrix YF (p x f) - an element, yf_{ij}, in this matrix represents the dollar value of the annual use of primary input i (i = 1 to p) by final demand sector j (j = 1 to f);

vector n (p x 1) - an element, n_i, in this vector represents the dollar value of the total annual use of primary inputs by industries and final demand sectors;

vector e' (1 x f) - an element, e'_j, in this vector represents the dollar value of the total annual use of commodities and primary inputs by final demand sector j (j = 1 to f).

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[25] The final demand categories included in the input/output framework are: personal expenditure on goods and services, fixed capital formation expenditures, values of withdrawals and additions to inventories of goods, gross government current expenditures, value of domestic exports, value of re-exports of previously imported goods, the value of imports (as a negative demand for domestically produced goods), and the value of government revenues from sales of goods and services (also as a negative demand).

[26] The primary inputs that are included in the input/output framework are: commodity and other indirect taxes, government subsidies (a negative input), wages and salaries, supplementary labour income, net income of unincorporated business and other operating surplus.

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4. "Incorporation dans les comptes des revenus et dépenses d'une décomposition de l'investissement en machines et matériel", tiré à part de *Comptes nationaux des revenus et dépenses*, troisième trimestre 1989.

5. "Les nouvelles estimations provinciales de la demande intérieure finale en prix constants", tiré à part de *Comptes nationaux des revenus et dépenses*, quatrième trimestre 1989.

6. "Produit intérieur brut en termes réels: sensibilité au choix de l'année de base", tiré à part de *l'Observateur économique canadien*, mai 1990.

7. "Révisions des données de la période 1986-1989 dans les comptes nationaux des revenus et dépenses", tiré à part de *Comptes nationaux des revenus et dépenses*, premier trimestre 1990.

8. "Les indices de volume dans les comptes des revenus et dépenses", tiré à part de *Comptes nationaux des revenus et dépenses*, premier trimestre 1990.

9. "Un nouvel indicateur des tendances de l'inflation par les salaires", tiré à part de *l'Observateur économique canadien*, septembre 1989.

10. "Tendances récentes des salaires", tiré à part de *l'Emploi et le revenu en perspective*, hiver 1990.

11. "Le système de comptabilité nationale du Canada et le système de comptabilité nationale des Nations Unies", tiré à part de *Comptes nationaux des revenus et dépenses*, troisième trimestre 1990.

12. "La répartition des impôts indirects et des subventions aux composantes de la dépense finale", tiré à part de *Comptes nationaux des revenus et dépenses*, troisième trimestre 1990.

13. "Le traitement de la TPS dans les comptes des revenus et dépenses", tiré à part de *Comptes nationaux des revenus et dépenses*, premier trimestre 1991.

14. "L'introduction des indices de volume en chaîne dans les comptes des revenus et dépenses", tiré à part de *Comptes nationaux des revenus et dépenses*, premier trimestre 1991.

15. "Révisions des données de la période 1987-1990 dans les comptes nationaux des revenus et dépenses", tiré à part de *Comptes nationaux des revenus et dépenses*, deuxième trimestre 1991.

16. "Estimations en volume du commerce international des services commerciaux", tiré à part de *Comptes nationaux des revenus et dépenses*, troisième trimestre 1991.

17. "Le défi de la mesure dans les comptes nationaux", tiré à part de *Comptes nationaux des revenus et dépenses*, quatrième trimestre 1991.

18. Étude sur le flux des services de consommation générés par le stock de biens de consommation, tiré à part de *Comptes nationaux des revenus et dépenses*, quatrième trimestre 1991.