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North American economic integration and industrial pollution in the Great Lakes region

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Abstract. This paper provides an assessment of the impact of increased economic integration within North America on industrial pollution intensities within the Great Lake states of the United States. It utilizes a three-country, applied general equilibrium model of the North American economy, data from the World Bank's Industrial Pollution Projection System, and employment data from the US Bureau of Economic Analysis to simulate the industrial pollution impacts of North American trade liberalization within the Great Lakes region. The results reflect the liberalization of tariff and non-tariff barriers, their trade and production impacts, state-level shares in the production changes, and the resulting industrial effluent changes. Two trade liberalization experiments show that, in many cases, the Great Lake states account for a substantial portion of the total emission changes caused by North American economic integration. Of particular concern to the Great Lake states are the emissions of the base metals, transportation equipment, and petroleum sectors.

JEL classification: C68, F14, Q2

1. Introduction

In the policy debates over NAFTA, the trade and environment issue has been at center-stage, its importance being reflected in the creation of a North American Commission for Environmental Cooperation. In the specific area of trade and industrial pollution within North America, Grossman and Krueger (1993), Reinert and Roland-Holst (2001a), and Reinert and Roland-Holst (2001b) have provided economy-wide evidence for detailed pollutants in each of the three countries of this free trade area. Much of the debate over trade and industrial pollution in North America has focused on the US-Mexico border region. Little attention, however, has focused on the environmentally-sensitive

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Great Lakes region. This paper takes up this latter region by examining the implications of increased trade under NAFTA for industrial pollution in the Great Lake states of the United States using an applied general equilibrium approach.

The issue of industrial pollution in the Great Lakes is not just speculative. It has entered into the discussions of the Great Lakes Regional Pollution Prevention Roundtable, the Great Lakes Information Network, the Great Lakes Pollution Prevention Initiative, and the Bi-National Toxins Strategy.[1] Most recently, concerns have been expressed over the impact of industrial pollutants on the safety of Great Lakes fish for human consumption, sediment contamination, and the safety of swimming in Great Lakes waters (US Department of State and US Environmental Protection Agency, 2001). Levels of industrial pollution in the Great Lakes region can directly impact human and aquatic ecosystem health.

This paper models the impact of trade liberalization in North America under NAFTA on industrial pollution in the Great Lakes states of the United States: Illinois, Indiana, Ohio, Michigan, Minnesota, New York, Pennsylvania, and Wisconsin. It utilizes an applied general equilibrium model of North America, state-level employment data from the US Bureau of Economic Analysis, and detailed effluent data from the World Bank's Industrial Pollution Projection System. Two experiments provide initial estimates of NAFTA trade liberalization on industrial pollution in these states. In many cases, the Great Lakes states account for a *substantial portion* of the total US effluent changes caused by North American economic integration. Of particular concern in this regard is the highly-polluting base metal, transportation equipment, and petroleum sectors.

Section 2 describes the general equilibrium modeling approach utilized, as well as its extension to provide regional effluent effects. Section 3 presents the results of two simulations, and Sect. 4 presents conclusions and final caveats.

2. General equilibrium modeling approach

There are a number of complementary approaches to analyzing the linkages between trade liberalization and industrial pollution.[2] The applied general equilibrium (AGE) approach used here is that developed by Lee and Roland-Holst (1997). It has the advantage of providing an integrated assessment of production, trade, intermediate demand (input-output linkages), final demand, and pollution effluent levels. In doing so, it simulates the base-year economy with certain *counter-factual* policy changes in place. The AGE approach to analyzing trade-pollution linkages does have some limitations, however. To utilize the terminology of Beghin and Potier (1997), it focuses primarily on sectoral composition effects and static scale effects but neglects dynamic scale (growth) effects and trade-liberalization-induced efficiency effects. That said, suggestive "quasi-growth" effects are provided through the relaxation of labor supply constraints. As implemented here, the AGE approach also does not account for the way in which "non-market" valuations of environmental outcomes can influ-

[1] See Allardice and Thorp (1995), Dworsky (1993), Lichty, McDonald, and Lamphear (1996), and Valiente et al. (1997). On US regional trade with Canada and Mexico, see Nissan (1999).
[2] For a review, see Huang and Labys (2000).

ence household welfare and consumption behavior (e.g., Espinosa and Smith 1995). Nevertheless, the AGE modeling framework captures a number of essential linkages in the trade and industrial pollution process.[3]

The AGE model used here has a base year of 1991. As detailed in the Appendix, it is a three-country model, incorporating production, consumption and trade relationships in Canada, the United States, and Mexico. The model is calibrated to the three-country, multi-sector social accounting matrix detailed in Reinert and Roland-Holst (2001b), thereby capturing both direct and indirect production (and therefore pollution) linkages.[4] The trade specification follows that of de Melo and Robinson (1989). In each sector of each country, domestic demand is constituted of goods that are differentiated by origin (domestic good, imports from each North American trading partner, and imports from the rest of the world) and destination (domestic good, exports to each North American trading partner, and exports to the rest of the world) using constant elasticity of substitution (CES) and constant elasticity of transformation (CET) functions, respectively. With regard to each country's relationship to the rest of the world, the small-country assumption of fixed world prices is maintained. Exchange rates are flexible, while trade balances are fixed.

Production in each sector of each country utilizes physical capital and labor. As is standard practice in AGE modeling, these factors are assumed to be perfectly mobile among the sectors of each country but immobile among countries. Production takes place under constant returns to scale using CES functions for value added and Leontief (fixed coefficient) functions for intermediates. Final demand in each country is modeled using the linear expenditure system (LES) functional form.

All markets are perfectly competitive, and two experiments bracket labor supply within the empirically-relevant range of the zero/unity interval.[5] The two trade liberalization experiments considered involve the removal of both observed tariffs and non-tariff barriers (NTBs). For NTBs, very rough estimates based on UNCTAD trade control measure data are used. As is general practice (e.g., Gaston and Trefler 1994), these NTB coverage ratios are utilized as *ad valorem* equivalents.[6]

As mentioned in the introduction, industrial pollutant effluent data are taken from the World Bank Industrial Pollution Projection System (IPPS).[7] These data were originally collected using US data and therefore have particular applicability for the case of the Great Lakes states. These data are utilized at the 3-digit level and, as recommended by their compilers, in their per-employee form. Table 1 describes the IPPS pollutants. In the case of air pollution, the IPPS data include particulates, carbon monoxide, sulfur dioxide, nitrogen dioxide, and volatile organic compounds. In the case of industrial bio-accumulative metals and toxins, the data distinguish among transmission to air, water, and

[3] For a cautionary analysis of AGE modeling in the environmental context, see Peters et al. (1999).
[4] This social accounting matrix is also utilized in the work of Jansen (2001). On pollution linkage analysis, see Fritz et al. (1998) and Reinert and Roland-Holst (2001b).
[5] See Killingsworth (1983). Behavioral elasticities of the above functions are reported in Reinert and Roland-Holst (1998).
[6] The NTB measures are detailed in Roland-Holst et al. (1994).
[7] On the IPPS, see Hettige, Lucas and Wheeler (1992) and the references therein. See also the New Ideas in Pollution Regulation website at www.worldbank.org/nipr/index.htm.

Table 1. The industrial pollution projection system pollutants

Name	Symbol	Description
Particulates	PT	Fine airborne particles that can damage respiratory systems.
Carbon monoxide	CO	A poisonous gas that inhibits the ability of blood to carry oxygen.
Sulfur dioxide	SO2	A gas that can contribute to respiratory disease and acid rain.
Nitrogen dioxide	NO2	A gas that contributes to both respiratory disease and to the formation of acid rain and ozone.
Volatile organic compounds	VOC	A class of chemicals associated with skin reactions, nervous system effects, sick-building syndrome, and multiple chemical sensitivity. Many are also suspected carcinogens.
Bio-accumulative metals	MetAir, MetWat, MetLand	Metals, including mercury, lead, arsenic, chromium, nickel, copper, zinc, and cadmium. They contribute to mental and physical birth defects.
Toxic pollutants	ToxAir, ToxWat, ToxLand	A class of chemicals that can damage internal organs and neurological functions, cause reproductive problems and birth defects. Many are also suspected carcinogens.
Biological oxygen demand	BOD	Organic water pollutants that remove dissolved oxygen. They can damage aquatic species and promote the growth of algae and pathogens.
Total suspended solids	TSS	Non-organic, non-toxic particles that can damage aquatic ecosystems and promote the growth of pathogens.

Source: World Bank

land. Finally, in the case of water pollution, the data distinguish between biological oxygen demand and total suspended solids. The result is a significant amount of detail in both sectoral and pollutant dimensions.

Estimate the impacts of North American economic integration on industrial pollution within the Great Lakes states are made using 1991 state-level employment data from the US Bureau of Economic Analysis. Employment shares by industry for Illinois, Indiana, Ohio, Michigan, Minnesota, New York, Pennsylvania, and Wisconsin are used to calculate the change in effluent levels for each if the IPPS pollutants caused by North American economic integration under the two experiments mentioned above. The calculation is that of Appendix Eq. 23:

$$E_{i,\,US,m,\,GL} = ip_m em_{i,\,GL,\,US} L_{i,\,US}$$

where $E_{i,\,US,m,\,GL}$ is the emissions of IPPS pollutant m from sector i of the Great Lakes region of the United States, ip_m is the IPPS emissions coefficient for pollutant m, $em_{i,\,GL,\,US}$ is the employment share of sector i in the Great Lakes region of the United States, and $L_{i,\,US}$ is the employment of sector i in the United States. As shown in this equation, changes in $L_{i,\,US}$ brought about through trade liberalization translate into changes in $E_{i,\,US,m,\,GL}$.

3. Results

Experiment 1 simulates NAFTA trade liberalization under the assumption that labor supplies are fixed. For this experiment, changes in industrial pollution emissions in the Great Lakes states are presented in Table 2. Consider first the changes in industrial *air pollution*. In the case of particulates, the two most important contributors are the base metal and transportation equipment sectors.[8] This is also the case for sulfur dioxide and volatile organic compounds. For carbon monoxide and nitrogen dioxide, the two most important contributors are the base metal and chemical sectors. The petroleum sector is also of note as a significant source of some air pollutants. In case of sulfur dioxide, the Great Lake states account for just short of one half of the additional US emissions cause by North American economic integration. This may be important since, along with nitrogen oxides, sulfur dioxide is a leading contributor to the acid rain dispute between the United States and Canada. The Great Lake states are therefore strongly implicated in this problem.

Next consider the changes in industrial *bio-accumulative metals pollution* in the Great Lake states. For all three pollution types (metals to air, metals to water, and metals to land), the base metals sector is the most important source of emissions. For the case of metals to land, the chemicals, wood and metal products and transportation equipment sectors are also significant sources. For all three pollution types, the Great Lake states account for approximately one half of the additional US emissions caused by North American economic integration.

Next consider the changes in industrial *toxin pollution* in the Great Lake states. Except for the case of toxins to water, where the transportation equipment sector is not important, the chemicals, base metals, and transportation equipment sectors are the most significant sources of toxin pollution accumulating to air, water, and land. The accumulation of toxins in water is an important issue for the Great Lakes. As stated by Munton and Kirton (1994), "increasing scientific evidence points to the seriousness and complexity of the toxic waste problem in the (Great) Lakes" (p. 63). Thus, the TWater column of Table 2 is of particular importance for the concerns of this paper. For toxin pollution as a whole, the Great Lake states are less important in contributing to US totals than for air and bio-accumulative metals.

If there is a most important area of concern for the Great Lakes in increased North American economic integration, it is *water pollution*. Indeed, Munton and Kirton (1994) state that "Without doubt, the to major Canada-US transboundary environmental issues in recent decades have been the serious water pollution problems long affecting the Great Lakes" (p. 59–60).[9] Once again, the base metals sector appears as a significant source of emissions. In the case of biological oxygen demand, the food processing sector is also a significant

[8] With regard to base metals, the Great Lakes states account for approximately 70% of total US steel production. See Allardice and Thorp (1995).

[9] "The Great Lakes region's abundant water supply is an important resource connection for industry. Water use in manufacturing operations is concentrated in five major sectors: steel production, food processing, petroleum refining, chemicals/allied products and paper – all of which are well-represented in the regional economy. This intensity of water use is illustrated by the fact that the Great Lakes states account for 40% of US industrial water use, and much of this demand is based in the Basin" (Allardice and Thorp 1995).

Table 2. North American trade liberalization and industrial pollution in the Great Lake states (experiment 1, thousands of pounds)

Sector	Air					Metals			Toxins			Water	
	PT	CO	SO2	NO2	VOC	MAir	MWater	MLand	TAir	TWater	TLand	BOD	TSS
petrol	279	1,104	2,153	1,252	1,027	1	0	7	95	7	378	23	116
foodpr	681	214	1,008	905	451	0	0	3	49	10	120	1,089	427
textl	14	13	68	89	41	0	0	2	28	5	17	3	4
cloth	0	0	−1	0	0	0	0	0	0	0	0	0	0
leath	38	5	70	17	124	0	0	41	171	6	308	30	61
paper	7	42	37	20	10	0	0	0	9	2	3	20	67
chem	400	3,919	2,068	1,975	1,700	4	4	128	1,284	370	2,911	470	1,734
rubber	29	10	235	79	436	1	0	28	637	2	206	154	124
nmtmn	−71	−13	−98	−65	−5	0	0	0	−3	0	−4	0	−2
bsmetl	6,682	41,965	47,883	8,797	3,498	330	29	9,053	3,303	443	11,816	2,304	229,424
wdmetl	719	1,591	322	699	1,748	5	1	143	635	22	491	24	274
nelcmc	31	226	209	94	238	2	0	41	152	4	101	1	17
elcmc	−3	−18	−32	−16	−21	0	0	−7	−30	0	−30	−1	−2
trnseq	1,279	2,177	3,096	1,609	11,563	37	1	447	6,210	24	2,679	5	40
othmn	0	0	0	0	2	0	0	0	5	0	2	0	40
GL tot	10,086	51,236	57,018	15,458	20,811	379	35	9,887	12,544	893	18,998	4,122	232,325
US tot	24,349	103,913	127,442	35,750	55,991	776	65	20,765	32,920	2,261	44,826	11,615	385,891

Sectors are: Petroleum; food processing; textiles; clothing; leather; paper; chemicals; rubber; non-metalic mineral products; base metals; wood and metal products; non-electrical machinery; electrical machinery; transportation equipment; and other manufactures.
Pollutants are: PT – particulates; CO – carbon monoxide; SO2 – sulfur dioxide; NO2 – nitrogen dioxide; VOC – volatile organic compounds; MAir – metals to air,; MWater – metals to water; MLand – metals to land; TAir – toxins to air; TWater – toxins to water; TLand – toxins to land; BOD – biological oxygen demand; and TSS – total suspended solids.

source of emissions, and in the case of total suspended solids, so is the chemicals sector. The case of total suspended solids is very notable here in that the Great Lake states contribute approximately 60% of the US total. This type of water pollution would appear to be of major concern to the Great Lakes ecosystem.

Experiment 2 simulates NAFTA trade liberalization under the assumption that labor supply elasticities are unity. This involves a modification of Appendix Eq. 6 in which L_j becomes an endogenous variable rather than a parameter. For this experiment, changes in industrial pollution emissions in the Great Lakes states are presented in Table 3. For at least two reasons, the results presented in Table 3 should be interpreted cautiously. First, unity is the empirical *upper bound* on labor supply elasticities in industrial countries.[10] Second, due to the lack of trade in services data for North America, trade expansion is confined to agricultural and manufacturing sectors. This can *overstate* the output and industrial effluent effets in the manufacturing sectors of the Great Lake states. For both reasons, the results of Table 3 are probably overestimates. Nevertheless, they are suggestive of "quasi-dynamic" effects that occur when resource constraints are relaxed, effects that are important to many policy analysts concerned with environmental and natural resource issues.

The first thing to note about Table 3 is that, in contrast to Table 2, there are no negative effects in the non-metalic mineral and electrical machinery sectors. With the relaxation of the labor supply constraint, labor is not bid away from these two sectors. Second, the pollution effects are larger than in Table 2 because there is more trade creation among the three North American NAFTA members, contributing more greatly to both direct and indirect pollution effects in the Great Lake states. Third, however, the increases in pollution emissions that occur when labor supply constraints are relaxed are not uniform in percentage terms across sectors. Whereas emissions from the chemical sector more than doubles, those of the wood and metal product sector rise by less than sixty percent. Consequently, the list of high-polluting sectors increases beyond base metals, transportation equipment, and petroleum to include paper and chemicals.

4. Conclusions and caveats

The Great Lakes are positioned on the border of two countries in the process of increased economic integration. Given the fragile nature of these water resources, there has been a great deal of concern about the linkage in the Great Lakes region between increased economic activity and environmental degradation. In the case of industrial pollutions, the Great Lake states are particularly important since these account for approximately one third of US manufacturing output. Indeed, as demonstrated by the results presented in Tables 2 and 3, the Great Lake states account for a substantial portion of the total industrial pollution generated by increased integration of the North American economies. These effects are concentrated in the base metal, transportation equipment, petroleum, paper, and chemical sectors.

The AGE methodology used here has much to contribute to analyzing the trade and industrial pollution at the national and regional levels. Most notable

[10] Again, see Killingsworth (1983).

Table 3. North American trade liberalization and industrial pollution in the Great Lake states (experiment 2, thousands of pounds)

Sector	Air					Metals			Toxins			Water	
	PT	CO	SO2	NO2	VOC	MAir	MWater	MLand	TAir	TWater	TLand	BOD	TSS
petrol	907	3,586	6,995	4,070	3,337	2	1	23	307	22	1,228	76	378
foodpr	1,218	383	1,802	1,619	806	0	0	6	87	17	214	1,947	764
textl	20	18	97	127	58	0	0	2	39	7	23	4	6
cloth	0	0	1	0	0	0	0	0	0	0	0	0	0
leath	42	6	77	19	136	0	0	46	188	6	339	33	67
paper	530	3,098	2,707	1,496	744	1	1	3	625	127	220	1,451	4,881
chem	1,003	9,833	5,189	4,956	4,265	9	9	321	3,222	928	7,304	1,180	4,349
rubber	47	17	380	128	707	1	1	46	1,032	3	333	250	201
nmtmn	1,081	202	1,504	993	72	1	0	7	41	1	55	2	27
bsmetl	8,207	51,541	58,810	10,805	4,296	406	36	11,119	4,057	544	14,512	2,829	281,776
wdmetl	1,139	2,522	511	1,109	2,771	8	2	227	1,007	36	779	38	435
nelcmc	83	606	560	252	637	6	0	110	407	10	269	2	44
elcmc	17	85	154	76	103	1	0	35	144	1	144	6	9
trnseq	1,419	2,416	3,435	1,785	12,829	41	1	496	6,890	26	2,973	6	44
othmn	4	2	9	10	46	0	0	9	115	1	55	0	906
GL tot	15,719	74,313	82,232	27,445	30,808	476	50	12,449	18,162	1,729	28,448	7,825	293,888
US tot	38,143	164,753	183,428	73,200	86,001	953	109	24,482	47,678	4,647	69,085	20,357	559,526

Sectors are: Petroleum; food processing; textiles; clothing; leather; paper; chemicals; rubber; non-metalic mineral products; base metals; wood and metal products; non-electrical machinery; electrical machinery; transportation equipment; and other manufactures.
Pollutants are: PT – particulates; CO – carbon monoxide; SO2 – sulfur dioxide; NO2 – nitrogen dioxide; VOC – volatile organic compounds; MAir – metals to air,; MWater – metals to water; MLand – metals to land; TAir – toxins to air; TWater – toxins to water; TLand – toxins to land; BOD – biological oxygen demand; and TSS – total suspended solids.

in this regard is the integrated treatment of production, trade, intermediate demand, final demand, and pollution effluent levels. The most notable limitation of the methodology, however, is its failure to address dynamic technological change of the sort emphasized by Porter and van der Linde (1995). The crucial policy issue facing the Great Lakes region is how to capture the gains from increased North American economic integration without suffering unduly from the increased industrial pollution involved. While taxes and tradable pollution permits are the first-best instruments suggested by most AGE economists (e.g., Lee and Roland-Holst 1997, and Rendlemen et al. 1995), the technological changes ignored in the AGE approach are also crucial, especially those that can be leveraged through the many existing institutions concerned with the environmental quality of the Great Lakes. Perhaps for this reason, the analysis here is best interpreted as a crucial screening exercises that identifies where problems exist. The alleviation of the problems, however, requires an expanded frame of reference.

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Appendix
General equilibrium model equations

This appendix presents the equation structure for a three-country applied general equilibrium (AGE) model of trade and industrial pollution in North America. The equations of the model are presented first, and these are followed by a description of the variables and parameters. The equation that determines each variable is given in parentheses after the variable's definition.

Consumer behavior (LES)

$$P_{ij}^{Q} C_{ij} = P_{ij}^{Q} \mu_{ij} + s_{ij}\left(Y_j - \sum_h P_{hj}^{Q} \mu_{hj} \right) \quad \forall i,j \tag{1}$$

Cost equations and production (CES with Leontief intermediates)

$$V_{ij} = \left(\frac{X_{ij}}{a_{ij}} \right) [b_{ij}^{\phi_{ij}} w_j^{(1-\phi_{ij})} + (1 - b_{ij}^{\phi_{ij}}) r_j^{(1-\phi_{ij})}]^{1/(1-\phi_{ij})} \quad \forall i,j \tag{2}$$

$$T_{ij} = V_{ij} + \sum_h P_{hj}^{Q} io_{hij} X_{ij} \quad \forall i,j \tag{3}$$

Factor markets (CES demands and full employment)

$$L_{ij} = V_{ij}^{\phi_{ij}} X_{ij}^{(1-\phi_{ij})} b_{ij}^{\phi_{ij}} w_j^{-\phi_{ij}} a_{ij}^{(\phi_{ij}-1)} \quad \forall i,j \tag{4}$$

$$K_{ij} = V_{ij}^{\phi_{ij}} X_{ij}^{(1-\phi_{ij})} (1 - b_{ij})^{\phi_{ij}} r_j^{-\phi_{ij}} a_{ij}^{(\phi_{ij}-1)} \quad \forall i,j \tag{5}$$

$$\sum_i L_{ij} = L_j \quad \forall j \tag{6}$$

$$\sum_i K_{ij} = K_j \quad \forall j \tag{7}$$

Commodity demands, supplies, and allocation of traded goods (CES and CET)

$$Q_{ij} = \alpha_{ij}\left[\sum_k \beta_{ijk} D_{ijk}^{(\sigma_{ij}-1)/\sigma_{ij}}\right]^{\sigma_{ij}/(\sigma_{ij}-1)} \quad \forall i,j \tag{8}$$

$$\left(\frac{D_{ijk}}{D_{ijj}}\right) = \left[\left(\frac{\beta_{ijk}}{\beta_{ijj}}\right)\left(\frac{P_{ijj}}{P_{ijk}}\right)\right]^{\sigma_{ij}} \quad \forall i,j,k,\ j \neq k \tag{9}$$

$$X_{ij} = \gamma_{ij}\left[\sum_k \delta_{ijk} S_{ijk}^{(\tau_{ij}+1)/\tau_{ij}}\right]^{\tau_{ij}/(\tau_{ij}+1)} \quad \forall i,j \tag{10}$$

$$\left(\frac{S_{ijk}}{S_{ijj}}\right) = \left[\left(\frac{\delta_{ijk}}{\delta_{ijj}}\right)\left(\frac{P_{ijj}}{P_{ijk}}\right)\right]^{\sigma_{ij}} \quad \forall i,j,k,\ j \neq k \tag{11}$$

Commodity prices

$$P_{ij}^{Q} Q_{ij} = \sum_k P_{ijk} D_{ijk} \quad \forall i,j \tag{12}$$

$$P_{ij}^{X} X_{ij} = \sum_k P_{ijk} S_{ijk} \quad \forall i,j \tag{13}$$

$$P_{ijj} = \frac{T_{ij}}{X_{ij}} \quad \forall i,j \tag{14}$$

$$P_{ijk} = (1+t_{ijk})(1+\rho_{ijk}) e_j PW_{ijk} \quad \forall i,j,k,\ j \neq k \tag{15}$$

$$P_{ijl} = (1+t_{ijl})(1+\rho_{ijl}) e_j PW_{ijl} \quad \forall i,j,l = R \tag{16}$$

Commodity market equilibrium

$$Q_{ij} = C_{ij} + \sum_h io_{ihj} X_{hj} \quad \forall i,j \tag{17}$$

$$D_{ijk} = S_{ijk} \quad \forall i,j,k \tag{18}$$

Income and revenue

$$RT_j = \sum_i \sum_k t_{ijk} e_j PW_{ijk} D_{ijk} \quad \forall j \tag{19}$$

$$RQ_j = \sum_i \sum_k \rho_{ijk} e_j PW_{ijk} D_{ijk} \quad \forall j \tag{20}$$

$$Y_j = w_j L_j + r_j K_j + RT_j + RQ_j \quad \forall j \tag{21}$$

Foreign balance

$$\sum_{k \neq j} \sum_{i} PW_{ijk} S_{ijk} = \sum_{k \neq j} \sum_{i} PW_{ijk} D_{ijk} \quad \forall j \tag{22}$$

Regional pollution emissions

$$E_{ijmn_j} = ip_m em_{in_j j} L_{ij} \tag{23}$$

Sets and indices

$h, i \in I$	sectors
$j, k \in J$	NAFTA member countries (US, Canada, Mexico)
$l \in L$	NAFTA non-member countries (R = rest of world)
$m \in M$	IPPS pollutants
$n_j \in N_j$	regions of country j

Quantity variables

C_{ij} = final demand for composite consumption good i in country j (1)
D_{ijk} = demand for good i in country j from source country k (8, 9)
K_{ij} = input of physical capital in sector i of country j (5)
L_{ij} = input of labor in sector i of country j (4)
Q_{ij} = demand for composite consumption good i in country j (17)
S_{ijk} = supply of good i from country j to country k (10, 11)
X_{ij} = output of sector i in country j (14)
E_{ijmn_j} = emissions of IPPS pollutant m from sector I of region n_j of country j (23)

Price variables

e_j = exchange rate for country j (22)
P_{ijk} = domestic price of good i in country j demanded from country k (15, 16)
P^Q_{ij} = domestic purchaser price of composite consumption good i in country j (12)
P^X_{ij} = domestic producer price of composite good i in country j (13)
PW_{ijk} = world price of good i demanded in country j from country k (18)
r_j = rental rate on physical capital in country j (7)
w_j = wage rate in country j (6)

Nominal variables

RQ_j = quota rents in country j (20)
RT_j = tariff revenue in country j (19)
T_{ij} = total costs in sector i of country j (3)
V_{ij} = value added in sector i in country j (2)
Y_j = income in country j (21)

Parameters

a_{ij} = intercept parameter in CES production function in sector i of country j
b_{ij} = share parameter in CES production function in sector i of country j
em_{in_jj} = employment share of sector i in region n_j of country j
io_{hij} = input of good h needed per unit of sector i output in country j
ip_m = IPPS emissions coefficient (per employee) for pollutant m
K_j = total physical capital stock in country j
L_j = total labor force in country j
s_{ij} = consumption share for composite good i in country j
t_{ijk} = ad valorem tariff on imports of good i into country j from country k
α_{ij} = intercept parameter in CES product aggregation function for sector i of country j
β_{ijk} = share parameter in CES product aggregation function for product i in country j from source country k
δ_{ij} = share parameter in CET allocation function for sector i in country j
γ_{ij} = intercept parameter in CET allocation function for sector i in country j
μ_{ij} = subsistence minimum for composite consumption good i in country j
ϕ_{ij} = elasticity of substitution between labor and capital in sector i of country j
ρ_{ijk} = ad valorem equivalent quota on imorts of good i into country j from country k
σ_{ij} = elasticity of substitution among sources of product i in country j
τ_{ij} = elasticity of transformation among destinations for sector i of country j