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Greenhouse gas emissions in Canada and Japan: Sector-specific estimates and managerial and economic implications[☆]

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Abstract

Many firms generate large amounts of carbon dioxide and other greenhouse gases when they burn fossil fuels in their production processes. In addition, production of raw materials and other inputs the firms procure for their operations also generates greenhouse gases indirectly. These direct and indirect greenhouse gas emissions occur in many sectors of our economies. In this paper, we first present sector-specific estimates for such greenhouse gas emissions. We then show that estimates for such sector-specific greenhouse gas emissions are often required for various types of corporate as well as public policy analyses in both domestic and international contexts. Measuring greenhouse gas emissions resulting from firms' multi-stage production processes in a multi-sector context is relevant for policies related to the Kyoto protocol, an international agreement to limit global greenhouse gas emissions. For example, since the protocol allows firms to engage in trading and offsetting of their greenhouse gas emissions across national borders, provided that emissions are correctly measured, the firms can take advantage of such trading schemes by placing their energy-intensive production facilities globally and strategically. We present several case studies which illustrate the importance of this and other aspects of greenhouse gas emissions in firms' environmental management. We also argue that our modeling and estimation methods based on input–output analyses are suitable for the types of research goals we have in this paper. Our methods are applied to data for Canada and Japan in a variety of environmental management circumstances.

Keywords: Global warming; Kyoto protocol; Firms' greenhouse gas emissions; FDI; Canada; Japan

1. Introduction

According to the Kyoto protocol developed countries must reduce their carbon dioxide and other greenhouse gas emissions (referred to collectively in this paper as CO_2 emissions) by specified amounts by target dates. More specifically, under the terms of the protocol, Canada and Japan, for example, must bring down their CO_2 emissions levels over the period of 2008–2012 to a level which is 6% below their respective 1990 levels.[3] Canada's largest trading partner, the United States, has opted not to sign the protocol. However, Japan has signed, and Japan is also Canada's important trading partner.[4]

In Canada, Japan and some other countries that have agreed to the Kyoto protocol, the mechanisms for achieving the target reductions in emissions are still being determined. A main objective of this paper is to show the importance of taking account of the multi-stage and multi-sector nature of firms' production processes in implementing

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[3] This means that Canada must reduce its CO_2 emissions by 240 million tons a year by 2010 (Government of Canada, 2000). Similarly, Japan must reduce the current (2002) level of CO_2 emissions by 14% by 2010.

[4] EU, which is a significant trading partner for Japan as well as Canada, has also ratified the protocol.

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the protocol requirements. This is because firms' operations in procurement of raw materials, manufacturing, distribution, usage and disposal involve many economic sectors of domestic and international economies in multiple stages. An Input–Output (I–O) model provides a framework for doing this. Differing amounts of CO_2 emissions are produced in many economic sectors at different stages in production. For example, the use of electric power in the household sector generates little or no CO_2, but production of electric power can produce considerable amounts.

We use I–O analysis for tracing the production of CO_2 emissions through the various stages of production.[5] The design of policies for achieving the promised reductions can be facilitated by allowing for the multi-stage and multi-sector nature of production processes and the fact that companies need not carry out all production activities at the same location.[6] We use a Canada–Japan bilateral trade and economic cooperation framework to make a number of policy and methodology-related points. Both these countries have agreed to the Kyoto protocol, and hence have a common reason to be interested in trade arrangements that might ease the burdens of meeting the Kyoto emissions reduction targets. Moreover, the differences in the Canadian and Japanese economies are helpful for illustrating the points of interest.[7]

The Japanese government, like the governments of most developed EU countries, now requires corporations to account for the CO_2 emissions their corporate operations generate and to try to achieve substantial year-by-year reductions in their CO_2 emissions over time. Such reductions in CO_2 emissions must also be accurately measured. We show that our methodology presented in this paper is an effective tool for measuring CO_2 emissions associated with corporate activities. Precise measurement of CO_2 emissions generated by corporate activities is an important aspect of the government policies in order to achieve the greenhouse gas emission reductions mandated by the Kyoto protocol.

The total amounts of CO_2 emissions have been increasing for both Canada and Japan. Over the period 1985–1995 CO_2 emissions climbed in volume from 435 million tons in 1985 to 478 million tons in 1990 and to 500 million tons in 1995 for Canada and from 895 million tons in 1985 to 1122 million tons in 1990 and to 1213 million tons in 1995 for Japan. The business sector generates over 80% of total CO_2 emissions for both Canada and Japan, as in many developed countries.[8] In both countries, electric power generation generates most emissions.[9]

1.1. Estimating CO_2 emissions

In this paper we first estimate, using I–O analysis, CO_2 emissions in the 1990s that are attributable to Canadian and Japanese firms in various economic sectors.[10] We then use these estimates in our case studies later in the paper. For this reason we explain briefly how we obtain these estimates.

Using 1990 and 1995 Canadian and Japanese I–O tables and emissions data, we have estimated total CO_2 emissions for each of the I–O table components of the business sectors for Canada and for Japan: 479 commodity sectors for Canada and 405 commodity sectors for Japan for 1990.[11] Our sector-specific estimates take account of the emissions from various stages of production processes including the emissions associated with production of the raw materials and intermediate product inputs. For example, whereas auto assembly produces very little in

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[5] Leontief (1970, 1986) proposed that input–output (I–O) analysis is a potentially useful tool for analyzing the environmental implications of economic activities. Details of our model are given in the Appendices along with a discussion of the limitations of I–O models as a policy tool. Generally speaking, these models assume fixed technologies and relative prices. Hence, policy makers need to proceed with caution when these models are used, for example, to analyze the effects of price changes including price changes that are in response to changes in technologies over the period of analysis.

[6] This is a relevant issue for Japan, since Japan already adopted many energy saving measures since the oil crises of the 1970s and has relatively little slack left for improving energy efficiency in its industrial and household sectors.

[7] Multi-national firms from EU and Japan, for example, are often required by their home governments to make sure that their new investment in energy-intensive projects will not add new CO_2 emissions to their nations' total emissions. The firms typically cope with this kind of CO_2 emissions requirement by locating their production facilities outside their home countries and also by buying CO_2 emission rights from developing nations. This paper provides a practical framework in which multi-national firms can analyze this kind of global CO_2 emission problem.

[8] Since our focus is CO_2 emissions in the business sector, we do not include in our calculations the CO_2 emissions generated, for example, when heating oil, natural gas or auto gas are burned in the household sector. We do include, however, the emissions generated when these fossil fuel products are produced (including production of what the household sector uses). We also include emissions from fossil fuels used to generate electric power.

[9] CO_2 emissions from electric power generation increased in volume from 84 million tons in 1985 to 95 million tons in 1990 and to 101 million tons in 1995 for Canada, and from 275 million tons in 1985 to 340 million tons in 1990 and to 365 million tons in 1995 for Japan.

[10] The sample years used are 1990 and 1995 (most recent year for which all relevant data for the present research are available for Canada).

[11] Our analysis requires extensive sector-specific CO_2 emission data. The emissions data used are described in Statistics Canada (1996a, 2000) for Canada and in Yoshioka et al. (1996) and Hayami et al. (2000) for Japan. (See Appendix B for details.) If our approach is to be used for forecasting purposes, it is important to bear in mind the standard I–O assumption that the input–output matrix (matrix A in Appendix A) is stable over time. For broadly defined sectors there is evidence that matrix A changes very slowly (Carter, 1970), though for narrowly defined commodity sectors such as the ones used in this paper technical change could cause important changes in some elements of A even within a 5-year period. This does not mean that our model cannot be used for forecasting purposes. It is a limitation that must be remembered in interpreting model results. We also note that not all technical change would necessitate adjustments in the results obtained with our approach. For example, there has been rapid technical change in Japan in the electronics and computer industries but these industries have had little impact on Japanese CO_2 emissions.

Table 1
Business sectors with large amounts of CO_2 emissions: Canada and Japan, 1990 and 1995[a]

Canada	1995	1990	Japan	1995	1990
Cement	13.76	11.53	Cement	10.16	12.29
Electric power	4.88	5.44	Self-Power gener.	9.27	12.24
Pipeline transport.	3.74	2.71	Coal products	7.51	5.42
Diesel and fuel oil	3.31	2.79	Pig iron	6.23	6.10
Motor gasoline	3.29	2.79	Ammonia	3.57	2.30
Lime	3.14	2.50	Crude steel	3.39	4.04
Natural stone prod.	3.14	2.50	Salt	2.25	4.15
Mineral wool build.	3.14	2.50	Ferro alloy	2.23	4.10
Ready-mix concrete	2.94	3.80	Ready-mix concrete	2.20	3.14
Asphalt compound	2.86	2.74	Electric power	2.19	3.47
Lubricating oils	2.58	2.78	Hot rolled steel	2.08	2.83
Iron ores and con.	2.54	2.95	Industrial soda chem.	1.94	2.90
Flat iron and steel	2.45	3.29	Other sanitary serv.	1.85	3.06
Crude mineral oils	2.38	2.21	Cast and forged mat.	1.81	2.06
Natural gas	2.38	2.21	Miscellaneous ceramics	1.75	3.37
Air transport	2.31	2.09	Crude steel (elec. furnace)	1.65	2.87
Liquid petroleum gas	2.31	2.20	Pulp 1.56	1.31	
Petrochemical feed	2.25	2.79	Air transport	1.41	1.30
Chlorine	2.24	2.34	Foreign and Japanese paper	1.40	2.19
Oxygen	2.24	2.34	Paperboard	1.35	1.66

[a] Numbers are estimated amounts of emissions of CO_2 in kilo tons generated per million US dollars worth of production. The exchange rates used are: 144.79 (99.68) yen per US dollar for 1990 (1995) and 1.1668 (1.32724) Canadian dollars per US dollar for 1990 (1995).

the way of CO_2 emissions, production of the steel that goes into automobiles and transport of automobiles to market produce substantial amounts of CO_2 emissions. For illustrative purposes we show in Table 1 the 20 commodity sectors responsible for the largest quantities of CO_2 emissions per million US dollars worth of output.[12] We then show in Table 2[13] CO_2 emissions per unit volume of output rather than per unit value for selected commodities for which we have output quantity data for both Canada and Japan.[14] These sector-specific emission estimates will be used in our case studies to follow.

We present in the rest of the paper a number of inter-related case studies which focus on certain CO_2 emissions-related sector-level managerial issues in the context of the Kyoto protocol objectives. In Section 2, we show how I–O analysis can be used to evaluate domestic recycling policies in Japan in terms of CO_2 emissions. In Section 3, we discuss CO_2 emissions associated with location choice for production facilities of photovoltaic power generation systems. This case study discusses location choice in terms of Japanese firms' foreign direct investment (FDI) but no foreign trade is explicitly modeled.

In Section 4 we first present two case studies, which require a methodology to calculate CO_2 emissions arising from bilateral foreign trade explicitly. We present such a methodology in this section and then apply it to two case studies: calculating CO_2 emissions associated with Canada's imports of Japanese passenger cars and Japan's imports of Canadian pulp.[15] These two case studies are of interest because they exploit the two countries' comparative advantages. Such comparative advantages are reflected by the fact that Japan imports large quantities of energy-intensive natural resources from Canada, while Canada buys large quantities of manufactured goods from Japan. Given that CO_2 emissions rights have commercial value and are being traded, these case studies are of potential interest for both profit-maximizing firms and government policy makers. In the second part of Section 4 we show that, using the I–O model incorporating the above methodology, it is possible to evaluate numerically the effects on domestic and trading partner's prices of a carbon tax introduced in one country. Section 5 concludes.

2. Japanese recycling policy and CO_2 emissions

Transport of material inputs to production facilities and transport of products to markets can result in CO_2 emissions that must be counted as part of the full emissions for that product. For example, paper recycling was introduced to begin with for environmental reasons but, as we show below, its environmental effectiveness crucially depends on how much CO_2 emissions are generated in transporting the paper to be recycled.

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[12] We used (A.5) in Appendix A to derive Table 1. Complete estimation results are available on request from the authors.

[13] We used (A.5) in Appendix A to derive Table 2.

[14] The results in Table 2 are more suitable for making inter-country comparisons than the results shown in Table 1. Some of the differences between the two countries that are apparent from Table 2 are interpretable in light of recognized inter-country differences in production conditions and methods. (See Hayami and Nakamura, 2004).

[15] The Kyoto protocol provides some flexibility for allowing for international substitutions of CO_2 emissions.

Table 2
Firms' CO_2 emissions (in kilo tons) per unit volume of output, 1990 and 1995[a]

Canada	1995	1990	Japan	1995	1990
Coal (1000 t)	0.04	0.03	Coal (1000 t)	0.10	0.10
Natural gas (million m^3)	0.18	0.10	Natural gas (million m^3)	0.18	0.10
Gasoline (1000 kl)	0.64	0.55	Gasoline (1000 kl)	0.34	0.29
Wheat unmilled (1000 t)	0.14	0.12	Wheat and barley (1000 t)	0.34	0.29
Eggs in the shell (1000 t)	0.93	1.62	Hen eggs (1000 t)	0.35	0.45
Hogs (1000 head)	0.13	0.21	Hogs (1000 head)	0.71	0.09
Cattle and calves (1000 head)	0.22	0.36	Beef cattle (1000 head)	1.93	—
Logs, poles, pilings (1000 m^3)	0.02	0.03	Logs (1000 m^3)	0.04	0.03
Fish and seafood (1000 t)	0.14	0.14	Coast. & dist. fishing (1000 t)	2.15	1.70
Salt (1000 t)	0.02	0.02	Salt (1000 t)	0.90	0.71
Beer, incl. coolers (100 kl)	0.07	0.04	Beer (100 kl)	0.06	0.05
Pulp (1000 t)	0.41	0.44	Pulp (1000 t)	1.18	0.75
Newsprint paper (1000 t)	0.77	0.82	Newsprint paper (1000 t)	1.92	1.99
Cement (1000 t)	0.95	1.32	Cement (1000 t)	0.84	0.76
Crude steel (1000 t)	0.86	—	Crude steel (1000 t)	1.26	1.14
Crude steel (elec. furn., 1000 t)	—	—	crude steel (elec. furn., 1000 t)	0.71	1.13
Aluminum (primary forms, 1000 t)	1.73	2.00	Aluminum (regenerated, 1000 t)	2.54	1.32
Electric power generation (gwh)	0.16	0.20	Electric power generation (gwh)	0.38	0.42

[a] Numbers for CO_2/volume are estimated amounts in kilo tons of emission per unit volume of production.

Japan has been promoting public policy measures to recycle many types of consumer products including paper products. The Japanese Recycling Act of 1997 requires all supermarket stores to collect and sort used paper products (e.g., milk cartons and cereal packages) and recycle them. Significant amounts of both public and private R&D funds have been spent on the development of technologies that facilitate recycling of these products. Recycling has been promoted in Japan for the purpose of reducing the quantity of solid waste. In Japan, many localities face severe limitations on space for solid waste disposal. These laws, however, do not address the issue of the CO_2 emissions that are generated as a consequence.

Japan consumes a large quantity of paper. Indeed, its per capita consumption of paper is the world's seventh largest. Japan is also the largest consumer of recycled paper in the world (17.92 million tons).[16] In 2000, Japan recycled 58% of paper products, and 57% of pulp input in its paper production was recycled paper pulp (with the rest being virgin pulp).[17] CO_2 emissions can be reduced by using recycled paper because production of recycled paper does not result in the burning of the byproducts of virgin pulp production (pulp black liquor and waste). However, collecting paper products for recycling from households and business firms at the municipality level results in transportation activities and these activities consume significant amounts of fuel, resulting in CO_2 emissions.

Using the Japanese I–O model and emissions data for 1995, we conducted simulation experiments to assess the impact of the input ratio between new and recycled paper pulp on the total CO_2 emission from paper producing firms (Table 3). Required transportation energy levels were fixed at various plausible levels in the reported simulations. We used the current (industry-average) ratio of new to recycled pulp of 52:48 and specified the required unit transportation energy as 121 Megacalories (Mcalories) per ton for the bench mark case. Increasing the recycled pulp content from the bench mark level to the new to recycled pulp ratio of 28:72 while holding the unit transportation energy level fixed at 242 Mcalories per ton reduces total emissions. We found no improvement in emissions, however, beyond the ratio of 33:67 for new to recycled pulp. For Japan we estimate that a ton of truckload can be transported for about 360 km using 725 Mcalories. Considering the amounts of transportation required to collect and transport recycled paper, we also conducted simulation experiments using alternative unit transportation energy levels while fixing the new to recycled pulp input ratio at 28:72. As the required transportation energy level increases from 242 to 1449, the total emission also increases by 6 million tons.

We have also calculated the shadow prices for newsprint quality and high-quality paper produced using recycled pulp. Given the low price for recycled newsprint, the shadow price of newsprint paper using recycled pulp does not exceed the bench mark price (1.00) until the required unit transportation energy level exceeds 725 Mcalories/ton. On the other hand, the shadow price of high-quality paper is considerably higher than the bench mark level for all unit

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[16] Japanese local governments collected at most 11 types of wastes separately in 2001. The waste collected for recycling in 2001 included paper packages (49,723 ton), corrugated cardboards (448,855 ton), and paper milk cartons (13,136 ton). (http://www.env.go.jp/recycle/kaden/fuho/index.html).

[17] These figures were: 46% and 24.5% for Canada, 40.1% and 5.2% for Finland, 33.9% and 51% for China, 46.6% and 57.8% for France and 48.7% and 42% for the US (METI (2001)). The new vs. recycled pulp ratio is a standard parameter to measure the degree of environmental friendliness in both company and government policy decision processes.

Table 3
Japanese firms' use of recycled paper pulp: simulation results (million tons)

New vs. recycled pulp ratio	52:48 (bench mark)	42:58	33:67	24:76	28:72	28:72	28:72	28:72
Unit transport energy parameter for recycling (Mcal cal per ton)	121	242	242	242	242	725	966	1449
1. CO2 emission due to fossil fuels	991	992	994	996	995	997	998	1001
2. CO2 emission due to pulp black liquor and discards	14	13	9	7	8	8	8	8
3. Total emission[a]	1005	1005	1003	1003	1003	1005	1006	1009
Recycled newsprint replaces new pulp as a raw material								
Newsprint shadow price[b]	1.00	—	—	—	0.98	1.00	1.02	1.05
Recycled high-quality paper with whiter than newsprint color replaces new pulp as a raw material								
High-quality paper shadow price[b]	1.00	—	—	—	1.08	1.105	1.12	1.145

[a] These figures are the sums of the figures in rows 1 and 2.

[b] The paper price for the benchmark case is set equal to one.

transportation energy levels. This reflects the high cost of recycling high-quality paper.

Japan's paper recycling policy involves 3246 local governments, but a relatively small number of these separately collect or sort out different types of paper products for recycling. The production of high-quality paper requires high-quality paper to be recycled separately. Our simulation results suggest that significant governmental subsidies may be needed to expand the paper recycling movement to support the production of high-quality paper.[18]

3. Location choice of the production site of photovoltaic power generation systems and CO_2 emissions

Photovoltaic (PV) technology is one of the most promising methods of power generation that can reduce CO_2 emissions.[19] In this section we compare the CO_2 emission performance of Canadian and Japanese production facilities of photovoltaic power cells and modules (often called PV units or PV systems also) using data for 1995.

Several types of PV production technologies are available now: monocrystalline silicon, polycrystalline silicon, amorphous silicon, ribbon silicon, cadmium-tellurium (CdTe), $CuInSe_2$ (CIS), their thin-film types and the hybrid types.[20] At this time the two most popular types of cells produced are polycrystalline silicon cells (with an annual global electricity generating capacity of about 128 MW in 2000) and monocrystalline silicon cells (annual electricity output of about 90 MW in 2000). Other types of photovoltaic cells produced were estimated to have an annual generating capacity of about 60 MW in total in 2000.

Our analysis uses actual production data for polycrystalline solar cells.[21] Production of this type of cell is done in three stages: (1) solar-grade silicon (SOG-Si) production process (including wafer production), (2) cell processing and (3) module processing. For example, Table 4 shows the input requirements in quantities of raw materials and energy for the first SOG-Si production process.[22] Figs. in Table 4 do not include delivery costs. We estimated transportation margins, wholesaling margins, retailing margins and storage fees, using I–O tables.[23]

These input materials requirements are first matched to the sector (commodity) classifications of the I–O tables and then their volumes in the I–O tables are multiplied by the commodity unit prices to obtain the energy-materials cost structure vectors (in monetary units) for each of the above three production processes.[24]

The polycrystalline silicon solar cell production cost structure vectors calculated this way for Canada and Japan are presented in Tables 5 and 6, respectively. The highest cost shares for each of the three production processes are incurred by: abrasive products in SOG-Si production; aluminum production in cell processing; and glass production in module processing for Canada. For Japan the highest cost shares are incurred by: electric power rather

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[18] It is also possible to design simulation experiments using various numerical optimization procedures.

[19] Photovoltaic devices use semiconducting materials to convert sunlight directly into electricity. Photovoltaic cells typically come in 10 × 10 cm size and generate about half a volt of electricity. PV cells are bundled together in modules or panels to produce higher voltages and increased power.

[20] See, for example, Alsema and Nieuwlaar (2000), Photovoltaic Power Generation Technology Research Association (PVTEC) (2000) and PVTEC's website, http://www.pvtec.or.jp.

[21] Data were obtained from PVTEC (2000) and from the Mitsubishi Electric Corporation in Japan.

[22] The input requirement tables used for the other two stages of production processes are available from the authors.

[23] Japanese 1995 I–O tables report all of these margins for each commodity by sector for Japan. We used average margin rates for each commodity for Canada.

[24] We thank Mr. Satoshi Nakano, a graduate student at Keio University, for collecting the required price data for the materials and also classifying them according to the I–O table format. The price data for Japan were obtained mainly from Japan's 1995 I–O tables. Some Japanese data were also obtained from Japanese commodity prices data and the PPP index. The price data for Canada were obtained from OECD International Trade by Commodities Statistics HS Rev.1 Edition 1998 and from Municipal Water Pricing, 1991–1999.

Table 4
Materials and energy requirement in PV production: (1)SOG-Si production[a]

(1) SOG-Si prod. (10 MW)		
Item	Volume	Unit
Silica production		
Raw material		
Silica sandfor glass	462.00	t
Melting		
Sodium carbonate	273.00	t
Crude oil	172.80	kl
Extraction/Purification		
Mineralacid	1050.00	t
Limestone	960.00	t
Electric power	439.86	MWh
Water supply	23100.00	kl
Carbon pellet production		
Acetylene black	161.00	t
Resorcinol	97.00	t
Electric power	3370.95	MWh
Chlorine	36.60	t
Sodium hydroxide	21.90	t
SOG-Si production		
SiO2 Reduction		
Argon	16.38	1000 m
Graphite nozzle	1.82	t
Graphite electrode	9.10	t
Electric power	2132.37	MWh
Carbon Removal		
Electric power	258.93	MWh
Directional Solidification		
Brick	4830.00	kg
Electric power	441.87	MWh
Wafer production		
SiC grindstone	210.00	t
Piano wire for cutting	34.00	t
Electric power	2766.22	MWh

[a] Materials and energy requirements data for the other two stages, (2) cell processing and (3) module processing, are available from the authors on request. Materials and energy requirements data used in this paper were provided by the Mitsubishi Electric Corporation and also PVTEC (2000).

Table 5
Polycrystalline silicon solar cell production (10 MW): cost structure, Canada, 1995 (in Canadian dollars)[a]

Sector	SOG-Si	Cell	Module
Crude mineraloils	19,503		
Stone and silica sandfor ind. use	11,071		
Other plastic products		507	1,757,543
Carbon and graphite products	55,429		
Aluminum, other primary forms		1,423,761	
Other inorg. bases and metal. oxides		2185	
Aluminum and alum.alloyfabricated mat.		268,723	786,769
Other metal end products		3305	
Iron and steel wire and cable	641,164		
Wire and cable insulated excl. alum.			45,276
Electric light bulbs and tubes		554	
Refractory products	4944		
Glass and other glass products		172,832	4,024,336
Abrasive products	1,782,058		
Ethylene polymers			869,343
Chlorine	7189		
Oxygen		96,494	
Other chemical elements	21,005		
Sulphuric acid	58,590		
Caustic soda	7295		
Sodium carbonate	54,484		
Other inorganic chemicals		154,973	
Other alcohols and derivatives		38,824	
Other phenols	132,617		
Other organic chemicals		43,184	
Carbon	179,130		
Synthetic rubber			87,689
Truck transportation	10,187	7099	23,676
Electric power	274,515	50,905	5490
Water andother utilities	10,890	15,273	
Wholesaling margins	168,551	117,448	391,737
Retailing margins andservice	926	645	2152
Other rent	20,374	14,197	47,353
Transportation margins	29,635	20,650	68,877
Subtotal	3,488,872	2,431,040	8,108,606
Total			14,028,518

[a] Figures reported in this table are based on the authors' calculations (see the text for details).

than abrasive products in SOG-Si production; and aluminum and glass in cell and module processing.

Using Tables 5 and 6 we can calculate the unit cost for PV production for both countries (Table 7).

Our estimates presented in the last row of Table 7 show that the overall material and energy cost of PV power systems is US$1.19 per Watt for both countries when PPP is used as the exchange rate. However, if we use the actual exchange rates, the unit cost for Canada (US$1.02) is much smaller than the unit cost for Japan (US$2.15).

We also note that our estimates for the unit costs in local currencies are 202 yen per Watt for Japan and CAN$1.40 for Canada. This estimate for Japan is very close to the previously estimated Japanese manufacturers' unit cost of 189 yen per Watt for 1995 for a residential PV unit (PVTEC, 2000). This is reassuring.

Manufacturers' unit costs of PV power systems for non-residential use (e.g., industry and public facility applications) are not available but are expected to be close to the unit cost for residential systems. The manufacturing cost accounts for about 16% of the price of an installed PV system.

Tables 8 and 9 present total (direct and indirect) CO_2 emissions from three stages of photovoltaic power system production processes. The largest amounts of CO_2 emissions come from the use of electric power for both Canada and Japan. We also note that Japan's CO_2 emissions from electric power used in PV modules production is more than twice that of Canada's. The second largest amounts of CO_2 emissions come from the glass production sector for both countries. For Canada (Japan), 87.3% (97.7%) of the total CO_2 emissions from PV module production is generated by the 40 sectors listed in Table 8 (Table 9). Japan's total CO_2

Table 6
Polycrystalline silicon solar cell production (10 MW): cost structure, Japan, 1995 (in million Japanese yen)[a]

Sector	SOG-Si	Cell	Module
Materials for ceramics limest	2.942		
Crude petroleum Natural gas	2.068		
Industrialsoda chemicals	13.448		
Inorganic pigment	19.036		
Compressedgas and liquidisedgas	2.233		
Compressedgas and liquidisedgas		10.114	
Other industrialinorganic chemical	8.360	19.336	
Aliphatic intermediates		6.555	
Cyclic intermediates	14.103		
Synthetic rubber			9.300
Other industrialorganic chemical		4.580	
Thermoplastics resin			92.200
Plastic products		54.600	186.700
Sheet glass and safetyglass			426.817
Other glass and glass products		18.330	
Clay refractories	1.057		
Carbon and graphite products	5.880		
Abrasive	189.000		
Aluminum(inc.regenerated)		151.000	
Electric wires and cables			4.799
Rolledaluminum products		28.500	103.092
Other metal products	68.000	0.351	
Electric bulbs		0.059	
Electric power	197.615	36.642	3.952
Water supply		10.970	
Industrialwater supply	1.155		
Wholesale trade	71.755	38.010	135.809
Retailtrade	0.705	2.414	2.813
Railway freight transport	0.322	0.126	0.168
Road freight transport	17.709	6.627	25.173
Coastaland inland water trans	5.541	0.675	1.849
Transport service in harbor	0.692	0.301	1.421
Air transport	0.001	0.007	
Railway forward	1.547	0.316	1.206
Storage facility service	8.127	1.628	3.677
Subtotal	631.296	391.244	998,977
Total			2021.517

[a] Figures reported in this table are based on the authors' calculations (see the text for details).

emissions (13,574 ton) are 37.8% larger than Canada's (9847 ton). The primary reason for this is that Japan's electric power generation produces much more CO_2 emission than Canada's.[25]

Our estimates of CO_2 emissions generally fall in the range of estimates obtained by other researchers under a variety of assumptions.[26] If we assume the same capacity, efficiency and lifespan as assumed for PVTEC's poly-Si system given in Table 10, then the resulting CO_2 emission per kWh is 58.8 g CO_2 for Japan and 42.6 g CO_2 per kWh for Canada (compared to 71.5 g CO_2 for the PVTEC system).

3.1. Location choice and CO_2 emission

Our estimates suggest that using Canada as a location for their photovoltaic cell production would reduce the global CO_2 emissions generated by Japan's PV production sector. One feasible implementation scheme for this might be to produce solar-grade silicon (SOG-Si) in Canada and do cell and module processing in Japan. This scheme would take advantage of (1) Canada's low CO_2 emission-based electric power in the first stage of production and (2) Japan's manufacturing sectors (excluding the electric power generation sector) which generate relatively low levels of CO_2 emissions in the second and third stages of production (see Tables 8 and 9). This type of division of labor in production activities of photovoltaic modules based on comparative advantage could be implemented, for example, by Japanese multi-national firms using foreign direct investment in Canada or by collaboration between firms from Canada and Japan.[27,28]

4. Relationships of CO_2 emissions to foreign trade: Canada and Japan

In this section, we show our estimates for CO_2 emissions that are generated by foreign trade between Canada and Japan. While two-way merchandize trade flows between Canada and Japan have been generally in balance, the types of goods Canada exports are quite different from the types of goods Japan exports.[29,30]

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[25] Japan's CO_2 emission from the use of electric power (including self-power generation) is 7900 ton, while Canada's is 2141 ton.

[26] For example, using a PV production facility for rooftop residential use PV modules similar to ours (irradiation 1427 kWh/m^2/yr) Photovoltaic Power Generation Technology Research Association (2000) estimates that the total emissions from the production activities equal 1434 g CO_2-per kWh (Table 10). Our estimate is 1357 g CO_2 per kWh (Table 10). Estimates by Alsema and Nieuwlaar (2000) are also shown to be close to ours.

[27] No further PV-related trade issues are discussed in this paper since, as of now, little trade exists in the PV cell industry between Canada and Japan. This is not the case for pulp and auto industries and hence their trade issues involving CO_2 emissions are discussed in detail in the next section.

[28] We should note that this type of location issue is not limited to Canada and Japan. Given that multinational firms must typically consider trading (i.e., selling or buying) the rights of CO_2 emissions associated with investing in new energy-intensive projects these days, countries with the potentially most attractive offers for CO_2 emissions rights may become very competitive in the global race for attracting FDI projects.

[29] Both imports and exports between Canada and Japan fluctuated between 7 and 9 billion dollars US in the 1990s. There are basically four data sources for Canada–Japan trade. Some of the reported discrepancies in these trade statistics are illustrated using 1990 data in the following. Canada's exports to Japan in 1990 are given as 7.013 (billion dollars US) in the Trade Statistics, and 5.599 in the I–O Tables. Japan's imports from Canada are given as 8.426 in the Trade Statistics (CIF), and 8.876 in the I–O tables (CIF + tariff + import tax). Canada's imports from Japan are given as 8.161 in the Trade Statistics, and 8.419 in the I–O tables. Japan's exports to Canada are given as 6.739 in the Trade Statistics (FOB) and 6.398 in the I–O tables (FOB-transport margin).

[30] Japan buys Canada's natural and agricultural resources while exporting manufactured goods to Canada. Trade between Japan and the US or trade between Canada and the US, on the other hand, involves

Table 7
Unit material and energy costs comparison (10 MW PV unit): per watt at peak (Wp), 1995

	Canada			Japan		
	(A)In Cdn$ per Wp	(B)In US$ per Wp	(C)In US$ (PPP) per Wp	(D)In Japan. yen per Wp	(E)In US$ per Wp	(F)In US$ (PPP) per Wp
SOG-Si	0.35	0.25	0.30	63.1	0.67	0.37
Cell	0.24	0.18	0.21	39.1	0.42	0.23
Module	0.81	0.59	0.69	99.9	1.06	0.59
Total	1.40	1.02	1.19	202.1	2.15	1.19

Notes: Figures reported in this table are based on the authors' calculations.
The 1995 exchange rates used are 1.3724 Canadian dollar per US dollar and 94.06 yen per US dollar columns (B) and (E). The 1995 PPP rates used are 1.18 Canadian dollar per US dollar, and 170 yen per US dollar. (PPP rates were obtained from the OECD *National accounts of OECD countries: main aggregate*, vol. 1, 2001.)

Table 8
CO_2 emission from three stages of PV production by sector: Canada, 1995 (in kg per 10 MW)

Sector	Production stage			
	SOG	Cell	Module	Total
Electric power	1,188,214	392,163	561,067	2,141,444
Glass and other glass products	2688	46,746	1,047,006	1,096,440
Aluminum in primary forms	3480	482,475	8987	494,942
Abrasive products	462,681	115	372	463,168
Flat iron and steel	92,381	64,904	230,885	388,170
Other plastic prod. and rubber end prod.	1406	1211	341,688	344,305
Crude mineral oils	99,473	48,155	165,220	312,848
Truck transportation	66,101	47,783	155,474	269,358
Polymers	5428	3626	259,641	268,695
Aluminum and aluminum alloy fabricated materials	4163	60,745	179,053	243,961
Cement	52,770	40,002	134,230	227,002
Carbon	205,187	984	3235	209,406
Natural gas	42,270	32,261	104,690	179,221
Wholesaling margins	42,207	29,353	99,808	171,368
Iron and steel wire and cable	161,534	1189	4000	166,723
Pipeline transportation	39,343	26,870	84,797	151,010
Diesel and fuel oil	37,143	27,557	85,907	150,607
Motor gasoline	28,704	22,288	73,261	124,253
Ethylene	29,578	16,528	76,566	122,672
Oxygen	1956	111,409	5052	118,417
Railway transportation	20,132	14,561	47,331	82,024
Reinforcing bars and rods	20,070	13,906	47,518	81,494
Other metal ores and concentrates	14,114	31,425	34,933	80,472
Liquid petroleum gases	16,310	12,906	42,083	71,299
Traveling and entertainment	16,557	10,983	40,039	67,579
Fluid milk	15,741	9922	39,123	64,786
Air transportation	15,091	10,143	36,184	61,418
Petrochemical feed stock	14,090	9081	25,697	48,868
Deuterium oxide	498	42,496	1287	44,281
Asphalt compound and other asphalt products	9584	7584	24,706	41,874
Iron ores and concentrates	8448	6647	21,779	36,874
Other phenol	34,632	77	255	34,964
Lubricating oils and greases	7934	6242	20,350	34,526
Water and other utilities	8419	7950	15,287	31,656
Canola	7233	5713	18,667	31,613
Other paper	7231	5389	18,402	31,022
Other rent	7308	5018	17,423	29,749
Caustic soda	12,584	3373	10,977	26,934
Paperboard	6066	4244	15,931	26,241
Synthetic rubber	693	545	24,389	25,627
Subtotal (40 sectors)	2,809,442	1,664,569	4,123,300	8,597,311
Total	3,141,114	1,891,306	4,814,916	9,847,336

Notes: Figures reported in this Table were calculated by the authors as follows: first, using three columns (f_i, $i =$ SOG, cell and module) from Table 5 and Canadian I–O table for 1995, calculate $x_i = (\mathrm{I}-(\mathrm{I}-\mathrm{M})\mathrm{A})^{-1}f_i$; then calculate CO_2 emissions by $\mathrm{E}x_i$ where E is the emission matrix.

Table 9
CO_2 emission from three stages of PV production by sector: Japan, 1995 (in kg per 10 MW)

Sector	Production stage			
	SOG	Cell	Module	Total
Electric power	4,705,751	1,190,138	869,623	6,765,512
Sheet glass and safety glass	501	301	1,359,291	1,360,093
Self-Power generation	288,570	302,714	543,166	1,134,450
Coal products	323,906	140,873	160,196	624,975
Aluminum (inc. regenerated)	3872	336,184	40,830	380,886
Thermoplastics resin	1690	19,685	303,813	325,188
Road freight transport	81,152	44,301	135,449	260,902
Industrial soda chemicals	102,162	26,499	79,121	207,782
Aliphatic intermediates	9655	46,709	99,515	155,879
Petroleum refinery products	36,403	21,911	84,862	143,176
Coastal and inland water transportation	68,757	20,214	51,319	140,290
Self-passenger transport	41,870	25,464	66,988	134,322
Miscellaneous ceramic & stone	79,608	16,923	37,629	134,160
Abrasive	132,432	28	99	132,559
Other industrial inorganic chemicals	33,788	67,861	10,608	112,257
Petrochemical basic products	7682	10,387	89,474	107,543
Self-freight transport	28,791	15,231	55,507	99,529
Pig iron	60,088	7847	23,180	91,115
Cyclic intermediates	38,497	5525	44,736	88,758
Other glass and glass products	988	76,364	4705	82,057
Rolled aluminum products	965	17,136	61,937	80,038
Plastic products	1115	16,047	56,428	73,590
Other ind. sanitary services	25,773	9504	27,723	63,000
Inorganic pigment	57,772	778	3984	62,534
Other industrial organic chemicals	8927	15,571	24,705	49,203
Foreign paper and Japanese pap	19,584	6918	22,333	48,835
Ammonia	15,576	13,147	18,651	47,374
Synthetic rubber	2991	1141	42,057	46,189
Petrochemical aromatic product	18,623	3658	23,284	45,565
Air transport	11,934	7695	21,478	41,107
Wholesale trade	9237	6818	17,923	33,978
Cement	13,767	4191	9014	26,972
Other resin	745	4831	17,074	22,650
Carbon and graphite products	12,320	6971	1046	20,337
Paperboard	5980	4051	10,038	20,069
Pulp	7182	3088	9308	19,578
Salt	10,325	2401	6384	19,110
Materials for ceramics limestone	5168	618	12,936	18,722
Other metal products	16,352	272	1488	18,112
Hired car and taxi transport	4823	2915	8816	16,554
Subtotal	6,295,322	2,502,910	4,456,718	13,254,950
Total	6,415,646	2,566,109	4,592,172	13,573,927

Notes: Figures reported in this table were calculated by the authors as follows: first, using three columns (f_i, $i =$ SOG, cell and module) from Table 6 and Japanese I–O table for 1995, calculate $x_i = (I-(I-M)A)^{-1}f_i$; then calculate CO_2 emissions by Ex_i where E is the emission matrix.

Our I–O approach[31] allows us to estimate the potential effects on CO_2 emissions in each country of various forms of production activities in bilateral trade.[32] Tables 11 and 12 show the amounts of exports for 20 representative commodity groups, respectively, from Canada to Japan and from Japan to Canada, together with the associated total sector-specific CO_2 emissions induced in the exporting activities.[33] For example, Table 11 shows that Canadian firms exported US $693 million worth of coal to Japan in 1990. This coal export induced industrial activity in

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(*footnote continued*)
large amounts of exchange of manufactured goods and hence the types of issues discussed here do not necessarily arise.

[31] See appendices and also Hayami and Nakamura (2004) for further details on how to calculate these quantities and data.

[32] Our approach is sector specific. Antweiler (1996), on the other hand, proposes a macro-index for the pollution terms of trade between two countries.

[33] The 20 commodity groups used here generally capture the current patterns of trade-related CO_2 emissions. Results for all commodity groups are available on request from the authors.

Table 10
CO_2 emissions of rooftop residential use PV systems (irradiation: 1427 kWh/m^2/yr)

	Poli-Si PV unit (10 MW)		
	PVTEC (2000) system	Our system	
		Canada	Japan
SOG-Si (g, CO_2/W)	664	314	642
Cell (g, CO_2/W)	411	189	257
Module (g, CO_2/W)	359	481	459
Total (g, CO_2/W)	1,434	985	1,357
CO_2 (g, CO_2/kWh)	71.5	42.6	58.8

Notes: Figures for the PVTEC system are from Photovoltaic Power Generation Technology Research Association (2000). Their estimates are based on Japanese 1990 input-output tables; the system life span is assumed to be 20 years; the system output coefficient (system performance ratio) is 0.81; module efficiency is 11.9%; system capacity is 3502 W; and the system array area is 29.4 m^2. Our figures above (for 1995) were obtained using numbers reported in Table 8 for Canada and Table 9 for Japan. The parameters used for our calculations are identical to those used by PVTEC (2000) system. We also note that the total amount of power generated by a system over its lifetime is calculated as follows: given irradiation (1427), array area (29.4), system output coefficient (0.81), module efficiency (0.119) and the system life span (20), the annual output is 1427—0.81—0.119—29.4 = 4044 kWh/yr and the total lifetime output is 4044 kWh/yr—20. This and the unit CO_2 emission of the system in turn gives the lifetime CO_2 emission of the system.

Canada worth US $698 million and generated 599 kilo tons of CO_2 in Canada.

Table 11 shows, as expected, that Canada's exports contain, for both 1990 and 1995, many resource commodities, production of which generates considerable industrial activity and significant amounts of CO_2 emissions in Canada. These include mined products (e.g., coal, metal ores and primary metals), forest products (e.g., pulp, lumber) and an agricultural product (Canola). We also note that certain production activities induced indirectly by Canada's exports to Japan generate considerable CO_2 emissions in Canada. For example, while Canada does not export (or exports very little) electrical power and crude mineral oils to Japan, other Canadian exports induce considerable demands for these commodities, production of which generates substantial amounts of CO_2. In total, in 1995 (in 1990), Canada's commodity exports to Japan generated economic activity worth US $17.53 billion (US $10.56 billion) and 6.96 million tons (5.44 million tons) of CO_2.

Table 12 reports CO_2 emissions attributable to Japanese firms' exports to Canada. The structure of CO_2 emissions generated by Japanese exports to Canada, as shown in Table 12, is remarkably different from that for Canada. CO_2 emissions generated by Japan's exports to Canada are almost entirely indirectly induced emissions, since Japan's manufacturing assembly processes are almost CO_2 free. On the other hand, CO_2 emissions generated by Canada's exports to Japan consist of both the emissions generated directly by production of the exported commodities themselves and the emissions generated indirectly by the production activities required for producing the commodities Canada exports to Japan.

Using the same I–O framework adopted in this study it is shown[34] that, for 1990, the quantity of CO_2 emissions that would be generated in Japan if Japan's imports from Canada were replaced entirely by domestic production, assuming that such import substitutions were feasible, is 6.55 million tons, and the quantity of CO_2 emissions that would be generated in Canada if Canada's imports from Japan were replaced entirely by domestic production is 5.34 million tons. We note from Tables 11 and 12 that in 1990, Canada's exports to Japan induced 5.44 million tons of CO_2 in Canada and Japan's exports to Canada induced 2.83 million tons of CO_2 in Japan. Thus, under the scenario of no trade between Canada and Japan, the net change in the total combined amounts of CO_2 emissions for both countries is calculated to be the sum of the net change for Canada, -0.09 (= 5.34–5.44) and the net change for Japan, 3.62 (= 6.55–2.83). This combined net change is an increase in the total CO_2 emissions of 2.53 (= 3.62–0.09) million tons.[35]

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[34] Hayami et al. (1999).

[35] Similar results are also obtained for 1995. This scenario is based on the assumption of the existing production technologies, competitive imports, consumption (final demand) preferences and abundant production inputs. Under a more realistic scenario we need to specify which countries would replace Canada (Japan) as Japan's (Canada's) trading partner and recompute.

Table 11
Canadian firms' CO_2 emissions generated by their exports to Japan, 1990 and 1995[a]

Sector	1995			1990		
	Exports (US$million)	Induced Output (US$million)	CO_2 (kilo tons)	Exports (US$million)	Induced Output (US$million)	CO_2 (kilo tons)
Coal	583.480	597.358	396.735	693.163	697.728	599.020
Pulp	1164.529	1259.311	633.151	531.567	577.067	495.392
Canola and other oil seeds	629.445	650.989	362.140	444.349	461.466	256.132
Cement	0.000	6.676	65.226	0.000	1.411	15.350
Other metal ores and concentrates	562.674	669.429	134.980	805.170	899.378	204.87
Aluminum in primary forms	358.223	374.882	147.947	255.885	263.226	161.37
Flat iron&steel, incl. galv. Tinplate	1.340	85.698	136.289	0.027	17.363	38.865
Electric power	0.000	281.243	1144.535	0.000	193.575	994.221
Iron and steel ingots, billets, etc.	0.000	11.636	4.012	4.116	7.667	17.251
Iron ores and concentrates	15.027	24.553	40.129	25.959	28.238	59.259
Natural stone building products	0.955	2.534	5.496	1.033	1.1124	2.043
Fertilizers, excl. nitrogenous	54.870	110.290	87.743	43.348	72.995	88.072
Lumber and treated wood	2113.437	2190.640	264.114	750.408	787.112	90.258
Methyl alcohol	69.685	73.523	22.131	43.685	44.098	55.810
Asbestos, crude and milled	30.115	30.388	25.326	27.950	27.976	27.823
Flat iron and steel, alloy	1.340	85.698	136.289	0.476	3.218	7.179
Antifreezing preparations	0.000	0.888	0.268	0.004	1.070	1.630
Crude mineral oils	0.000	100.338	184.013	11.786	97.562	191.215
Gypsum	0.000	0.734	0.612	0.000	0.0000	0.000
Lime	0.000	2.591	5.620	0.000	5.018	9.123
Total	8483.731	17535.239	6960.079	5599.331	10560.259	5439.621

[a] Figures reported in this table are based on the authors' calculations (see the text for details). CO_2 emissions reported here arise from the production for each commodity sector resulting from Canadian exports to Japan.

Table 12
Japanese firms' CO_2 emissions generated by their exports to Canada, 1990 and 1995[a]

Sector	1995			1990		
	Exports (US$million)	Induced Output (US$million)	CO_2 (kilo tons)	Exports (US$million)	Induced Output (US$million)	CO_2 (kilo tons)
Salt	0.000	0.367	0.673	0.001	0.539	1.642
Cement	0.013	0.485	4.576	0.742	1.278	14.479
Pig iron	0.032	48.240	204.165	0.015	80.434	314.655
Self power generation	0.000	15.371	123.540	0.000	15.100	176.549
Industrial soda chemicals	0.685	11.200	6.364	1.856	17.200	19.161
Miscellaneous ceramics	2.222	13.686	19.213	2.512	18.016	51.043
Coal products	0.000	26.442	172.798	0.000	54.973	254.188
Ocean transport	0.000	0.041	0.043	0.000	0.050	0.068
Oil and fat industrial chemicals	0.005	1.857	0.187	0.000	2.926	0.927
Ferro-alloys	0.000	5.632	5.797	0.000	8.582	23.200
Self-freight transport by private	0.000	27.428	23.434	0.000	20.530	29.297
Petroleum refinery production	0.296	69.743	16.503	0.305	99.170	39.215
Coastal and inland water transport	0.000	15.150	12.181	0.000	18.074	29.063
Other structural clay products	0.007	0.326	0.128	0.013	0.287	0.183
Other sanitary service (public)	0.000	0.688	1.169	0.000	0.596	1.721
Electric power	0.000	195.465	359.651	0.000	211.760	700.745
Zinc incl. regenerated zinc	0.000	7.018	3.984	0.000	9.603	9.816
Western and Japanese paper	2.070	31.589	20.557	4.880	43.476	52.459
Tires and inner tubes	2.127	7.164	0.530	109.460	154.448	22.089
Passenger cars	814.677	814.677	3.315	2227.676	2222.676	21.215
Total	6130.153	14153.685	1562.451	6398.270	16564.405	2832.382

[a] Figures reported in this table are based on the authors' calculations (see the text for details). CO_2 emissions reported here arise from the production for each commodity sector resulting from Japanese exports to Canada.

4.1. Auto and pulp firms' CO_2 emissions

In implementing the Kyoto protocol commitments to reduce CO_2 emissions the Japanese government relies primarily on voluntary efforts by industry.[36,37] At this point it seems unlikely, however, that voluntary measures alone will be enough for Japan to meet its Kyoto target. For this reason the Japanese government began introducing a number of stricter measures for industry environmental performance.[38] It seems likely that each Japanese firm will be given mandatory CO_2 emissions reduction requirements in the near future.

In anticipating mandatory CO_2 emissions reduction programs Japanese firms are also adopting various other environmental management strategies. For example, Toyota, Nippon Paper and Mitsui & Co. have already jointly invested in tree planting in Australia and other countries in Asia for future offsetting of their CO_2 emissions as is allowed under the terms of the protocol. Another way for firms to reduce CO_2 emissions from their production processes is to use foreign sourcing of the intermediate goods that are energy-intensive.

In this section, we present two case studies in which we show how much CO_2 emissions are generated in Canada and Japan for two traded goods, passenger cars and paper pulp.[39] Computing CO_2 emissions generated in every step of their production processes, as shown here, has become an important dimension in management planning for many firms. In particular, such calculations may be used as well by other manufacturers interested in import strategies for shifting CO_2 emissions.

This sort of offsetting strategy is becoming more important for Japanese firms as reducing greenhouse gas emissions has become an importance corporate goal. From the overall public policy perspective, however, emissions reduction strategies need to be considered in conjunction with other public policy concerns and objectives including the potential loss of employment. So far this issue has received only modest attention from the Japanese government.[40]

4.1.1. Canadian imports of Japanese cars and the overall CO_2 emissions[41]

The Canadian demand for 1000 US dollars worth of Japanese passenger cars generates Japanese firms' production activities in many sectors.[42] CO_2 is generated in every stage for each of the production activities. Table 13 shows estimated amounts of Japanese production activities and associated CO_2 emissions resulting from the Canadian demand for 1000 US dollars worth of Japanese cars. They add up to US $3114 in 1995 (US $3077 in 1990) worth of commodity output and 297 kg in 1995 (458 kg in 1990) of CO_2 emissions. Assuming the average producer price of an auto to be US $10,000, the amount of CO_2 emissions in Japan per exported vehicle was 2.97 ton in 1995 (4.58 ton in 1990). The corresponding induced production activities and CO_2 emissions in Canada have been calculated and found to be negligible.[43] Table 13 shows that the use of electric power and ocean transport as parts of the production cycle for cars generated significant portions of the resulting CO_2 emissions in both 1995 and 1990. These

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[36] e.g., ISO 14000 certification. Obtaining certifications for internationally acceptable standards for environmental management is often required for manufacturers to enter global markets (e.g. European and Japanese markets). Many Japanese firms have obtained the ISO 14001 certification that attests that they possess ISO-acceptable environmental management systems. The current interest in business certification focuses on ISO 14040–14044 which certify that firms possess environmental management systems for controlling the environmental impacts of their products over their product life cycles, the stages of which include procurement of raw materials, manufacturing, distribution, usage and disposal. Controlling the amounts of CO_2 emissions throughout the life cycle of a product is an important factor for such certifications. Many of these environment-certified firms are betting that green consumerism is and will continue to be an important component in marketing their products globally. Firms' responses to global warming issues are analyzed, for example, in Nakamura et al. (2001) for Japan and Takahashi et al. (2001) for Canada. The latter find, as the Pembina Institute (1995 and 1996) did, that Canadian voluntary programs are not effective in reducing firms' CO_2 emissions. See also Kollman and Prakash (2001) and Prakash (2000).

[37] Nippon Keidanren (Japan Business Federation) established its own environment charter and keeps track of and publishes detailed emissions data for its member associations (Nippon Keidanren, 2002). As of now it is not supporting government allocation of CO_2 emission reductions among Japanese firms, nor energy or other types of environmental taxes. Nevertheless these policy measures are under serious consideration by the government and industry.

[38] One such measure in the revised energy savings law of April 1999 is termed a "top runner method" which sets a compulsory target for the energy consumption level for a particular line of products at the level attained by the most energy-efficient product currently available in the market. For example, based on 1999 performance, gasoline-based passenger cars were given the target of a 22.8% reduction in energy usage over the period 1999 and 2010, while home air conditioners were given the target of 63% over the period 1997 and 2004. The penalty for non-compliance will include public announcement of the violators and a fine. Many large Japanese manufacturers have been preparing to meet these targets for the last few years (Yamaguchi, 2000). The US raised concerns that this law might be used as an invisible barrier against foreign products but Japan argues that it is completely consistent with the WTO rules.

[39] Results reported below were obtained using the method discussed in the previous section and Appendix B.

[40] Since the 1980s, there has been massive global outward foreign direct investment by Japanese firms. Many view this as a significant source of Japanese employment loss. Nevertheless, the Japanese government has not taken any measures to restrict this sort of outward FDI. Since this policy is likely to continue into the future, it is entirely up to individual firms to decide how to meet their respective CO_2 emissions requirements using a mix of domestic and foreign production.

[41] The computational method used for this and the next case studies is described in detail in Appendix C.

[42] Cars made in Canada by Japanese transplants are not included in our calculations here.

[43] Car parts, aluminum and pulp are the three largest commodity sectors in Canada whose production is affected by the Canadian purchase of US $1000 worth of Japanese automobiles. However, numerically the total effects are quite small (US $1.39 per $1000 or $13.9 per car). The associated CO_2 emissions are 0.77572 kg per $1000, or 7.7572 kg per car. Further details are available from the authors on request.

Table 13
Japanese firms' sector-by-sector output and CO_2 emissions from all stages of production resulting from Canadian imports of US$1000 worth of Japanese automobiles, 1990 and 1995

Sector output (US$1000)	1995	1990	Sector CO_2 emissions (kg)	1995	1990
Passenger cars	1.00000	1.00000	Electric power	63.60278	106.17770
Motor vehicle parts and access	0.61076	0.53466	Ocean transport	57.16338	83.93054
Internal combustion engine for	0.24520	0.22152	Pig iron	23.20254	31.65077
Wholesale trade	0.10184	0.11748	Coal products	24.11604	29.35207
Electrical equipment for inter	0.08424	0.08209	Self-Power generation	15.94432	19.63334
Research and development	0.07630	0.06740	Cast and forged materials	17.27735	15.14578
Motor vehicle bodies	0.07676	0.06725	Motor vehicle parts and access	7.52644	11.57419
Ocean transport	0.05481	0.06257	Road freight transport	7.78989	10.28545
Plastic products	0.06289	0.06100	Passenger cars	4.06859	9.52356
Financial service	0.04788	0.04054	Petroleum refinery products	3.18253	7.01917
Electric power	0.03457	0.03209	Self-Passenger transport	4.50340	6.47464
Hot rolled steel	0.02140	0.02638	Sheet glass and safety glass	4.01217	5.64517
Goods renting and leasing	0.02481	0.02409	Coastal and inland water trans	2.90249	5.58544
Other business services	0.02302	0.02405	Hot rolled steel	2.63502	5.48003
Machine repairing	0.01937	0.02356	Crude steel (converters)	3.24736	5.31962
Other rubber products	0.02378	0.02321	Miscellaneous ceramic, stone etc	2.49456	5.24723
Cast and forged materials	0.02117	0.02088	Foreign paper and Japanese paper	2.23811	5.01293
Road freight transport	0.01937	0.02062	Internal combustion engine	3.74894	4.91431
Cold-finished steel	0.01795	0.02016	Research and development	2.23419	4.52891
Petroleum refinery products	0.01345	0.01775	Thermoplastics resin	2.11478	4.50226
Real estate rent	0.01482	0.01763	Petrochemical basic products	0.96413	4.31515
Transport service in harbor	0.01477	0.01614	Cold-finished steel	2.17044	4.30387
Non-ferrous metal castings	0.01681	0.01608	Self-freight transport by priv	2.50564	4.22287
Sheet glass and safety glass	0.01592	0.01507	Synthetic rubber	1.66303	2.99657
Printings, engraving and book ndings	0.01287	0.01469	Crude steel (electric furnaces)	—	2.90390
Tires and inner tubes	—	0.01448	Air transport	2.00997	2.49041
Advertising agencies	0.01601	0.01408	Activities not elsewhere class		2.37526
Electric audio equipment	0.01345	0.01384	Other sanitary services	1.87519	2.35077
Information service	—	0.01325	Ferro alloy	—	2.31446
Batteries	—	0.01251	Aliphatic intermediates	1.94590	2.26295
Others	0.38847	0.44208	Others	25.55578	50.44436
Total	3.11432	3.07715	Total	296.69086	457.98368

Notes: Figures reported in this table are based on the authors' calculations (see the text for details).

sources of emissions in Japan would be curtailed if production were moved to Canada.

4.1.2. *Japanese imports of Canadian pulp and overall CO_2 emissions*

Table 14 shows estimated amounts of Canadian firms' production activities and associated CO_2 emissions resulting from the Japanese demand for 1000 US dollars worth of Canadian pulp: US $2001 in 1995 (US $2137 in 1990) worth of commodity output and 1103 kg in 1995 (1721 kg in 1990) of CO_2 emissions. We have also estimated the amounts of Japanese firms' production activities and associated CO_2 emissions resulting from the Japanese demand for 1000 US dollars worth of Canadian pulp and found these to be numerically small.[44] We can also show, for example for 1990, that production of 1000 ton of pulp generates 444 ton of CO_2 emissions in Canada, whereas the same amount of pulp production generates 755 ton of CO_2 emissions in Japan. This difference (444 ton vs. 755 ton of CO_2 emission) is far less than the amount of CO_2 emissions generated by transporting pulp from Canada to Japan.[45] Thus a reduction in CO_2 emissions could presumably be achieved if Japanese paper mills imported more pulp from Canada.[46]

4.2. *Carbon tax*

One possible policy tool to reduce greenhouse gas emissions is a carbon tax which taxes the carbon content of goods and services consumed. Suppose Japan introduces a carbon tax of 1 US dollar per ton of CO_2 emitted. It is shown in Appendix D that the domestic price increases as a result of this carbon tax are given in Table 1. (That is,

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[44] For example, US $2.26 worth of commodity output and 0.77077 kg of associated CO_2 for 1990. The detailed estimated figures are available from the authors on request.

[45] The same conclusion also holds for 1995.

[46] As of now manufacturers who invest in FDI need not worry about their CO_2 emissions that they generate using their FDI plants overseas for their home country regulation purposes so long as they satisfy the host country requirements. (Some may still care about this because of their corporate image.) This is one area where international coordination is clearly needed.

Table 14
Canadian firms' sector-by-sector output and CO_2 emissions from all stages of production resulting from Japanese imports of US$1000 worth of Canadian pulp, 1990 and 1995

Sector output (US$1000)	1995	1990	Sector CO_2 emissions (kg)	1995	1990
Pulp	1.05823	1.07209	Pulp	532.05383	920.36371
Wood chips	0.10854	0.09446	Electric power	287.09669	388.16776
Pulpwood	0.05312	0.08865	Truck transportation	49.30222	31.58195
Spare artsandmaint.suppl.machandequip	0.10294	0.08840	Water transportation	14.51580	30.09386
Electric power	0.07055	0.07558	Crude mineral oils	14.86494	29.33568
Wholesaling margins	0.06461	0.05563	Pulpwood	17.76706	29.18842
Transportation margins	0.05869	0.05070	Diesel and fuel oil, aviation fuel	20.39584	26.89690
Truck transportation	0.04486	0.04606	Natural gas	4.66758	21.03574
Logs, poles, pilings, bolts, etc	0.03723	0.03762	Railway transportation	16.11019	17.04658
Custom forestry	0.02195	0.03709	Pipeline transportation	20.06214	15.66706
Repair service for mach and equip	0.01524	0.02216	Caustic soda	—	13.52631
Water transportation	0.01285	0.02177	Logs, poles, pilings, bolts, etc	12.88909	12.94343
Diesel and fuel oil, aviation fuel	0.01231	0.02069	Custom forestry	7.48064	12.25323
Govt. royalties on nat. resources		0.01785	Wholesaling margins	12.39139	11.71371
Other finance and real estate serv	0.02348	0.01780	Wood chips	16.81328	11.69195
Repair construction	0.01248	0.01763	Sodium chlorate	1.84928	11.07504
Crude mineral oils	—	0.01497	Water, waste disp. and other utilities	—	10.03095
Railway transportation	—	0.01357	Serv incidental to water transport	—	6.90354
Other rent	0.01077	0.01193	Chlorine	—	5.86235
Professional service to business management	—	0.01108	Other industrial chemical prep.	—	5.76928
Natural gas	—	0.01074	Air transportation	4.95776	4.91669
Caustic soda	—	0.01069	Other inorganic chemicals	—	4.85746
Travelling and entertainment	0.01095	0.01035	Other liquid petroleum gases	—	4.14150
Advertising and promotion	0.00943	0.01034	Repair service for mach and equip	2.19088	3.98385
Felt	—	0.00911	Travelling and entertainment	—	3.86320
Sodium chlorate	0.00811	0.00875	Gasoline	2.25890	3.77340
Rental, oth mach and equip incl onst.	0.00671	0.00875	Petrochemical feed stock	—	3.49398
Telephone and other telecommunications	0.00769	0.00794	Rental, oth mach and equip ncl const.	—	3.45924
Other services to business and rsons	0.00943	0.00765	Other metallic salts and roxysalts	—	3.16642
Retailing margins	0.00728	0.00753	Ethylene	—	3.05921
Others	0.16803	0.22919	Others	36.00855	71.13803
Total	2.00075	2.13677	Total	1103.62576	1721.00043

Notes: Figures reported in this table are based on the authors' calculations (see the text for details).

figures in Table 1 are also estimated shadow prices.) For example, the Japanese domestic cement price would increase by 1.22864% ((= 12.2864/1000) times 100) because of the carbon tax.[47] Estimated price increases for some other goods are: 1.224309% (self power generation), 0.610124% (pig iron) and 0.541976% (coal products). It is interesting to note that if the same carbon tax is adopted in Canada, Canadian domestic price increases will be somewhat less than the corresponding Japanese price increases. For example, estimated price increases for Canada are: 1.153425% (cement), 0.543939% (electric power), 0.327569 (iron and steel ingot) and 0.303469% (coke).

The introduction of a carbon tax influences the domestic prices of trading partners through trade. Table 15 shows the estimated price increases for Canadian (Japanese) domestic prices when the above carbon tax is introduced in Japan (Canada), assuming that no substitutions take place in the supply of and the demand for these goods in both countries (see Appendix D for details). For example, Canada's carbon tax will increase Japanese domestic prices of vegetable oil, coal, copper, paper and nuclear fuels by 0.0100%, 0.0066%, 0.0062%, 0.0044% and 0.0023%, respectively. On the other hand, Japan's carbon tax will have much smaller effects on Canadian domestic price increases. For example, oil and gas pipe prices will increase by 0.0027% while auto prices would increase by 0.0011%. We conclude that Japan's carbon tax will have only a modest impact on the Canadian prices of goods. Such Japanese carbon tax-induced price increases in Canada may be mitigated relatively easily by Canada's ability to locate alternative suppliers other than Japan. On the other hand Canada's carbon tax will potentially have a much more significant impact on the Japanese prices of goods which are energy-intensive. Furthermore, it may be difficult for Japan to locate alternative exporting countries which could supply Japan with energy-intensive materials in large quantities for prices which are low enough to mitigate the impact of Canada's carbon tax.

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[47] Calculations given in this section are based on 1990 estimates given in Table 1. Similar results hold for 1995 estimates also given in Table 1.

Table 15
Carbon tax and price increases in Canada and Japan

Price increases in Canada induced by Japan's carbon tax ($1US tax per ton of CO_2 generated)		Price Increases in Japan induced by Canada's carbon tax ($1US tax per ton of CO_2 generated)	
Oil and gas line pipe	0.000027032	Other edible crops	0.000100682
Oil and gas casing and drill pipe	0.000025761	Vegetable oil and meal	0.000100537
Other iron and steel pipes and tubes	0.000025055	Coal products	0.000066015
Iron and steel wire and cable	0.000015048	Copper	0.000062660
Chain, excl motor vehicle and power trans.	0.000015048	Other non-ferrous metals	0.000046911
Welding rods and wire electrodes	0.000015048	western paper and Japanese paper	0.000044035
Railway and telecommunications const.	0.000014651	Zinc (inc. regenerated zinc)	0.000043965
Iron and steel wire fencing and screen	0.000013574	Lead (inc. regenerated lead)	0.000042876
Automobiles, incl vans	0.000011504	Coal-tar products	0.000032106
Trucks, tractors and chassis	0.000011504	Pig iron	0.000030651
Buses and chassis	0.000011408	Paperboard	0.000028384
Hardware	0.000010241	Aluminum (inc. regenerated alum.)	0.000027964
Iron and steel forgings	0.000009915	Rolled aluminum products	0.000026602
Spare parts and maint. suppl. mach and equip	0.000009881	Ferro alloy	0.000024513
Valves	0.000009793	Nuclear fuels	0.000023542
Kitchen utensils and wire products	0.000009496	Flour and other grain milled prod.	0.000023323
Gas and oil facility construction	0.000008628	Organic fertilizers	0.000022546
Commercial cooking equipment	0.000008587	Non-ferrous metal castings	0.000019905
Bulldozers, farm and garden tractors	0.000008587	Rolled and drawn copper	0.000019149
Pumps, compressors and blowers	0.000008587	Rayon ,acetate	0.000018497
Industrial furnaces, kilns and ovens	0.000008587	Corrugated cardboard	0.000018006
Pkg., air pur. and other gen. purp. Mach	0.000008490	Crude steel(converters)	0.000017921
Bearings & power trans. eq.	0.000008445	Animal oil and fat	0.000017667
Ind. trucks and mat. handling equip	0.000008392	Other non-ferrous metal prod.	0.000015747
Corrugated metal culvert pipe	0.000008268	Feeds	0.000015510
Iron and steel stampings	0.000008241	Oil and fat industrial chemicals	0.000013436
Metal containers and closures	0.000008192	Crude steel (electric furnaces)	0.000012415
Household equip. excl range.microw.refrig.	0.000008151	Coated paper and paper convert	0.000012277
Conveyors, elevators and hoist. Mach	0.000008093	Electric wires and cables	0.000012095
Fire fight. and traffic contr. Equip	0.000008062	Sulfuric acid	0.000012055
Radio, TV, stereo, VCR and unrec. tape	0.000007996	Hot rolled steel	0.000011433
Other metal end products	0.000007975	Other pulp, paper and converted	0.000011066
Industry specific machinery	0.000007380	Cement	0.000010924
Iron and steel pipe fittings	0.000007352	Newspapers	0.000010256
Other agricult. machinery	0.000007196	Pulp	0.000010248

Notes: Figures reported in this table are based on the authors' calculations using 1990 estimates given in Tables 1 and 2. Estimates for 1995 are similar to these and available from the authors on request (see the text for details).

5. Concluding remarks

In this study, we first computed estimates for CO_2 emissions for over 400 economic sectors of the Canadian and Japanese economies.[48] We then used these estimates and our models for analyzing various policy implications of CO_2 emissions as related to recycling, foreign direct investment and also trade between Canada and Japan. In particular detailed case studies were presented for paper recycling, photovoltaic cell production, automobile and pulp production, and carbon tax, among other topics. These case studies illustrate some of the common types of tradeoffs that underlie firms' managerial decisions as well as public policy decisions on greenhouse gas emissions. Policy suggestions were also presented for these applications.

One methodological contribution of this paper is that, using our method, Canada (Japan) can estimate detailed sector-specific CO_2 emissions in Canada (Japan) resulting from its trading activities (both importing and exporting) with Japan (Canada).[49] Using this methodology we show, for example, that the complementary nature of international trade between Canada and Japan adds considerable flexibility to Japan's planning for meeting its CO_2 emission target.[50] Despite their limitations discussed in Appendix A, only I–O based models such as ours can analyze and provide estimates for many sectors required for the types of applications discussed in this paper.

We have also argued that firms can apply our methodology for estimating sector-specific CO_2 emissions which result from their production activities.

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[48] To save space this paper does not report CO_2 emissions for all of these sectors. Complete results are available on request from the authors.

[49] Technical details are given in Appendix C.

[50] Potential sources for such flexibility include Japanese firms' foreign direct investment in Canada and more imports from Canada.

This measurement issue is becoming an important part of implementation of the Kyoto protocol. Japanese firms, for example, are now required to account for their CO_2 emissions accurately in order for Japan to comply with the Kyoto protocol requirements. As noted above our methodology allows Japanese firms to compute direct and indirect sector-specific CO_2 emissions resulting from their operations not only in Japan but also in Canada. Because greenhouse gas issues are global in nature, this aspect of our method should prove useful when trading CO_2 emissions between countries is at issue. Another application of our method is in the area of life cycle assessment (LCA) in which firms are required to estimate all greenhouse gas emissions associated with a product over its life cycle (i.e. from its conception to its consumption and disposal).[51]

Finally, even though we have presented our empirical examples using data for Canada and Japan, our methodology and models can be applied to other countries for which relevant data exist.[52]

Appendix A. Input–output analysis and estimation of CO_2 emissions

The input–output data used for this study are the 1990 and 1995 Input–Output tables for the Japanese economy (Management and Coordination Agency, 1994, 2000) and the 1990 and 1995 Input–Output tables for Canada (Statistics Canada, 1996b, 2000). These data sets are available for public use. The Japanese I–O table is provided in square matrix form (matrix A below) with additional columns representing various types of final demand (columns d_j below) and additional rows representing various types of value added (Yoshioka et al., 1996; Hayami et al., 2000). The Canadian I–O matrices are based on the system of national accounts (SNA) and consist of a use matrix, a make matrix, final demand columns and value-added rows. (See, for example, Statistics Canada, 1989; Miller and Blair, 1985; Miller et al., 1989; Polenske, 1989.) A detailed derivation of the I–O square matrix (A) for Canada and other information on Japanese and Canadian data are given in Hayami et al. (1999).

Our basic I–O model is as follows. We divide an economy into n broad industrial and other relevant sectors where production of goods and services takes place. We define I–O technical coefficients a_{ij} ($i,j = 1,2,\ldots,n$) to be the dollar amount of input from sector i per dollar's worth of output of sector j, where the a_{ij} lie between 0 and 1 and their column sums are less than one. We denote by x an $n \times 1$ vector in which each component x_j represents the domestic production of sector j ($j = 1,2,\ldots,n$). We denote by d_j, e_j and m_j the final domestic demand, exports and imports for sector j, respectively. We also denote by d, e and m their corresponding $n \times 1$ vectors. Then we have the I–O equation

$$Ax + d + e = x + m. \tag{A.1}$$

Assuming a competitive imports structure, m is given by

$$m = M(Ax + d + e), \tag{A.2}$$

where M is an $n \times n$ diagonal matrix with its diagonal element M_{jj} representing the imports coefficient for sector j. The import coefficient matrix M is derived in Hayami et al. (1999). Substituting (A.2) into (A.1), we get

$$x = (I - (I - M)A)^{-1}((I - M)(d + e)). \tag{A.3}$$

Suppose we have estimates $E1_j$ ($j = 1,2,\ldots,n$) for the amounts (in kilo tons) of CO_2 produced per million US dollars worth of production in each of n sectors. We denote by $E1$ the corresponding $n \times n$ diagonal matrix with $E1_j$ in the jth diagonal position. Then the amount of CO_2 produced by a unit demand for the output of sector j is given by

$$E1(I - (I - M)A)^{-1}u_j, \tag{A.4}$$

where u_j is a unit $n \times 1$ vector with one in the jth position.[53] Let i be a $1 \times n$ vector of ones. Then the total CO_2 co-produced with a unit of output in sector j is given by

$$E_j = iE1(I - (I - M)A)^{-1}u_j, \; j = 1, 2, \ldots, n. \tag{A.5}$$

(A.5) is a standard open I–O model formulation of pollutants. See Miller and Blair (1985, Ch. 7) for other types of models. In this paper we focus on CO_2 emissions from industrial production processes only. We should also note the standard limitations of I–O analysis. For example, if policy alternatives of interest involve, in reality, significant changes in the relative prices of production inputs, I–O analysis will not reflect this since, as is typical for I–O models, the technical coefficients are fixed.[54] Another limitation of our approach is the time lags involved in obtaining I–O data. This problem, however, is becoming less severe as national statistical agencies improve their timeliness in providing this data. Despite these potential limitations, I–O analysis is a useful supplement to macro simulation models of the sort used by many government offices, and the only realistic alternative for taking account of the CO_2 emissions

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[51] LCA is an essential part of the ISO 14000 family of environmental management standards, for which major manufacturers, for instance, in Japan and EU are trying to get certified for staying competitive in global markets.

[52] Our approach can also be used to compute the amounts of CO_2 emissions to be traded using the Clean Development Mechanism (CDM) clause of the Kyoto Protocol. CDM allows multinational firms to buy reductions in CO_2 emissions in return for investing in their CO_2 emissions-saving FDI projects in a developing country. Such FDI projects must be authorized as CDM projects (Hayami et al., 2003). The CDM clause provides the current international framework for the commercial market mechanisms by which multinational firms and developing nations trade their CO_2 emissions rights.

[53] The data on CO_2 emissions used were taken from Environment Canada (1992), Jaques (1990), Smith (1993), Statistics Canada (1996a) as well as unpublished data provided by Statistics Canada for Canada; and Yoshioka et al. (1996) and Hayami et al. (2000) for Japan.

[54] See, for example, Smith (1991, 1993, 1995).

generated in many sectors in different stages of production processes.[55]

Appendix B. Data and model derivation details

In Appendices B and C we give detailed descriptions of our methodology and data analyses for Canada and Japan for 1990. The same methodology and data analyses also apply for 1995.

B.1. Japan

The original 1990 Japanese public use I–O data consists of an I–O matrix representing intermediate transactions with 527 column sectors (based on the Japanese 7-digit classification) and 411 row sectors (based on the 6-digit classification), an 11×411 value-added matrix, a 527×30 final demand matrix and an output (527×1) vector.[56] In order to derive a square I–O table with sectors which are comparable to the Canadian sectors the 527 column sectors were first aggregated into 6-digit classification sectors (i.e. 411 sectors). In this process iron scrap and metal scrap were, respectively, combined with pig iron and other nonferrous metal sectors. Then 10 sectors in agriculture, fishery and utility industries were aggregated into 4 sectors: vegetables, fishery, inland water culture and power generation.[57] The resulting I–O table for Japan is 405×405. The input coefficient matrix $A = (a_{ij})$ is derived from the following balance equation (Hayami et al., 1997):

$$\sum_j \{a_{ij} Q_j\} + \mathrm{FD}_i + \mathrm{EX}_i = Q_i + \mathrm{IM}_i, \quad i,j = 1,2, \ldots m, \tag{B.1}$$

where $m = 405$, FD_i, EX_i, Q_i and IM_i denote, respectively, final demand, exports, output and competitive imports for sector i.

B.2. Canada

The Canadian System of National Accounts for 1990 provide the I–O matrices: a 478×161 use matrix (U_{ij}), an 161×478 make matrix (V_{ij}), a 478×136 final demand matrix (FD_{ij}), and a 7×161 and a 7×136 value-added matrices (VA_{ij} and VAFD_{ij}).[58] The total industry sector output vector (161×1) is also given (g_i). Because of the privacy requirement of the provisions of the Canadian Statistics Act some cells in both use and make matrices report figures which have been rounded up from thousands of dollars to millions of dollars (Statistics Canada, 1996a, b, 2001). Such rounding occurs when the sources of reporting units (company establishments) are identifiable because of too few reporting units in particular cells. Such processing implies that the columns of the use and final demand matrices do not sum to the given output vector:

$$\sum_{i=1}^{478} U_{ij} + \sum_{i=1}^{7} \mathrm{VA}_{ij} \neq g_j, \; j = 1, \ldots, 161, \tag{B.2}$$

$$\sum_{i=1}^{478} \mathrm{FD}_{ij} + \sum_{i=1}^{7} \mathrm{VAFD}_{ij} \neq (g_f)_j, \; j = 1, \ldots, 136. \tag{B.2*}$$

Similarly the row sums of the make matrix do not equal the output vector:

$$\sum_{i=1}^{478} V_{ij} \neq g_i, \; j = 1, \ldots, 161. \tag{B.3}$$

In order to accommodate these discrepancies we have introduced an adjustment row as the last (479th) row, U_{479j} and FD_{479j}, in the use and final demand matrices. The adjustment rows are set equal to the differences between the right and left sides of (B.2) and (B.2*) above. Similarly we have introduced an adjustment column vector as the last (479th) column, V_{i479}.

$$\sum_{i=1}^{478} U_{ij} + U_{479j} + \sum_{i=1}^{7} VA_{ij} = g_j, \; j = 1,2, \ldots, 161, \tag{B.2a}$$

$$\sum_{i=1}^{478} \mathrm{FD}_{ij} + \mathrm{FD}_{479j} + \sum_{i=1}^{7} \mathrm{VAFD}_{ij} = (g_f)_j, \; j = 1,2, \ldots, 136, \tag{B.2*a}$$

$$\sum_{i=1}^{478} V_{ij} + V_{i479} = g_i, \; i = 1,2, \ldots, 161. \tag{B.3a}$$

The resulting I–O input technical coefficient matrix A is 479×479 and is obtained as follows.

We first define a technical coefficient:

$$u_{ij} = \{U_{ij}/g_j\}, \; i = 1, \ldots, 479, \; j = 1, \ldots, 161.$$

Let $m = 479$ and $n = 161$.

Then the commodity balance equation is

$$\sum_{j=1}^{n} u_{ij} g_j + \mathrm{FD}_i + \mathrm{EX}_i = Q_i + \mathrm{IM}_i, \; i = 1, \ldots, m. \tag{B.4}$$

We next introduce the industry-based technology assumption which is a standard assumption in input–output modeling. This assumption states that the total output of a commodity is provided by industries in fixed proportions and hence that the following commodity output proportion

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[55] See, for example, Environment Canada (1997) and Natural Resources Canada (1999) for the use of a macro-simulation model for obtaining forecasts for Canada's future CO_2 emissions. In this simulation model population and GDP growth, oil prices and other model inputs are assumed given.

[56] The corresponding dimensions of these matrices for 1995 are as follows: I–O matrix (519×403), value-added matrix (10×403), final demand matrix (519×23) and output vector (1×519).

[57] In this process we reduced the number of column (and also row) sectors by 6 from 411 to 405.

[58] The corresponding dimensions of these matrices for 1995 are as follows: 476×167 use matrix (U_{ij}), 167×476 make matrix (V_{ij}), 476×122 final demand matrix (FD_{ij}), and 7×167 and 7×122 value-added matrices (VA_{ij} and VAFD_{ij}).

(market share coefficient) forms a constant matrix:

$d_{jk} = \{V_{jk}/Q_k\}, \; k = 1, 2, \ldots, m, \; j = 1, 2, \ldots, n.$

Using (B.3a) we get

$$\sum_{k=1}^{m} d_{jk} Q_k = g_j, \; j = 1, 2, \ldots, n. \tag{B.5}$$

Substituting (B.5) into (B.4) we get

$$\sum_{k=1}^{m} \left\{ \sum\nolimits_{j=1}^{n} u_{ij} d_{jk} \right\} Q_k + \mathrm{FD}_i + \mathrm{EX}_i = Q_i + \mathrm{IM}_i, \quad i = 1, 2, \ldots, m. \tag{B.6}$$

Defining the I–O technical coefficient matrix A,

$$A = \{a_{ij}\}, \; a_{ij} = \sum_{k=1}^{n} u_{ik} d_{kj}, \; i = 1, \ldots, m, \; j = 1, \ldots, m$$

we obtain from (B.6) the following balance equation for each commodity

$$\sum_{j=1}^{m} \{a_{ij} Q_j\} + \mathrm{FD}_i + \mathrm{EX}_i = Q_i + \mathrm{IM}_i, \; i = 1, 2, \ldots, m. \tag{B.7}$$

Thus the d_{jk} allocates the u_{ik} across m commodities into a_{ij}.

B.3. Derivation of the imports coefficients and the Leontief inverse

The standard definition of the imports coefficient for competitive imports in sector i is

$$M_i = \mathrm{IM}_i \Big/ \left(\sum_j \{a_{ij} Q_j\} + \mathrm{FD}_i \right), \; i = 1, 2, \ldots, m, \tag{B.8a}$$

where it is assumed that exported commodities do not include imported commodities. In order for the Lentief inverse to exist, however, we require that the imports coefficient is non-negative and strictly less than 1:$0 \leqslant M_i < 1$.

We have found that imports coefficients calculated by definition (B.8a) using the Canadian I–O data exceed one for some sectors. This is because the above assumption for (B.8a) is not satisfied. This is explained as follows. Some sectors of the Canadian economy import commodities which are in turn exported while transport margins and storage fees are domestically charged. In these cases domestic production Q_i consists of mostly transport margins and storage fees, and domestic production $\Sigma_j\{a_{ij}Q_j\}$ is relatively small and exports EX_i is close to import IM_i. When inventory stock decreases domestic final demand FD_i becomes negative and we may have

$$\sum_j \{a_{ij} Q_j\} + FD_i < IM_i \rightarrow M_i > 1.$$

For this reason we define our imports coefficient as follows:

$$M_i = \mathrm{IM}_i \Big/ \left(\sum_j \{a_{ij} Q_j\} + \mathrm{FD}_i + \mathrm{EX}_i \right), \; i = 1, 2, \ldots, m. \tag{B.8b}$$

Under this definition M_i will always be less than 1.

B.4. Data on CO_2 emissions

We use Japanese emission data provided in the Japanese Environmental I–O Table for 1990 (Yoshioka et al., 1996) and the revised Japanese Environmental I–O Table for 1995 (Hayami et al., 2000). These data consist of CO_2 emissions for intermediate production activity and final consumption activity for each sector j. Estimates of CO_2 emissions were obtained based on the amounts of carbon contained in the 50 energy commodities for 1990 (53 energy commodities for 1995) which were consumed in each of the 411 activities for 1990 (403 activities for 1995). Our Canadian emission data consists of emissions for 161 industrial sectors (corresponding to the rows in make matrix) and emissions for 136 final demand sectors. Emissions for 161 industrial sectors are allocated to commodity production sectors using the same type of equations as (B.5)–(B.7). In calculating CO_2 emissions per million US dollars worth of production activity we use a diagonal conversion matrix U whose jth diagonal element denotes monetary worth of energy per calorific value used in sector j and a row vector E whose jth element denotes the amount of CO_2 emitted per calorific value of energy used in sector j as follows. CO_2 emissions per million US dollars worth of consumption and production activities are, respectively, given by $E2 = \mathrm{EU}$ and $E1 = \mathrm{EUA}$, where $E1$ and $E2$ are both diagonal matrices.

B.5. Aggregation issues

For estimating CO_2 emissions for Canada we allocated CO_2 emissions of about 160 sectors to about 500 commodities. In doing so we used the standard assumption (called the industry-technology assumption) that all products produced by an industry are produced with the same input structure (i.e. the same input coefficients) (e.g., Miller and Blair, 1985, p. 166). This assumption is reasonable for some industries but not for some others. For example, the petroleum refinery industry produces four main products (commodities) on a single production line: gasoline, diesel oil, kerosene and heavy oil. These different products are produced only by differing the distilling temperatures of the system. For this industry it is reasonable that the above assumption holds and that the four oil refinery products get assigned the same amounts of CO_2 emission per dollar of production.

On the other hand, this assumption is less likely to hold in an industrial sector in which multiple products are produced, for example, using both product-specific production inputs and processes as well as some production inputs and processes that are common to all the products being produced in the same industry. For example, the precision equipment sector may produce multiple digital electronics products such as printers, photocopiers and cameras in the same factory. For such a sector the above assumption is less likely to hold and hence allocation of CO_2 emission based on the industry-technology assumption may not be reasonable.

This problem can be lessened to some extent by disaggregating industry sectors. For example, by having as many industry sectors as commodity sectors, the problem is somewhat lessened but it cannot be eliminated entirely. This is in part because firms almost always produce multiple products in the same establishments in an industrial sector. Allocation of the common indirect overhead costs and the associated CO_2 emissions incurred by these multiple products over the multiple products requires some subjective judgments and is not done in accordance to the industry-technology assumption.

One potentially confusing issue arises when we try to compare the quantities of the CO_2 emissions from two different products (e.g., apples and pears) produced in the same industry sector (e.g., fruit production). We note that, since I–O analysis is typically done using monetary units, it is generally not possible to distinguish the CO_2 emissions associated with production of 1 ton of apples from the CO_2 emissions associated with the production of 1 ton of pears. Also, the industry-technology assumption implies that, production of 100$ worth of apples and production of 100$ worth of pears each produces the same amounts of CO_2 emissions in the fruit production sector.

For example, at the aggregate industry sector level, a production process uses 100 units (say, 100$ worth) of industrial products, which generates 10 ton of CO_2 emissions in total. Suppose there are two industry sectors at the disaggregate sector level, the manufacturing products sector and the mining products sector. Suppose further that the above production process uses 50 units (50$ worth) of products from each of these two product sectors. So the total output of the production process measured in the aggregate industry level is 100$ and the amount of CO_2 emissions is 10 ton. In this case, can we say that, because of the industry-technology assumption which implies all products produced in the aggregate sector produce the same amounts of CO_2 emissions, the production process generates 5 ton of CO_2 emissions in each of the manufacturing products sector and the mining products sector at the disaggregate sector level? The answer is no, provided that we have CO_2 emissions estimates separately for the manufacturing products sector and the mining products sector at the disaggregated level. Under such a disaggregated situation the activity levels can be different for the two manufacturing sectors and hence the 50$ worth of output from each disaggregate sector need not have to generate the same amounts of CO_2 emissions. So CO_2 emissions from the two sectors might be 3.5 and 6.5 ton, 7.0 and 3.0 ton, etc. (They must sum to 10 ton).

Appendix C. Modeling CO_2 emissions induced by trade between Canada and Japan

Japan's demand for Canadian products generates production activities in Canada which in turn produce CO_2. Similarly Canadian demand for Japanese products generates production activities, together with accompanying CO_2 emissions in Japan. If commodity, industrial, final demand, imports and export sectors were all identically defined for both Canada and Japan, it would be straight forward to calculate CO_2 emissions generated by one country's exports, or partner country's demand for such imports. Unfortunately commodity groups for the I–O matrix and trade statistics, for example, are not identical for different countries. We show below how we translate Japan's imports from Canada (Canada's imports from Japan) into Canada's exports to Japan (Japan's exports to Canada). These translation formulas would allow us, for example, to translate Japan's imports from Canada given in Japanese I–O classification into Canada's exports to Japan given in Canadian I–O classification and vice versa. Using these formulas it would be straightforward to calculate the impact, for example, of Canada's imports from Japan on the Japanese economy and CO_2 emissions in Japan.

C.1. Conversion formula for translating Japan's imports into Canada's exports

The conversion consists of six steps using the following statistical databases including three different classification systems.[59] The statistical data bases used are (1) Canada's I–O table, (2) Canada's trade data, (3) Japan's I–O table and (4) Japan's trade data. The trade data are based on customs statistics. The three different classification systems are (1) Canada's I–O system with 479 sectors, (2) the Harmonized Commodity Descriptions and Coding System (HS) with 2420 commodities and (3) Japan's I–O system with 405 sectors.

We define the following quantities.

Xm^J: Japan's imports in Japan's I–O table (405×1 vector)

Rm^J: the ratio between Japan's imports from Canada and Japan's total imports from the world (405×405 diagonal matrix)

$Xm^{C,J}$: Japan's imports from Canada in Japan's I–O table (405×1 vector)

${}_{tr}Xm^J_{io}$: converter matrix from Japan's I–O table to Japan's trade data (405×405 diagonal matrix)

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[59] See OECD (1998) and Statistics Canada (1993). Details are available from the authors.

$\mathrm{T}_{\mathrm{J}}^{\mathrm{C,J}}$: Japan's imports from Canada in Japan's trade data system (405 × 1 vector)

${}_{\mathrm{hs}}\mathrm{R}_{\mathrm{tr}}^{\mathrm{C,J}}$: allocation matrix from Japan's trade system (405 commodities) into the 8-digit HS system (2420 × 405 matrix)

$\mathrm{HS}^{\mathrm{C,J}}$: Japan's imports from Canada in the 8 digit HS system (2420 × 1 vector)

${}_{\mathrm{tr}}\mathrm{R}_{\mathrm{hs}}^{\mathrm{C,J}}$: aggregation matrix from the 8 digit HS system into Canada's 479 trade data system (479 × 2420 matrix)

${}_{\mathrm{tr}}\mathrm{R}_{\mathrm{tr}}^{\mathrm{C,J}}$: data adjustments matrix from Japan's trade data to Canada's trade data in Canada's trade data system (479 commodities) (479 × 479 diagonal matrix)

$\mathrm{T}_{\mathrm{C}}^{\mathrm{C,J}}$: Canada's exports to Japan in Canada's trade data system (479 × 1 vector)

${}_{\mathrm{io}}\mathrm{Xe}_{\mathrm{tr}}^{\mathrm{C}}$: converter matrix from Canada's trade data system to Canada's I–O system (479 × 479 diagonal matrix)

$\mathrm{Xe}^{\mathrm{C,J}}$: Canada's exports to Japan in Canada's I–O system (479 × 1 vector)

C.2. Conversion formula for translating Canada's imports into Japan's exports

As before the conversion consists of six steps using four statistical data bases and three different classification systems.[60] Essentially the same procedure as before can be applied. The only difference to note here is that the Harmonized Commodity Descriptions and Coding System which we use here consists of 3578 (rather than 2420) commodities.

We define the following quantities.

Xm^{C}: Canada's imports in Canada's I–O table (479 × 1 vector)

Rm^{C}: the ratio between Canada's imports from Japan and Canada's total imports from the world (479 × 479 diagonal matrix)

$\mathrm{Xm}^{\mathrm{J,C}}$: Canada's imports from Japan in Canada's I–O table (479 × 1 vector)

${}_{\mathrm{tr}}\mathrm{Xm}_{\mathrm{io}}^{\mathrm{C}}$: converter matrix from Canada's I–O table to Canada's trade data (479 × 479 diagonal matrix)

$\mathrm{T}_{\mathrm{C}}^{\mathrm{J,C}}$: Canada's imports from Japan in Canada's trade data system (479 × 1 vector)

${}_{\mathrm{hs}}\mathrm{R}_{\mathrm{tr}}^{\mathrm{J,C}}$: converter matrix from Canada's trade system (479 commodities) into the 8 digit HS system (3578 times 479 matrix)

$\mathrm{HS}^{\mathrm{J,C}}$: Canada's imports from Japan in the 8 digit HS classification system (3578 × 1 vector)

${}_{\mathrm{tr}}\mathrm{R}_{\mathrm{hs}}^{\mathrm{J,C}}$: converter matrix from the 8 digit HS classification into Japan's 405 classification (405 × 3578 matrix)

${}_{\mathrm{tr}}\mathrm{R}_{\mathrm{tr}}^{\mathrm{J,C}}$: data adjustments from Canada's trade data system to Japan's trade system (405 × 405 diagonal matrix)

$\mathrm{T}_{\mathrm{J}}^{\mathrm{J,C}}$: Japan's exports to Canada in Japan's trade system (405 × 1 vector)

${}_{\mathrm{io}}\mathrm{Xe}_{\mathrm{tr}}^{\mathrm{J}}$: converter matrix from Japan's trade data to Japan's I–O system (405 times 405 diagonal matrix)

$\mathrm{Xe}_{\mathrm{J,C}}$: Japan's exports to Canada in Japan's I–O table (405 times 1 vector)

C.3. Conversion formulas: summary

It is shown that Japan's imports from Canada and Canada's exports to Japan are connected by the following formulas.[61]

$$\mathrm{Xe}^{\mathrm{C,J}} = {}_{\mathrm{io}}\mathrm{Xe}_{\mathrm{tr}}^{\mathrm{C}}\ {}_{\mathrm{tr}}\mathrm{R}_{\mathrm{tr}}^{\mathrm{C,J}}\ {}_{\mathrm{tr}}\mathrm{R}_{\mathrm{hs}}^{\mathrm{C,J}}\ {}_{\mathrm{hs}}\mathrm{R}_{\mathrm{tr}}^{\mathrm{C,J}}\ {}_{\mathrm{tr}}\mathrm{Xm}_{\mathrm{io}}^{\mathrm{J}}\ \mathrm{Xm}^{\mathrm{C,J}} \tag{C.1}$$

which can be rewritten as

$$\begin{aligned}\mathrm{Xe}^{\mathrm{C,J}} &= Z^{\mathrm{C,J}}\ \mathrm{Xm}^{\mathrm{C,J}}\\ &= Z^{\mathrm{C,J}}\ \mathrm{Rm}^{\mathrm{J}}\,\mathrm{Xm}^{\mathrm{J}}.\end{aligned} \tag{C.2}$$

where $Z^{\mathrm{C,J}}$ is the conversion matrix defined by

$$Z^{\mathrm{C,J}} = {}_{\mathrm{io}}\mathrm{Xe}_{\mathrm{tr}}^{\mathrm{C}}\ {}_{\mathrm{tr}}\mathrm{R}_{\mathrm{tr}}^{\mathrm{C,J}}\ {}_{\mathrm{tr}}\mathrm{R}_{\mathrm{hs}}^{\mathrm{C,J}}\ {}_{\mathrm{hs}}\mathrm{R}_{\mathrm{tr}}^{\mathrm{C,J}}\ {}_{\mathrm{tr}}\mathrm{Xm}_{\mathrm{io}}^{\mathrm{J}}. \tag{C.3}$$

Similarly it is shown[62] that Canada's imports from Japan and Japan's exports to Canada are connected by

$$\mathrm{Xe}^{\mathrm{J,C}} = {}_{\mathrm{io}}\mathrm{Xe}_{\mathrm{tr}}^{\mathrm{J}}\ {}_{\mathrm{tr}}\mathrm{R}_{\mathrm{tr}}^{\mathrm{J,C}}\ {}_{\mathrm{tr}}\mathrm{R}_{\mathrm{hs}}^{\mathrm{J,C}}\ {}_{\mathrm{hs}}\mathrm{R}_{\mathrm{tr}}^{\mathrm{J,C}}\ {}_{\mathrm{tr}}\mathrm{Xm}_{\mathrm{io}}^{\mathrm{C}}\ \mathrm{Xm}^{\mathrm{J,C}}. \tag{C.1a}$$

which can be rewritten as

$$\begin{aligned}\mathrm{Xe}^{\mathrm{J,C}} &= Z^{\mathrm{J,C}}\ \mathrm{Xm}^{\mathrm{J,C}}\\ &= Z^{\mathrm{J,C}}\ \mathrm{Rm}^{\mathrm{C}}\,\mathrm{Xm}^{\mathrm{C}}.\end{aligned} \tag{C.2a}$$

$Z^{\mathrm{J,C}}$ is the conversion matrix defined by

$$Z^{\mathrm{J,C}} = {}_{\mathrm{io}}\mathrm{Xe}_{\mathrm{tr}}^{\mathrm{J}}\ {}_{\mathrm{tr}}\mathrm{R}_{\mathrm{tr}}^{\mathrm{J,C}}\ {}_{\mathrm{tr}}\mathrm{R}_{\mathrm{hs}}^{\mathrm{J,C}}\ {}_{\mathrm{hs}}\mathrm{R}_{\mathrm{tr}}^{\mathrm{J,C}}\ {}_{\mathrm{tr}}\mathrm{Xm}_{\mathrm{io}}^{\mathrm{C}}. \tag{C.3a}$$

C.4. Our model of bilateral trade interactions

There are alternative ways to model trade interactions. As an example, consider meeting country *A*'s final demand. The final demand itself will generate demands for imports from country *B* and the rest of the world (ROW). *A*'s production activities to meet its final demand also generate demand for imports from *A* and the ROW. The demand for *B*'s output from the export sector will induce intermediate production activities in country *B*, which in turn will generate demands for imports from *A* and the ROW. These interactions will continue indefinitely. (Alternatively we can consider the above process triggered by country *A*'s exports to country *B*. *A*'s exports to *B* in turn generates demands for imports from *B* and the ROW, and so on.)

Suppose the trade interactions begin with meeting *A*'s final demand. We have the following sequence of events.

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[60] Details are available from the authors.

[61] Details are available from the authors.

[62] Details are available from the authors.

Step 1: A's final demand induces A's production in country A:

$$X^A = (I - (I - M^A)A^A)^{-1}\mathrm{Fd}^A$$
$$= B^A\ \mathrm{Fd}^A.$$

A's total imports from the world is derived by considering A's intermediate production and A's final demand

$$\mathrm{Xm}^A = M^A(A^A B^A(I - M^A)\mathrm{Fd}^A + \mathrm{Fd}^A)$$
$$= M^A(I + A^A B^A(I - M^A))\mathrm{Fd}^A.$$

A's imports from B is equal to B's exports to A

$$\mathrm{Xe}^{B,A} = Z^{B,A}\ \ \mathrm{Rm}^A\ \ \mathrm{Xm}^A.$$

B's exports induce B's production

$$X^{B,A} = B^B\,\mathrm{Xe}^{B,A}.$$

B generates CO_2 emissions in the production $X^{B,A}$.

Step 2: B's production activities induces A's production activities through trade

$$\mathrm{Xm}^{B,A,B} = \mathrm{Rm}^B M^B A^B X^{B,A},$$
$$\mathrm{Xe}^{B,A,B} = Z^{A,B}\ \ \mathrm{Xm}^{B,A,B},$$
$$X^{B,A,B} = B^A\ \ \mathrm{Xe}^{B,A,B}.$$

Step 3: A's production induced by its exports to B, in turn, induces B's production in the second round of the trade interactions between A and B.

$$\mathrm{Xm}^{B,A,B} = M^A A^A X^{B,A,B},$$
$$\mathrm{Xe}^{B,A,B,A} = Z^{B,A}\,\mathrm{Rm}^A\,\mathrm{Xm}^{B,A,B},$$
$$X^{B,A,B,A} = B^B\,\mathrm{Xe}^{B,A,B,A}.$$

B emits CO_2 from the production $X^{B,A,B,A}$.

Steps 2 and 3 can be summarized as follows:

$$X^{B,A,B,A} = (B^B Z^{B,A}\ \mathrm{Rm}^A M^A A^A B^A Z^{A,B}\ \mathrm{Rm}^B M^B A^B)X^{B,A} \tag{C.4}$$

or

$$X^{B,A,B,A} = Q^{B,A}\ \ X^{B,A} \tag{C.5}$$

where

$$Q^{B,A} = B^B Z^{B,A}\mathrm{Rm}^A \cdot M^A A^A B^A Z^{A,B}\mathrm{Rm}^B M^B A^B \tag{C.6}$$

If we iterate the above trade interaction process, we obtain the following for the nth iteration:

$$X^{B,A,\ldots,B,A} = (Q^{B,A})n\ \ X^{B,A}. \tag{C.7}$$

If we add up (B.12) over all iterations ($n = 0,1,2,3,\ldots$), the sum converges to

$$X^{\mathrm{sum}}(B,A) = (I - Q^{B,A})^{-1}X^{B,A}. \tag{C.8}$$

$X^{\mathrm{sum}}(B,A)$ is the total amount of production in country B that is induced by country A's final demand.[63]

Appendix D. Domestic and foreign price increases due to domestic carbon tax

D.1. Domestic carbon tax

The prices in our I–O model satisfy the following price equation

$$p^{\mathrm{d}} = [I - A'(I - M)']^{-1}(A'M'p^{\mathrm{m}} + v), \tag{D.1}$$

where p^{d} and p^{m} are domestic and imports price vectors, respectively. Suppose a domestic carbon tax of T_j dollars per unit output of the jth sector is introduced. We let T a diagonal matrix with T_j as the jth diagonal. Then the domestic price change induced by the carbon tax is given by

$$\Delta p^{\mathrm{d}} = p^{\mathrm{d}}(\mathrm{after}) - p^{\mathrm{d}}(\mathrm{before}), \tag{D.2}$$

where p^{d} (after) and p^{d} (before) denote, respectively the prices before and after the introduction of the carbon tax. It is easy to see that p^{d} (before) is a vector of ones. Since the jth component of $v(\mathrm{after}) - v(\mathrm{before}) = T_j$, it follows that

$$\begin{aligned}\Delta p^{\mathrm{d}} &= [I - A'(I - M)']^{-1}T\\ &= (T'[I - (I - M)A]^{-1})'\\ &= (i\,\mathrm{diag}(T)B)',\end{aligned} \tag{D.3}$$

where $B = [I-(I-M)A]^{-1}$ is a Leontief inverse and i is a vector of ones.

If the carbon tax rate θ is proportional to the CO_2 emission, $T_j = \theta E1_j$ for all j, then we have

$$\Delta p^{\mathrm{d}} = \theta(iE1B)', \tag{D.4}$$

where $E1_j$ is defined in this paper to be the amount of CO_2 in kilo tons generated for every million US dollars worth of sector j's output.

Numerical values for Δp^{d} are presented in Tables 1 and 2 for both Canada and Japan.

D.2. Foreign carbon tax

Suppose country A introduces a carbon tax which results in a domestic price change given by Δp^{d} (A). Denoting by $Zp\{A,B\}$ the price converter matrix which transforms prices in country A into prices in country B, the price changes for the goods imported by country B are given by a vector

$$\Delta p^{m}(B) = Zp\{A,B\}\Delta p^{\mathrm{d}}(A). \tag{D.5}$$

The change in domestic prices for country B is given by

$$\begin{aligned}\Delta p^{\mathrm{d}}(B) &= [I - A'(I - M)']^{-1}A'M'M_A\,\Delta p^{m}(B)\\ &= (\Delta p^{m}(B)'M_A\,\mathrm{MAB})'\end{aligned} \tag{D.6}$$

where M_A is a diagonal matrix with the jth diagonal representing the proportion of country B's imports of sector j from country A. Table 15 presents our estimation results for the effects of the Canadian (Japanese) carbon

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[63] Our model presented here may be viewed as an extension of the two-country competitive international I–O table to the case where the two countries have different numbers of commodity sectors.

tax on the Japanese (Canadian) domestic prices for the most highly affected goods.

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