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The Effect of NAFTA on Energy and Environmental Efficiency in Mexico

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Prior to Mexico's entry to the North American Free Trade Agreement (NAFTA), predictions of the consequent impact on the environment in that country ranged from the dire to very optimistic. This article investigates NAFTA's outcomes in terms of energy use and the emission of atmospheric pollutants. Specifically, has entry into NAFTA led to a convergence or divergence in indicators of emissions, environmental efficiency, and emissions-specific technology in Mexico, the United States, and Canada? A battery of tests is applied to these indicators for energy use and carbon, sulfur, and NOx emissions in the three countries. The results show that the extreme predictions of the outcomes of NAFTA have not materialized. Rather, trends that were already present before the introduction of NAFTA continue and, in some cases, improve post-NAFTA, but not yet in a dramatic way. There is strong evidence of convergence across the three countries toward a lower intensity of energy use and emissions per unit of GDP. Although intensity is rising initially for some variables in Mexico, it eventually begins to fall post-NAFTA. Per capita emissions of sulfur and NOx also show convergence, but this is not the case for energy and carbon, and the latter variables also drift moderately upwards. The state of technology in energy efficiency and sulfur abatement is improving in all countries, although there is little, if any, sign of convergence and NAFTA has no effect on the rate of technology diffusion. However, total energy use and carbon emissions increase both pre- and post-NAFTA and total NOx emissions increase in Mexico. Only total sulfur emissions are stable and falling in all three NAFTA partners.

Introduction

Prior to Mexico's entry to the North American Free Trade Agreement (NAFTA), predictions of the consequent impact on the environment in that country ranged from the dire to very optimistic. This article investigates NAFTA's outcomes in terms of energy use and the emission of atmospheric pollutants (carbon, sulfur, and NOx emissions). Up until now, there have been a very small number of economic evaluations of the environmental impact of NAFTA after the fact, whereas there were many discussions and predictions of its potential impacts. As Mexico was the smallest and the least liberalized of the three economies, pre-NAFTA concerns focused on the impact of NAFTA on Mexico. Although I focus on the implications for Mexico, the three countries are treated equally in my empirical analysis.

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Recent theory and empirical evidence on the relation between pollution and economic development suggests that there is a tendency for emissions per capita and per unit of gross domestic product (GDP) to converge over time across countries (Brock & Taylor, 2004; Stern, 2005). Convergence depends partly on the diffusion across countries of best practice technology in both emissions abatement and general economic productivity, which might be promoted by trade integration. Therefore, in addition to describing the pollution and energy use outcomes, I investigate whether or not entry into NAFTA led to a convergence in energy or emissions per capita and per unit of GDP and the state of emissions abating technology in Mexico, the United States, and Canada. The state of technology is estimated using the method developed by Stern (2005) who estimated a production frontier model for sulfur emissions for 16 Organization for Economic Cooperation and Development (OECD) countries. This approach allows each country to have its own stochastic state of technology and to converge to or move away from the best practice frontier over time. The production frontier model is estimated using the Kalman filter.

The structure of the article is as follows. Following this introduction, I discuss predictions of the impact of the NAFTA treaty on the environment in North America and review some of the evaluations to date of those impacts and the available information on Mexican environmental efficiency. These provide a background for evaluating the results of my analysis to be presented later. I then discuss theory relevant to the effects of NAFTA on economic and environmental variables of interest, which sets the scene for the development of my model. Following this, I describe the data and outline the research design, the model used for estimating emissions specific technological change, and the tests of convergence and structural breaks. Results and conclusions sections complete the article.

NAFTA's Impact on the Environment: Predictions and Outcomes

Predictions of the Effects of NAFTA

Much controversy surrounded the potential environmental impact of NAFTA in the early 1990s. Grossman and Krueger (1991) and Kaufmann, Pauly, and Sweitzer (1993) addressed this debate with predictions of what would happen to emissions of pollutants and the quality of the environment under NAFTA. Daly (1993) included the potential effects of NAFTA in a general article attacking free trade. Also of interest is the later study by Reinert and Roland-Holst (2001) that predicted the impacts of NAFTA on industrial pollution using an applied general equilibrium model. Grossman and Krueger (1991) concluded their influential article:

> [W]hile [environmental advocacy groups] raise a number of valid concerns, our findings suggest that some potential benefits, especially for Mexico, may have been overlooked. . . . Mexico is at the critical juncture in its development process where further growth should generate increased political pressures for environmental protection and perhaps a change in private consumption behavior. . . . Trade liberalization may well increase Mexican

> specialization in sectors that cause less than average amounts of environmental damage . . . a reduction in pollution may well be a side-benefit of increased Mexican specialization and trade (pp. 35–36).

In contrast, Kaufmann et al. (1993) took a much more pessimistic view that has been more accurate but far less influential in the economics community.[1] While Grossman and Krueger (1991) focused on finding potential environmental benefits for NAFTA, Kaufmann et al. (1993) "focus on . . . the potential for NAFTA to reduce social welfare by degrading the environment" (218). Mechanisms they cited include: the elimination of existing environmental regulation and using environmental externalities as a source of comparative advantage. The potential for the exploitation of genuine comparative advantages in the quality of resource stocks to mitigate the environmental impacts of their use was seen to be offset by NAFTA provisions allowing for subsidies to be retained in the extractive sector. Growth in scale of the economy was seen as exacerbating existing externalities, which would offset the possibly positive effects of the exploitation of economies of scale. Kaufmann et al. (1993) argued that it was impossible to know, *a priori*, whether NAFTA would have a positive or negative effect on the environment. Daly's (1993) view, in contrast, was very clear-cut. He saw the perils of freer trade as being so severe that he advocated more self-sufficiency and less trade. He predicted that Mexican production of agricultural staples would decline, being replaced by production of specialized crops for export, such as vegetables and flowers. Capital would flow to Mexico to exploit both low wages and environmental regulations resulting in increased pollution.

Reinert and Roland-Holst (2001) use an applied general equilibrium model calibrated to a 26-sector 1991 social accounting matrix for the three NAFTA countries linked to satellite accounts for 14 pollutants. The simulation removes tariffs among the partners and observes the resulting changes in pollution after the system moves to a new static equilibrium. Most types of pollution increase in the three countries but there are large differences in the changes in pollution across the different industries in each country. The greatest impacts are predicted in the United States and Canada and particularly in the base metals industry, although there are important increases in pollution from the Mexican petroleum sector. Regarding the pollutants examined in the current study, much greater increases in sulfur dioxide than NOx were predicted in each country with increases in the United States and Mexico about twice as large as in Canada. It is not easy however to compare these results to those in the current study as the Reinert and Roland-Holst model is a static equilibrium with no technological change and only covers industrial pollution and not electricity generation, transportation, or other important polluting sectors.

Evaluations of the Environmental Impacts of NAFTA

Eleven years after the introduction of NAFTA, there are relatively few general assessments of the impact of NAFTA after the fact from an economic perspective, which makes the three symposia organized by the Commission for Environmental

Cooperation of great value. Schatan (2002) reports on Mexico's manufacturing exports and the environment in the first five years of NAFTA. Cole (2004) investigates the effects from the perspective of U.S. production, consumption, and trade, while Gallagher (2004) examines the impacts of NAFTA from the Mexican perspective.

Schatan (2002) situates NAFTA in an ongoing process of trade liberalization in Mexico that began in 1987. Mexico saw very rapid export growth after 1994[2] but had already seen a greater change in the mix of its exports (from primary exports to manufactured and high-tech exports) in the two decades prior to NAFTA than any country in the Americas. The greatest growth in exports relative to imports occurred in relatively low pollution sectors. The largest amounts of foreign direct investment flowed into machinery, automobiles, food, and beverage production in 1994–98. The same is true when we look at exports to the United States alone. Schatan finds that manufactured exports increased by 171 percent between 1992/93 and 1997/98, but, if we assume that there were no technique effects, pollution emissions from manufacturing exports only increased by 87 percent as a result of the composition effect. It is hard to imagine that the technique effect could be big enough to offset the remaining scale effect. While the manufacturing sector itself and manufactured exports in particular are most directly and dynamically affected by NAFTA, direct emissions from manufacturing are only part of the picture, induced increases in emissions from transportation, electricity generation, oil refining, etc. need also to be considered.

Although Gallagher (2004) also focuses on the manufacturing sector, his is the first comprehensive assessment of the Mexico-wide impact of NAFTA on the environment. He finds that the growth of the Mexican economy during this period led to increased environmental degradation, but that the relative role of heavy industry declined in Mexico—there was no net pollution haven effect. Both sulfur and carbon dioxide emissions increased with increasing income, although growth in GDP was very moderate.

Cole (2004) concludes that while U.S. imports from Mexico have increased more than U.S. exports to Mexico, there is no evidence that this is resulting in "environmental displacement" from the United States to Mexico. In fact, while the United States does import more embodied pollution than it exports to all countries, its balance of trade in embodied pollution is reversed in the case of Mexico. Since the introduction of NAFTA, this pattern has become more and more pronounced.

The reality of NAFTA seems to be somewhere between the extremes painted by Grossman and Krueger (1991) and Daly (1993) and closest to the ambivalent picture outlined by Kaufmann et al. (1993).

Mexican Environmental Efficiency

Aguayo and Gallagher (2005) investigate changes in energy intensity in Mexico, which they find increased until 1988, after which it declined. This contrasts with results for most developed economies and China where intensity has been falling in recent decades and for some developed economies where energy intensity has been falling for a century or two including Sweden and Spain (Kander & Rubio, 2004) and the United States (Stern, 2004b).[3] However, Mexico's energy intensity in 2000 was less than that of the United States and several European countries, and comparable to Germany and Japan. Canada's energy intensity was higher than that of any other developed country.[4] As in other countries, the decline in energy intensity from 1988 to 1998 in Mexico was largely on account of declining intensity in industry. Within the industrial sector, declining energy intensity in energy intensive heavy industries offset increasing energy intensity in lighter industries. There has also been a shift away from the most energy intensive industries and the embodied energy in Mexican imports has increased. However, there also appears to be genuine technological progress within some industry sectors.

Interestingly, the decline in Mexican energy intensity starts just as liberalization began. China's energy intensity also only began to decline from 1979 with the opening of the economy. This suggests that NAFTA will continue to have beneficial effects on Mexican energy intensity.

Stern (2002) finds that, in a group of 64 countries between 1973 and 1990, Mexico is fairly inefficient in the emission of sulfur. It had roughly twice the level of emissions of the United States when the level of income and the input–output structure of the economy were taken into account. Canada's efficiency level was midway between that of the United States and Mexico. Relative efficiency was fixed in that study, while in the current study, the relative efficiency of countries can change over time.

Theory of Growth, Trade Liberalization, and the Environment

The effects of trade liberalization (including the formation of customs unions such as NAFTA) can be decomposed into scale, composition, and technique effects on emissions of pollutants (Copeland & Taylor, 2004; Gallagher, 2004; Grossman & Krueger, 1991). The technique effect can be further decomposed into the effects of changes in the mix of inputs and technological change; and technological change can be broken down into changes in general total factor productivity (TFP) and changes in emissions specific technology (Stern, 2004a). The scale effect is because of the increase in economic activity that results from trade liberalization and the composition effect is because of trade specialization, holding aggregate output constant. Technique effects do not result so obviously from standard trade theory. There are two main possible channels. Openness to trade favors the adoption of better practice technologies developed in other parts of the world, whether or not through foreign direct investment (Grossman & Krueger, 1991; Perkins & Neumayer, 2005). It is usually assumed, and the empirical evidence shows, that this direct effect is environmentally beneficial (Copeland & Taylor, 2004). A second indirect effect occurs when openness to trade results in changes in government policy. This could be detrimental to the environment if a "race to the bottom" ensues (Dasgupta, Laplante, Wang, & Wheeler, 2002), or if trade regulators see environmental policy as an unfair trade barrier. The effect will be positive if, instead, there is a harmonization of standards toward better practice. Grossman and Krueger (1991) pointed out that growth in income might affect the demand for environmental quality resulting in policy change affecting scale, composition, and technique. This is the environmental Kuznets curve (EKC) effect.

Recently, a new generation of emissions and growth models has emerged that emphasize technology and technological change rather than policy and preferences in determining the relationship between emissions and economic output and growth. These models are based on standard models of economic growth and the environment rather than the more specialized models of the earlier EKC literature. The models explain the more nuanced view of the stylized facts uncovered by myself and other authors who have carried out decomposition and convergence analyses. In particular, the pure income effect on emissions seems to be monotonic[5]—technique effects and, particularly, technological change, are the main cause of reduced emissions per capita.[6] Furthermore, environmental innovations are adopted with a fairly short time lag in developing countries but countries differ in the extent to which they adopt the best practice technology (Hilton, 2006). These differences cannot be explained by income per capita alone (Stern, 2005). Periods of fast economic growth tend to overwhelm the effect of improving technology in reducing emissions, which is why pollution rises in many fast-growing middle-income countries. Finally, the trajectory of individual countries depends on factors such as endowments of natural resources and the consequent effects on industrial structure and input mix (Stern, 2002, 2005).

In a theoretical piece, Chimeli and Braden (2005) try to explain these patterns by focusing on differences in TFP across countries with the state of technology held constant in each country. Presumably, as in the growth theory of Parente and Prescott (2000), institutions determine the level of TFP in each country. Parente and Prescott (1999, 2000) theorize that international differences in TFP are, in large part, because of the barriers that governments impose which make it impossible or more expensive for producers to adopt the more productive technologies that are available in other countries. Lopez and Mitra (2000) develop a similar theory about the income–emissions relationship, where corruption leads to higher levels of pollution and a higher turning point for the EKC. Therefore, according to these theories, trade liberalization reduces the "barriers to riches" and should result in a convergence in TFP levels and emissions intensities across countries. In Chimeli and Braden's model, each country monotonically converges on a steady state with rising consumption and environmental quality along the transition path.[7] However, it turns out that environmental quality has a U-shaped relation with TFP. Therefore, a cross-sectional EKC could be derived on account of differing levels of TFP across countries even though each country's environmental quality improves monotonically toward the steady state. An implication is that "ignoring country-specific characteristics likely correlated with TFPs and income may produce biased and inconsistent estimates of the relationship between development and the environment" (Chimeli & Braden, 2005, p. 377), which is exactly what is found in numerous EKC studies that compare random and fixed effects estimates using the Hausman test (Stern & Common, 2001).

Brock and Taylor (2004) develop four growth with pollution models that generate refutable predictions regarding the potential effects of technological change and shifts in composition on pollution emissions. Their "Green Solow Model" (GSM) is the standard Solow growth model with the addition of pre-abatement pollution emissions that are a linear function of output. They also assume that a fixed fraction of capital and effective labor is used for abatement. Exogenous technological progress lowers the emissions–output coefficient over time and augments labor at independent rates. Unless the rate of emissions reducing technological change is greater than the growth rate of effective labor, the economy needs to increase the share of inputs devoted to abatement in order to maintain environmental quality. If emissions are falling along the balanced growth path, then they will follow an EKC-type path along a transitional growth path and the share of abatement in output will remain constant. This is because growth is faster at lower income levels than higher income levels in the Solow model, and thus, overwhelms the abatement effort at lower income levels. This model matches some of the stylized facts. As in the standard Solow growth model, conditional convergence of developing countries with developed countries over time is expected.

The other models described in the article alter this basic model by: omitting technological change; allowing compositional change of inputs with pollution generated by energy use rather than output; and finally modeling both optimization of investment and abatement decisions and endogenous technological change (the Kindergarten Rule Model [KRM]). The second and third models result in predictions—that the share of abatement is rising rapidly and that energy prices should rise rapidly over time—that are refutable. Neither of these models includes technological change, and thus, this must be a major factor in explaining the historical evidence, which is exactly what is found by empirical studies.

The KRM generates similar but more complex results than the GSM. Abatement converges to a constant share along the transition path, there is initially no pollution regulation, and pollution rises and falls in an EKC-type pattern. However, each country will have a different income turning point and maximum emissions level. Nevertheless, countries converge to similar emission levels and intensities from different initial conditions, and thus, "environmental catch-up" occurs. Empirical studies by Strazicich and List (2003), Lindmark (2004), and Alvarez, Marrero, and Puch (2005) find evidence of convergence for a variety of pollutants across groups of mainly developed countries.

As discussed above, opponents of NAFTA argued that as regulation was weaker in Mexico, Mexico would be a pollution haven and the introduction of NAFTA would result in a shift of polluting industry to Mexico. Taylor (2004) summarizes the state of knowledge on the pollution haven hypothesis. It is clear that differences in environmental regulation across countries generate a pollution haven effect: changes in environmental regulation will have a marginal effect on the location of polluting industries and trade in pollution intensive products. However, it does not follow that reducing the barriers to trade will result in a shift in trade and investment patterns such that polluting activity shifts to the less-regulated regimes (the pollution haven hypothesis). This is because a host of other factors, such as endowments and laws and regulations, in other policy areas also determine trade flows and the location of investment. The empirical evidence is insufficient to either reject or accept this hypothesis in general. Taylor also concludes that "the relationship between trade, technology and the environment is not well understood . . . [because] too little [emphasis has been placed] on how openness to world markets affects knowledge accumulation and technology choice. This is surprising, because it is widely believed that technology transfer to poor developing countries will help them limit their pollution regardless of the stringency of their pollution policy or their income levels. If the diffusion of clean technologies is accelerating as a result of globalization, this indirect impact of trade may well become the most important for environments in the developing world" (p. 25).

Methods and Results

Data

The sources of the data are described in the Data Appendix. I constructed continuous time series for the three NAFTA countries for 1971–2003 for sulfur, NOx, and carbon emissions, energy use by fuel, GDP in purchasing power parity Dollars, population, shares of industries in value added, oil refining (as measured by crude oil consumption), and the smelting of copper, lead, nickel, and zinc. Complete series are available for all of the explanatory variables and energy use as well as sulfur emissions. Complete CO2 series were also obtained with the exception of 2003 emissions in Mexico. For NOx, availability is as follows: Canada, 1980–2002; Mexico, 1985–2003; and the United States, 1971–2003. All the underlying sources consist of annual time series data. I did not interpolate or extrapolate any data points. However, in a few cases, described in the Appendix, I have adjusted different sources so that they splice together smoothly.

Research Design—Overview

The method has three stages—computation of the various indicators of environmental efficiency, convergence analysis using the computed trends, and tests for structural breaks in the series. As the length of available time series for different countries and variables differ, the convergence tests are limited in each case by the country with the shortest emissions time series. As the structural break tests are applied to one country at a time, the full time series for each pollutant and country can be examined.

My methodology, on the one hand, does not allow us to specifically identify which changes are due to entry to NAFTA and which are not. On the other hand, it does allow us to assess both the overall change in environmental quality that has occurred and the changes in the different components of the technique effect. This allows us to determine whether or not environmental quality and environmental efficiency improved at a faster rate post-NAFTA in Mexico and whether or not Mexico is converging with the United States and Canada to a greater degree post-NAFTA than before. I compute each of the following measures and test for convergence among them pre- and post-NAFTA:

Changes in environmental quality—emissions per capita (assuming population change is not induced by trade liberalization)—encompasses scale, composition, and technique effects.

Changes in emissions intensity—emissions per unit output—express the effect of composition and technique effects (assuming constant returns to scale).

Changes in environmental efficiency—which hold constant the structure of inputs and outputs in each economy—express just technological change effects.

For pollutants such as sulfur and NOx, where there are viable abatement technologies, the technological change effect can be further decomposed into TFP between conventional inputs and outputs and the state of emissions-specific technology. For a given level of conventional output, output mix, and input mix, the level of inputs required is a function of TFP—the output per unit input that can be achieved. However, given these particular quantities of inputs, emissions will differ according to the abatement technology and the amount of abatement employed. The consequent level of emissions per unit input is the emissions-specific state of technology. This emissions-specific state of technology is estimated using an efficient frontier model described in the following subsection.[8] On account of lack of sufficient data for NOx, frontier models were only estimated for sulfur and energy efficiency. There are no significant carbon-abating technologies apart from fuel switching and adopting more energy efficient technologies, and there are no current technologies for sequestering carbon apart from growing trees, which is not accounted for in the computation of carbon emissions data. Therefore, changes in the carbon emitted per unit of energy are purely input mix effects and environmental efficiency reduces to simply a question of energy efficiency and, consequently, I did not estimate a separate model for carbon emissions.[9]

This section continues to present some exploratory empirical results, describes the efficient frontier models and their estimates, and then presents the convergence and structural break methodologies together with the results of those tests.

Exploratory Analysis of the Data

Figures 1–8 present per capita and GDP intensity series for each of the four environmental indicators—energy use, carbon emissions, sulfur emissions, and NOx—for the three countries. Table 1 gives the mean growth rates of the eight variables across the three countries in the column headed α. For all four indicators, a common pattern emerges. Mexico has far lower levels of the variable in per capita terms and similar levels to the United States and Canada in GDP intensity terms. In terms of GDP intensity, Canada is, in recent years, the "dirtiest country," while in per capita terms, either Canada or the United States is dirtiest depending on the variable considered.

The level and pattern of per capita energy use and intensity over time is very similar in both the United States and Canada. In Mexico, per capita energy use increases until the early 1980s and then flattens out at a level far below that of its neighbors to the North. Energy intensity in the three countries appears to converge over time and some of the same short-term movements are visible in all three

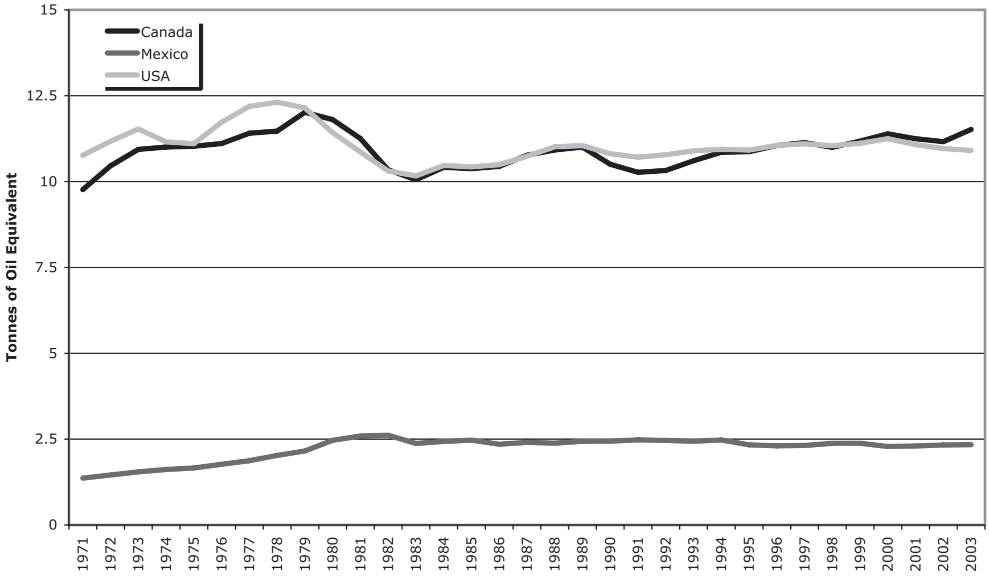

Figure 1. Energy Use per Capita.

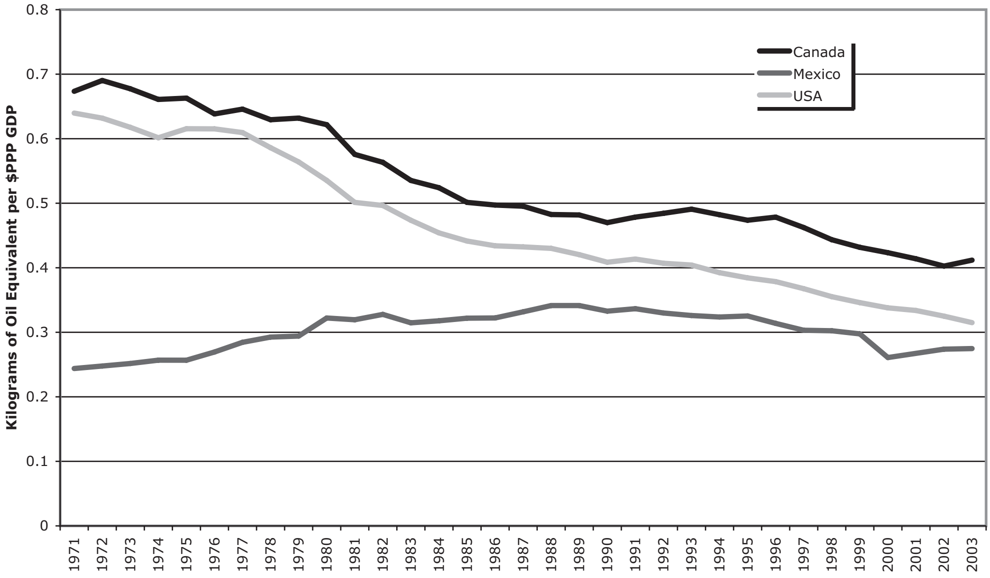

Figure 2. Energy Intensity.

countries. Not surprisingly, the patterns in the carbon series are quite similar. In recent years, energy and carbon intensity decline across the continent.

Convergence is more pronounced in the sulfur series. Per capita emissions declined in all three countries in recent years. Mexican sulfur intensity declines from the late 1980s after rising until the early 1980s and ends up essentially identical with

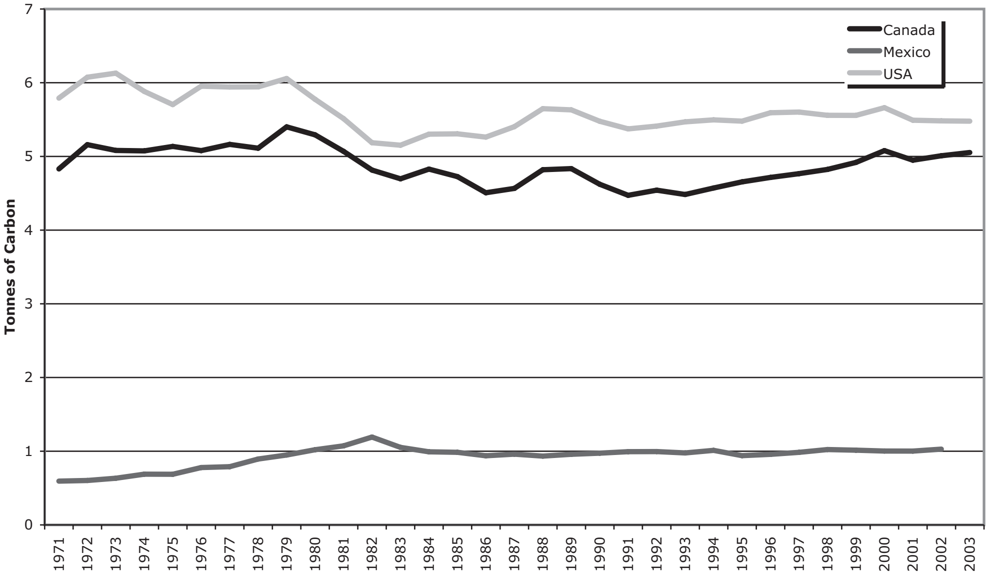

Figure 3. Carbon Emissions per Capita.

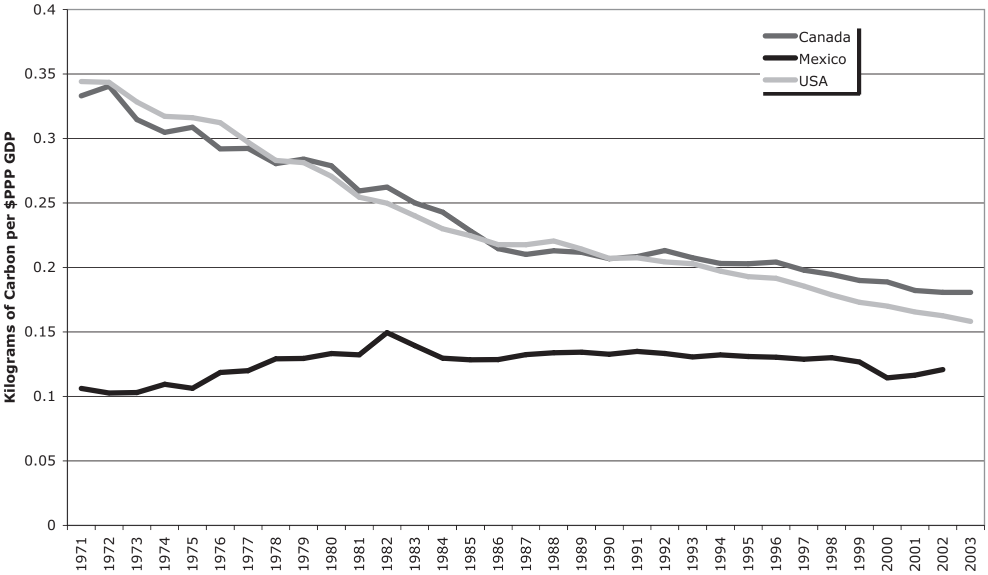

Figure 4. Carbon Intensity.

the level in Canada in the current decade. Differences in NOx emissions per capita are most pronounced with Mexico remaining the "cleanest" country over the period. However, per capita emissions and intensity rise in Mexico until the end of the 1990s and only show a sign of decline in the final year. There is no visually obvious structural break in the data in 1994. In the energy and carbon data, there is some sign

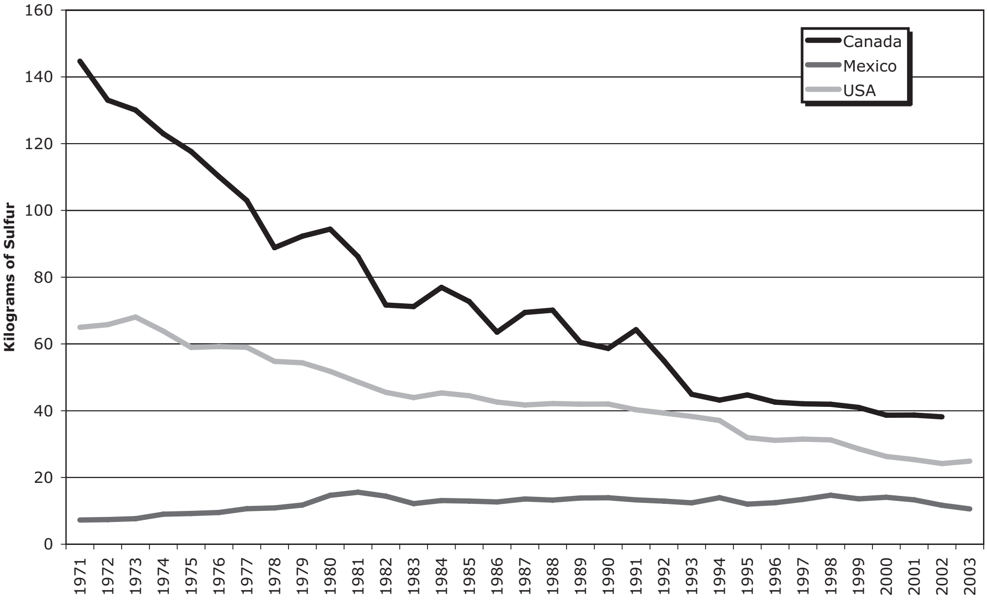

Figure 5. Sulfur Emissions per Capita.

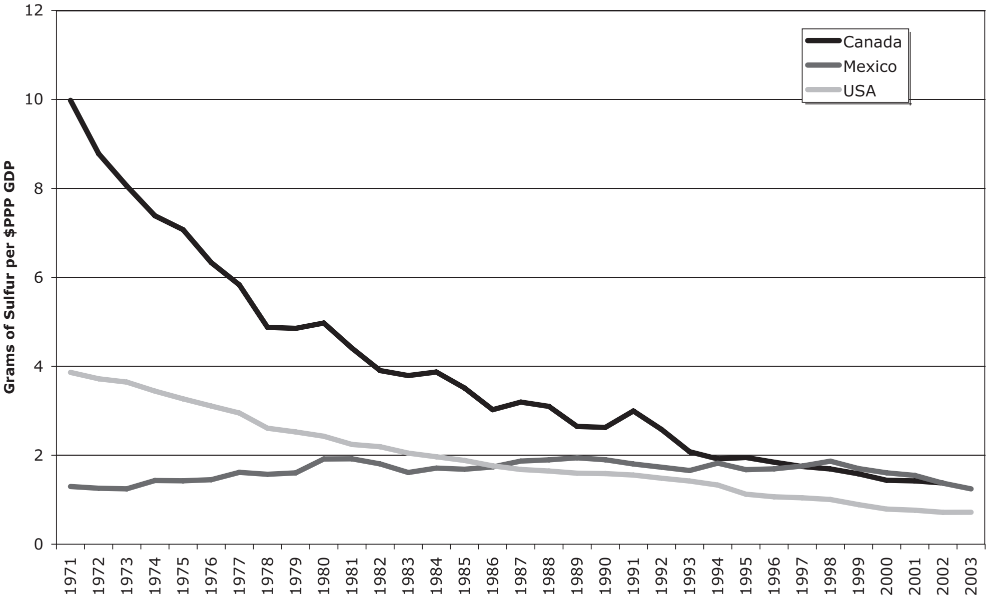

Figure 6. Sulfur Intensity.

of an increase in the per capita measure in Canada and a decrease in intensity in Mexico accelerating after that date.

These statistics do, however, hide important scale effects. Population rises 46 percent in Canada from 1971 to 2003, 95 percent in Mexico, and 40 percent in the

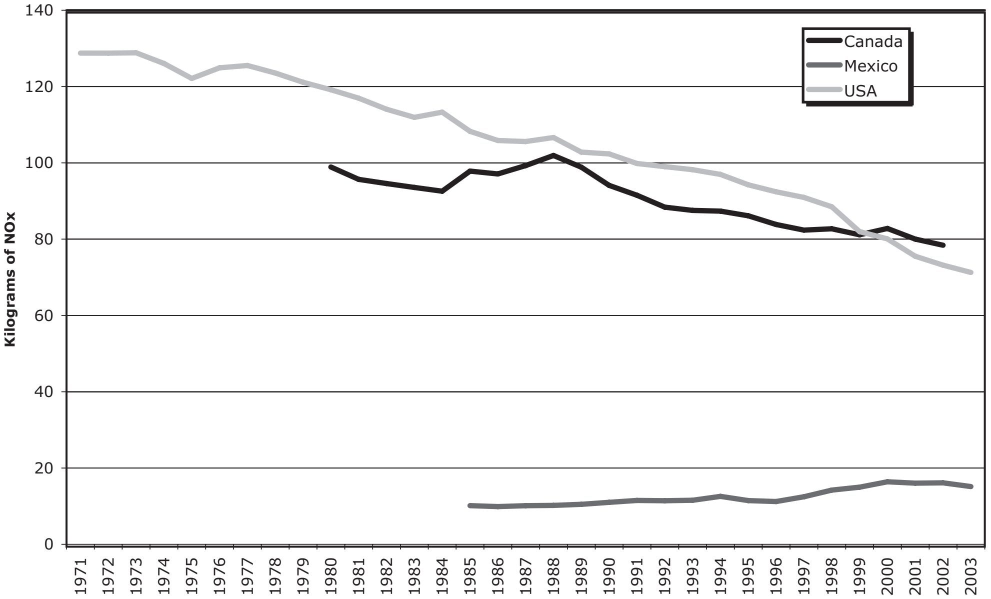

Figure 7. NOx per Capita.

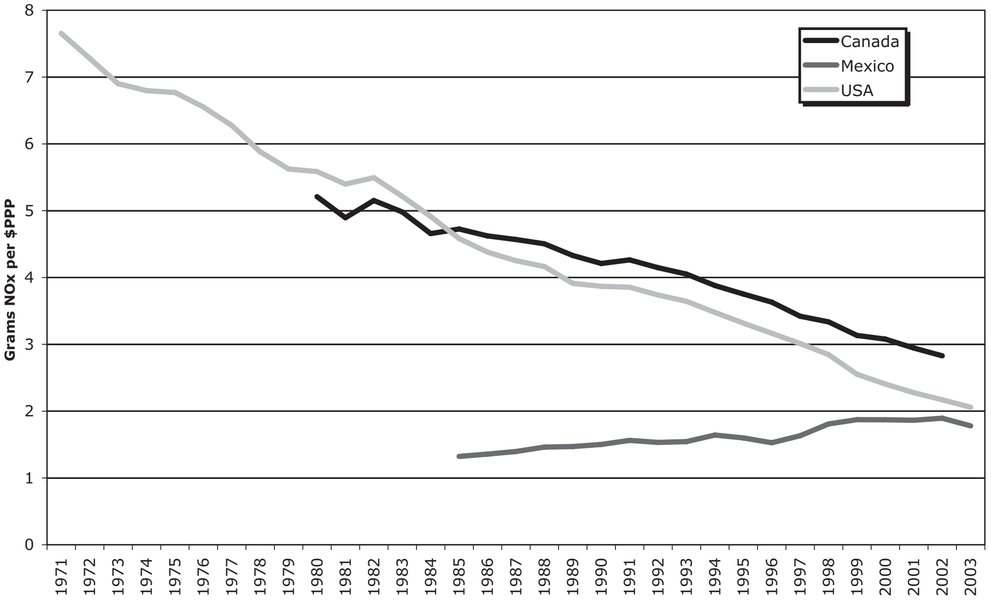

Figure 8. NOx Intensity.

United States. As noted above, energy use and carbon emissions have, therefore, risen in all three countries over the period. Sulfur and NOx emissions have risen in Mexico and NOx has only declined moderately in the two developed countries.

Table 1. β-Convergence Regressions

	α	β	δ_1	δ_2
Energy/P	0.0102	–0.0120	–0.0354	0.0160
	2.2096	*–2.2147*	*–1.5616*	*2.3446*
Energy/GDP	–0.0074	–0.0308	–0.0125	0.0269
	–2.4196	*–4.4297*	*–2.1323*	*1.7100*
A Energy	–0.0074	–0.0112	–0.0125	0.0165
	–2.1102	*–1.2173*	*–2.0478*	*1.1318*
Carbon/P	0.0055	–0.0116	0.0004	0.0114
	1.0535	*–1.9009*	*0.0613*	*1.4237*
Carbon/GDP	–0.0120	–0.0278	–0.0037	0.0183
	–2.8138	*–2.9776*	*–0.5991*	*1.2700*
Sulfur/P	–0.0176	–0.0251	–0.0084	0.0215
	–2.0489	*–3.2169*	*–0.5816*	*1.5910*
Sulfur/GDP	–0.0352	–0.0407	–0.0127	0.0311
	–4.5336	*–3.6881*	*–0.9895*	*1.8393*
A Sulfur	–0.017	–0.0156	2.87E–04	–8.60E–03
	–12.5263	*–5.9068*	*0.0996*	*–1.5254*
NOx/P	–0.0018	–0.0112	–0.0041	–0.0099
	–0.4951	*–3.1523*	*–0.4610*	*–0.9670*
NOx/GDP	–0.0114	–0.0301	–0.0163	–0.0102
	–2.9379	*–6.2859*	*–2.3161*	*–0.9238*

Notes: See equation (7) in the text for an explanation of the parameters. *t*-Statistics are in italics.

In summary, these data conform to the recent literature on the emissions-income relation discussed above. Per capita levels of local pollution emissions and energy and carbon intensity are declining with a lagged but eventual response in the developing country while in fact even in GDP intensity terms the developing country is cleaner than the developed world countries.

Efficient Frontier Models: Methods

The efficient frontier model for sulfur, developed by Stern (2005), is a logarithmic or Cobb–Douglas production frontier model with stochastic technological change. The Cobb-Douglas form is the simplest function with desirable properties for a production frontier. The model explains the level of emissions as a function of the inputs and outputs and the state of technology:

$$\ln E_{it} = \ln A_{it} + \sum_{k=1}^{4} \gamma_k \ln y_{kit} + \gamma_x \ln\left(\sum_{j=1}^{n} \beta_j x_{jit} \right) + u_{it} \tag{1}$$

This equation is estimated as a group of seemingly unrelated time series equations, one for each country, using the Kalman filter, which is described in the Appendix. The variables and parameters are defined as follows:

E_{it} is emissions of the pollutant in question in country *i* and year *t*.

A_{it} is the state of technology in emissions abatement modeled as a stochastically trending latent variable using the Kalman filter as described later in this section.

y_{kit} are four output variables: agricultural, non-manufacturing industry, manufacturing, and services value added.

γ_k are regression type parameters that sum to zero.[10]

γ_x is the returns to scale in inputs parameter which allows pre-abatement emissions to rise more slowly than the quantity of inputs, or vice versa. The parameter will be greater than one for decreasing returns and vice versa.

x_{jit} are the input variables: consumption of coal, oil, natural gas, hydropower, nuclear power, and biomass energy; primary smelting of copper, lead, zinc, and nickel; and oil refining (primary supply of crude oil).

β_j are regression type parameters which sum to unity.[11]

u_{it} is a random error term representing measurement error or short-run optimization error which may be correlated across countries so that the covariance matrix is unrestricted.[12]

To estimate the energy efficiency indicator, I estimate the output distance function (Shephard, 1970):

$$\sum_{k=1}^{4} \gamma_k \ln y_{kit} + \gamma_x \ln\left(\sum_{j=1} \beta_j x_{jit} \right) = A_{it} + \mathrm{v}_{it} \tag{2}$$

where v_{it} is a random error term. Homogeneity of degree one is imposed on the output coefficients and the input coefficients, β_j, sum to unity. The returns to scale parameter, γ_x, is expected to be negative as increasing inputs without increasing outputs represents a reduction in the state of technology A. Values greater than one in absolute value indicate increasing returns and vice versa. The vector x consists of the energy inputs only.

I model the technology trends as integrated random walks with noise,[13] which is the most general of the models typically used to represent the state of technology (Harvey & Marshall, 1991). In this case, the transition equations are:

$$\begin{aligned} A_{t+1} &= A_t + a_t + H_A \eta_t \\ a_{t+1} &= a_t + H_a \eta_t \end{aligned} \tag{3}$$

where η_t is a 6-vector of independent random error processes with a variance of one and mean zero. A_t and a_t are 3-vectors of stochastic trends—one trend A_{it} and one slope component a_{it} for each of the three NAFTA countries. The matrices $H_A = [h_A, h_a]$ and $H_a = [0, h_a]$ are 3×6 matrices that model the structure of the correlation of the random shocks across countries. The lower-case matrices h_A and h_a are lower triangular matrices. If these matrices are diagonal, then technology evolves completely independently in every country. Convergence of technology across countries requires that the state variables representing the state of technology in each country cointegrate with each other.[14] For this to occur, none of the random shock variables can be completely independent of all the others, which can be tested by examining the covariance matrix of the shocks. If any of the rows of h_a are null, then the relevant trend A_{it} is I(1) (first order integrated, or a simple random walk or unit root variable) with a constant drift.

If the relevant row of H_A is also null, then the trend is linear. The slope components, a, are, therefore, potentially time-varying. I also estimated a model without the slope components—this restriction can be rejected at a very high level of significance. The model is estimated using the diffuse Kalman filter algorithm (De Jong, 1991a, 1991b)—further description of these methods is presented by Stern (2005).

Frontier Models: Estimates

Tables 2–4 present the results of the estimation of the frontier models for energy and sulfur. Table 2 shows that the energy model passes the tests for whiteness of the residuals at reasonable significance levels. A likelihood ratio test (not reported in table) allows the rejection of the restriction that the observation errors are independent across the three countries at the 2 percent level.

The energy input coefficients shown in Table 3 should be reflective of energy quality—a joule of electricity has a different effect on economic output than a joule of coal. Usually electricity is found to be the highest quality (most productive) energy vector and biomass and coal to be the lowest quality. However, here, biomass has the highest quality factor and nuclear a negative coefficient. Clearly, these estimates are problematic. Possibly, the coefficients are biased because of the small sample of countries with differing economic structures, which can induce spurious correlations. The returns to scale parameter is –0.78, indicating decreasing returns to scale. The output coefficients should reflect the average shares of the four outputs in GDP and this seems to be approximately the case—only the coefficient for nonmanufacturing industry is too small.

The estimates of the variance parameters presented in Table 4 show that the energy model technology trends are simple random walks with constant drift terms as the variances of the slope components are all zero. The constant drift is important evidence against a structural break in technology. As $H_{33} = 0$, there are two common stochastic shocks shared by the technology trends in the three countries and,

Table 2. Frontier Models: Diagnostic and Trend Statistics

	Slope estimate	Standard error	*t*-Statistic	*p* Q(1)	*p* Q(8)	R-square
Energy model						
Canada	–0.0204	3.59E–03	5.68	0.61	0.56	n.a.
Mexico	–0.0127	2.52E–03	5.04	0.34	0.10	n.a.
United States	–0.0252	1.63E–03	15.46	0.49	0.36	n.a.
Sulfur model						
Canada	–0.0421	3.60E–03	–11.68	0.63	0.04	0.9825
Mexico	–9.49E–03	1.58E–03	–6.00	0.83	0.18	0.9843
United States	–0.0382	5.25E–03	–7.28	0.82	0.28	0.9981

Notes: The first three columns relate to the estimate of the slope component of the stochastic trend. The following two columns are *p* values for the Box–Pierce tests of generalized serial correlation in the model residuals. The final column presents the coefficient of determination for the respective equation. The dependent variable for the energy model is zero and, therefore, traditional measures of goodness of fit cannot be computed.

Table 3. Frontier Models: Parameter Estimates

Variable	Energy		Sulfur	
	Coefficients	*t*-Statistics	Coefficients	*t*-Statistics
Coefficients with respect to fuels				
Coal	0.1000	1.9103	0.03118	17.3148
Oil	0.1154	4.9275	0.00216	1.662
Natural gas	0.1041	3.6587	–0.00102	–0.5872
Hydro	0.3075	3.7969	9.80E-04	0.1351
Nuclear	–0.0569	–1.6001	–0.00384	–0.8704
Biomass	0.4299	n.a.	0.0037	1.5598
Coefficients with respect to other commodity production:				
Oil refining			0.00407	6.6929
Copper			0.19513	2.0713
Zinc			–0.22843	–3.276
Lead			–0.47014	–11.6613
Nickel			1.4662	n.a.
Output elasticities with respect to industries				
Agriculture	0.0451	n.a.	0.03706	n.a.
Nonmanufacturing Industry	0.0031	0.2361	–0.07958	–1.7075
Manufacturing	0.2740	8.2520	0.0434	0.8046
Services	0.6778	30.3142	–8.73E-04	–0.0216
Returns to scale in inputs				
	–0.7768	–10.9361	1.07482	52.4795

Notes: Parameter estimates for equations (1) and (2). The *t*-statistics have the usual *t*-distribution.

Table 4. Frontier Models: Covariance Parameters

Parameter	Energy model		Sulfur model	
	Coefficient	*t*-Statistic	Coefficient	*t*-Statistic
Error covariance matrix				
G_{11}	8.69E–03	–1.9930	0.0401	9.3461
G_{21}	6.94E–03	–1.4838	–0.0216	–2.2115
G_{22}	0.0112	3.6274	0.0409	9.4569
G_{31}	5.20E–03	1.4327	–6.92E–03	–1.5934
G_{32}	7.47E–03	3.4198	4.67E–03	0.9749
G_{33}	0	n.a.	0	n.a.
Trend shock covariance matrix				
H_{11}	0.0202	5.7678	0.0196	4.0597
H_{21}	1.14E–04	0.0336	–7.29E–03	–1.0565
H_{22}	0.0142	5.4470	0	n.a.
H_{31}	6.06E–03	2.4992	0.0292	15.2831
H_{32}	–6.87E–03	–3.8155	0	n.a.
H_{33}	0	n.a.	0	n.a.
H_{44}	0	n.a.	0	n.a.
H_{54}	0	n.a.	0	n.a.
H_{55}	0	n.a.	0	n.a.
H_{64}	0	n.a.	0	n.a.
H_{65}	0	n.a.	0	n.a.
H_{66}	0	n.a.	0	n.a.

Notes: G is the Choleski factor of the residual covariance matrix where the covariance itself is given by GG′. Similarly H is the Choleski factor of the trend shock covariance matrix. The parameters relating to the three countries are numbered alphabetical order, Canada first and USA third.

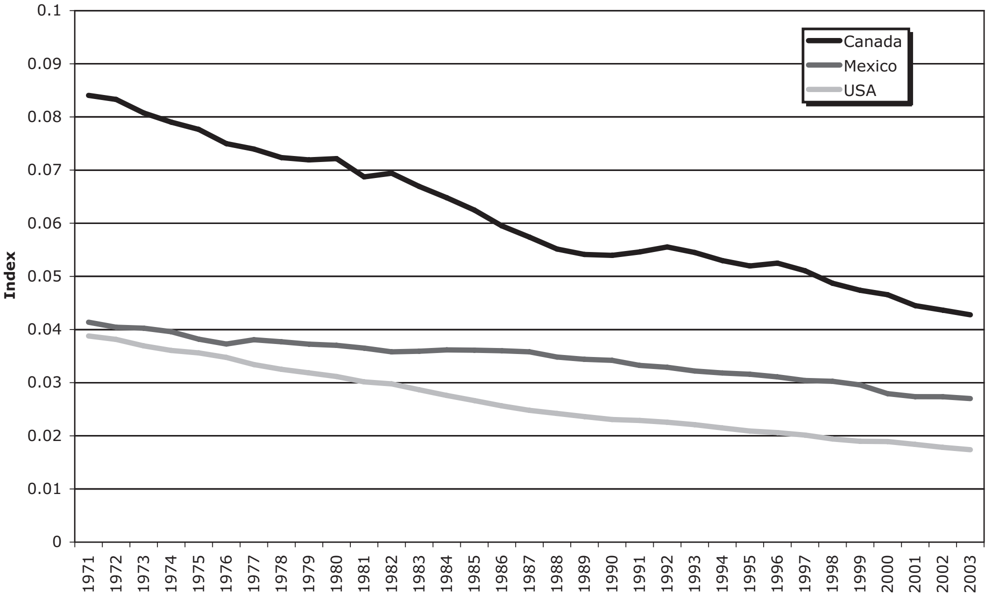

Figure 9. Energy Technology Trends.

therefore, we find that the trends cointegrate. However, the second shock has opposite effects on the Mexican and U.S. trends and Mexico only insignificantly participates in the first shock. The negative slope terms (Table 2 and Figure 9) show that the state of technology in energy efficiency is improving in all three countries, so that in absolute terms, there is convergence across the NAFTA region, but as the trends are more negative in Canada and the United States, convergence does not occur in logarithmic or percentage terms. As mentioned above, restricting these drift terms to zero can be strongly rejected, which is again confirmed by the highly significant *t*-statistics on the individual slope components presented in Table 2.

Figure 9 presents a chart of the technology trends for the energy model. The scale is arbitrary. According to these results, the United States is the most energy-efficient country throughout the period and Canada the least. The constant logarithmic drift term clearly dominates these series so that there is no apparent visual sign of a structural break in 1994.

Table 2 shows that the sulfur model also passes the tests for whiteness of the residuals at reasonable significance levels and that the model explains a very high percentage of the variation in the dependent variable. A likelihood ratio test (again not reported in the table) allows the rejection of the restriction that the observation errors are independent across the three countries at the 3 percent level. The estimated parameters for the sulfur model in Table 3 have some similarities and some differences with those estimated for a sample of 15 OECD countries by Stern (2005). On the whole, the values seem less plausible—in particular, the very large positive coefficient on nickel refining and negative coefficients on lead refining and non-manufacturing industry. The coefficients are likely biased on account of the small

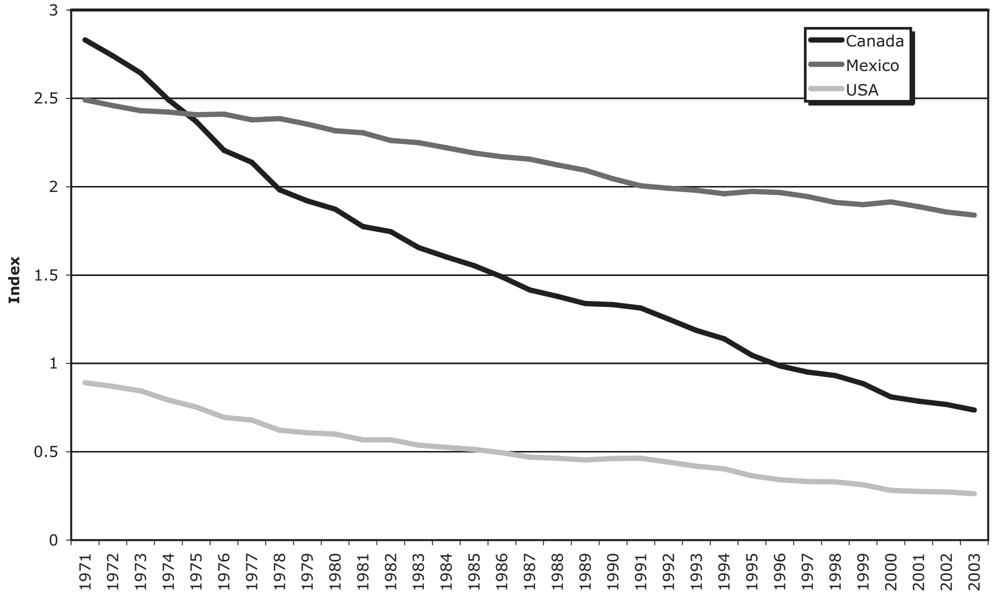

Figure 10. Sulfur Technology Trends.

sample of countries with differing economic structures, which can induce spurious correlations. For example, the highest level of nickel processing occurs in Canada, which also has the highest levels of sulfur emissions on either a per capita or per dollar of GDP basis, while the situation is exactly reversed in Mexico, and the United States has intermediate levels of both nickel processing and sulfur emissions. Also, all the coefficients should be interpreted on a *ceteris paribus* basis. Conditioned on primary fuel and metal smelting mix, additional nonmanufacturing industry could conceivably result in less emissions *ceteris paribus*. Furthermore, all the parameters indicate the marginal contribution to sulfur emissions given the average state of pollution abatement associated with that variable across the sample. An input that already has a high degree of abatement associated with it may have an insignificant effect on emissions, irrespective of what its contribution might be in the absence of any abatement. The modeled state of technology can only model changes in the level of abatement relative to an unknown baseline. The returns to scale term shows decreasing returns—as the inputs are increased by 1 percent, sulfur emissions increase by 1.07 percent *ceteris paribus*.

Table 4 shows that for the sulfur model, the optimal estimate finds that the technology trends are I(1) (simple random walks) with constant drift terms. There is only one common stochastic shock shared by the technology trends in the three countries, although the shocks in Mexico are negatively correlated with those in the United States and Canada. Therefore, we find that the trends do cointegrate. The negative drift terms (Table 2 and Figure 10) show that the state of technology in sulfur emissions is improving in all three countries, so that in absolute terms, there is convergence across the NAFTA region, but as the trends are more negative in

Canada and the United States, there is no convergence in logarithmic or percentage terms. As mentioned above, restricting these drift terms to zero can be strongly rejected, which is again confirmed by the highly significant *t*-statistics on the individual slope components presented here in Table 2.

Figure 10 presents the extracted technology trends for the sulfur model. Again, the scale is arbitrary. According to these results, the United States emits the least sulfur *ceteris paribus* throughout the period. Canada starts the period as the "dirtiest" country and improves significantly. Mexico improves at a slower pace. The trends in the figure are not in logarithms. It is clear, however, that the linear drift component of the logarithmic trends dominates the random walk component.

Structural Break Tests

The hypothesis we are testing is that the slope of the trend in each of the variables under consideration changed post-NAFTA. A test that allows for a change in both the intercept and the slope of the trend in the presence of a potential stochastic trend (unit root) was developed by Park and Sung (1994):

$$\Delta y_t = \alpha + \beta t + \delta_1 D_t + \delta_2 D_t t + (\rho - 1) y^*_{t-1} + \sum_{i=1}^{n/3} \Delta y_{t-i} + \varepsilon_t \tag{4}$$

where y_t is the logarithm of the series being tested and for $t > m$, $y^*_{t-1} = \frac{n}{n-m} y_{t-1}$; while for $t \le m$, $y^*_{t-1} = \frac{n}{m} y_{t-1}$ with the first m of the n observations occurring before the structural break. ε_t is a white noise error process, D_t is a dummy variable equal to zero before the structural change and one afterwards, and t is a linear time trend. The test for a unit root is the *t*-test on $\rho - 1$ with critical values tabulated in Park and Sung (1994). If this test finds that the series is stationary around the linear trend, then the appropriate model to estimate is:

$$y_t = \alpha + \beta t + \delta_2 D_t t + \upsilon_t \tag{5}$$

The test for a structural break in the slope is the standard *t*-test on δ_2. If the series has a stochastic trend, the appropriate model is:

$$\Delta y_t = \alpha + \delta_1 D_t + \upsilon_t \tag{6}$$

The test for a change in the drift term is the standard *t*-test on δ_1.

Table 5 presents the Park and Sung (1994) unit root tests that take into account a possible structural break in 1994 and a time trend. The critical value at the 5 percent level is –4.153 and at the 10 percent level is –3.869. Therefore, clearly we cannot reject the null hypothesis that all the series have a unit root. Therefore, I use equation (6) to test for a structural break.

Table 6 presents the *t*-statistics for the regression coefficients of the dummy variable in those regressions, which have standard *t*-distributions. The majority of

Table 5. Park and Sung Unit Root Statistics

	Canada	Mexico	United States
Energy/P	–0.36601	–1.63505	0.00973
Energy/GDP	–0.2391	0.17999	–0.90995
A Energy	–0.72959	0.50536	–0.75476
Carbon/P	–0.07764	–2.34267	–0.02427
Carbon/GDP	–0.56054	0.13296	–0.85952
Sulfur/P	1.58759	–1.00351	–1.57097
Sulfur/GDP	1.21039	–1.00923	–2.40736
A Sulfur	–3.03292	1.89150	1.57157
NOx/P	–0.39465	–0.32175	–0.2959
NOx/GDP	–0.92779	–1.84444	–0.63778

Notes: The null hypothesis is that the series contain a unit root. The critical value at the 5% level is –4.153 and at the 10% level –3.869.

Table 6. Structural Break Tests

	Canada	Mexico	United States
Energy/P	0.79495	–0.69035	–0.07093
Energy/GDP	–0.44981	–1.63003	–0.51523
A Energy	–0.57185	–1.08464	0.21887
Carbon/P	2.28982	–0.09798	0.40725
Carbon/GDP	0.40613	–1.05633	–0.53973
Sulfur/P	0.84956	–0.80493	–1.93413
Sulfur/GDP	0.09739	–1.00674	–1.9862
A Sulfur	–1.18220	1.17994	–1.17994
NOx/P	–0.35616	0.15483	–2.35752
NOx/GDP	–3.7493	–0.12953	–2.34738

Notes: The table presents the *t*-statistics for the coefficient δ_1 in equation (6). The null is that there is no structural break in the series in 1994.

the statistics are not significant at traditional significance levels. For the United States, the two NOx variables and the two sulfur variables all see increases in the rate of decline with significance levels of 5–10 percent. Canada sees a significant increase in the rate of decline only in the case of the NOx intensity and a significant increase in the growth rate of per capita carbon emissions. Mexico has no dummy coefficients that are significantly different from zero at greater than 10 percent levels but all except one of its *t*-statistics are negative. Therefore, while there is no strong evidence from this data that NAFTA improved environmental outcomes in Mexico, there certainly is no evidence that it made things worse and it may be associated with improvement in the United States.

Convergence Tests

I adapt the methods developed by Stern (2005) to test for convergence across the NAFTA countries and the effect of NAFTA on the convergence process. I test for convergence in three ways: the so-called β– and σ– convergence (Quah, 1996) and a cointegration-based test of convergence. The effect of NAFTA can be discerned by comparing the results in the pre-NAFTA period to those in the full sample. The post-NAFTA period is probably too short to be examined on a stand-alone basis.

In the current context, β– convergence tests whether there is a negative correlation between the initial levels of efficiency or technology and the growth rate of efficiency (or technology). If there is such a correlation, efficiency rose faster in initially less efficient countries, and thus, those countries converged to the best-practice frontier (Quah, 1996). I estimate the following regression:

$$\Delta y_{it} = \alpha + \beta y_{i0} + \delta_1 D_t + \delta_2 D_t y_{i0} + \varepsilon_{it} \tag{7}$$

where the variables are in logarithms and we can test whether β is significantly different from zero using a standard t-test computing the standard error using a method robust to serial correlation of unknown form (The RATS ROBUSTERRORS procedure).[15] The initial value, y_{i0}, is the first observation available.[16] The mean of the initial value across countries is deducted from these initial values so that α is the unconditional growth rate of the variable in question. The dummy variable D is used to test the effect of NAFTA.

σ-Convergence looks at the cross-sectional variance of efficiency over time. Decreasing variance over time implies convergence. On account of the small sample, I do not formally calculate the variance.

Cointegration implies that the state of technology in each country shares common stochastic trends with the states in other countries. In the absence of exogenous shocks, the countries' technologies will tend toward a long-run equilibrium with each other and converge. Without cointegration, convergence is impossible. However, this does not necessarily mean that convergence will occur within the period under consideration. Convergence will depend on the standard deviation of the shocks and the rate of adjustment to long-run equilibrium. Hence, the usefulness of the β– and σ– convergence tests.[17]

To apply cointegration testing to the computed or extracted trends, I use Strazicich and List's (2003) approach. First, the logarithm of the cross-country mean in each year is computed and subtracted from the logs of the trends in each country so that they are now in terms of deviations from the logarithm of the international mean. Then the Im, Pesaran, and Shin (2003) unit root test (IPS test) is applied to test if the panel of resulting series contains random walks or stochastic trends, also known as unit root processes. If we can reject the null hypothesis of a unit root, then the deviations are stationary and the series cointegrate. It seems that we could test the effects of NAFTA by splitting the panel into a group of NAFTA and non-NAFTA observations and applying the test to the subsets. However, there are only a total of 24 post-NAFTA observations for the NAFTA partners, therefore, the power of this test may not be high.

The cointegration test that is integrated into the Kalman filter procedure is based on testing the significance of the coefficients in the matrices H_A and H_a in equation (3). For cointegration of the trends, each of these matrices must be of reduced rank. This condition is necessary but not sufficient. For example, in the following structure for H_A:

$$H_A = \begin{bmatrix} H_{A11} & 0 & 0 \\ 0 & H_{A22} & 0 \\ 0 & H_{A32} & 0 \end{bmatrix} \tag{8}$$

the second and third trends will cointegrate as they share a common shock, but the first trend is completely independent of the second and third trends. Therefore, attention needs to be paid to the significance of each coefficient in H. Also, if two stochastic trends cointegrate but have coefficients with opposite signs then even though they cointegrate, they will tend to diverge rather than converge.

Table 1 presents the results of the β-convergence test. With the exception of energy and carbon per capita, all the series are declining, although the mean growth rate of NOx per capita as indicated by α is not significantly negative. The initial value of the variable in question has a significantly negative coefficient (β) in every case and in all but one case the coefficient is highly significant. This is strong evidence for convergence across the three countries. However, the apparent effect of NAFTA varies. On the whole, the effect of the NAFTA dummy on the intercept (δ_1) is negative but only significantly different from zero at the 5 percent level for Energy/GDP, the energy technology trend, and NOx/GDP. This implies that the rate of increase in efficiency accelerated post-NAFTA, although mostly not in a very significant way. The interaction variable between the dummy and the initial value of the variable has a positive coefficient (δ_2) with *t*-statistic greater than unity for the first seven variables, but a negative coefficient for the sulfur technology trend and insignificantly negative coefficients for the two NOx variables. Only the energy per capita coefficient, however, is significant at the 5 percent level. This implies that for the first seven variables, the effect of the initial level of the variable is reduced or eliminated in the post-NAFTA period, which implies that β-convergence comes to an end after NAFTA. However, as we can see from the figures, the reason for this is that the trend in the variables becomes flat or negative in Mexico during the post-NAFTA period. Therefore, the ending of β-convergence may be environmentally beneficial!

By looking at Figures 1–8, σ-convergence is apparent in the energy and carbon intensity series and both the emissions per capita and intensity series for both sulfur and nitrogen. As generally the trend in Mexico is rising in the first part of the sample period, this σ-convergence would also be apparent using a logarithmic scale. For the two technology trends (Figures 9–10) there is apparently no σ-convergence.

Table 7 presents the results of the Strazicich and List (2003) tests for cointegration using the IPS unit root test on transformed data. On account of the small number of observations in the post-NAFTA data, the results for the subperiods are based on the simple Dickey–Fuller test while I also present results for the full period using the augmented Dickey–Fuller regression with three lagged first differences. Based on the results in Im et al. (2003) for five and more countries, I estimate that the critical values for three countries with 30 time series observations are –2.25 and –2.10 at the 5 percent level and 10 percent significance level, respectively. Critical values are a little larger in absolute value for the two subperiods. In the full sample, clearly there is cointegration for per capita and GDP intensity indicators of energy, carbon, and

Table 7. Strazicich and List Cointegration Test

	ADF(3) full period	DF full period	DF pre-NAFTA	DF post-NAFTA
Energy/P	–4.79285	–5.02876	–0.88805	–0.59343
Energy/GDP	–4.47285	–4.36136	–0.23482	–2.67573
A Energy	–1.22699	1.60274	4.05947	–0.60359
Carbon/P	–5.34817	–4.22166	–0.66582	0.18266
Carbon/GDP	–6.52864	–2.76926	0.01584	–0.96668
Sulfur/P	–4.61205	–3.27023	–0.86442	–2.21813
Sulfur/GDP	–4.36008	–1.92497	–0.19412	–3.77367
A Sulfur	5.20038	6.07660	–1.47023	0.76350
NOx/P	4.34461	8.91437	3.22131	3.23997
NOx/GDP	7.62648	8.29985	–2.26952	2.89619

Notes: Critical values for the full period are: are –2.25 and –2.10 at the 5% level and 10% significance levels respectively and somewhat larger for the two subperiods. ADF is the augmented and DF the non-augmented IPS–Dickey Fuller test.

sulfur, but not for NOx nor the two technology trends. Looking at the two subperiods, a couple of the intensity series appear to cointegrate in the post-NAFTA period. Only NOx/GDP cointegrates in the pre-NAFTA period alone. However, the smaller sample sizes for these periods (and for the NOx data) reduce the power of the tests.

Table 4 provides the information we need for the Kalman filter-based test of cointegration for the technology trends. The energy model has two independent stochastic shocks. The first shock is shared by all three trends. There is, however, a second independent stochastic trend shared by Mexico and the United States but the coefficients for these two countries have opposite signs. Therefore, the three countries' technologies will not converge. For the sulfur model, there is only one independent stochastic trend, and thus, technically the three trends cointegrate. However, as the Mexican coefficient is negative (although not significant) this means that the series will not converge even though they cointegrate.

I conclude from this section that there is strong evidence for convergence across the three countries although the strength of this evidence varies across the different indicators. The rate of improvement in the environmental indicators may have picked up in the post-NAFTA period. The Mexican technology trends consistently move in the opposite direction to the Canadian and U.S. trends relative to the mean as the Mexican logarithmic drift term is less negative than the drift terms of the other two countries. Therefore, it is not surprising that there is little evidence of convergence in technology except for the significantly negative t-statistic for β in the β-convergence regression for the sulfur technology trend. This is driven by the fact that Canada starts the period as the least efficient country and experiences the fastest rate of improvement over the period (Figure 10). For energy, the difference between the rates of improvement in Canada and Mexico is not as great.

Conclusions

The results of this study show that regarding air pollution and energy efficiency, none of the more extreme predictions of the outcomes of NAFTA have come to fruition to date. Rather, trends that were already present before NAFTA continue and, in some cases, improve post-NAFTA, but not yet in a dramatic way. This result is not surprising, as NAFTA represents a continuation of the liberalization process that began in Mexico in the 1980s.

There is strong evidence of convergence for all four intensity indicators across the three countries toward a lower intensity level. Although intensity is rising initially, in some cases in Mexico, it eventually begins to fall post-NAFTA. Per capita measures for the two criteria pollutants also show convergence, but this is not the case for energy and carbon and these variables also drift moderately upwards. The state of technology in energy efficiency and sulfur abatement is improving in all countries, although there is little, if any, sign of convergence and NAFTA has no effect on the trend of technology diffusion. According to these results, Mexico's technology is improving at a slower rate than its two northern neighbors.

We can compare these results to those of the few studies that have examined the impact of NAFTA on economic convergence of the conventional sort among the NAFTA partners. Schiff and Wang (2003) find that trade with Mexico's NAFTA neighbors has had a large and significant impact on TFP in Mexico's manufacturing sector and that there is some convergence with the other North American economies. On the other hand, Madariaga, Montout, and Olivaud (2004) find divergence in income per capita among U.S. and Mexican states using both β and σ measures of convergence but they find that when agglomeration within countries is taken into account, there is significant conditional β-convergence. However, the rate of convergence seems unaffected by NAFTA. Similarly, Fernandez and Kutan (2005) find that the correlation between the business cycles in the three NAFTA countries was the same in the early 1980s as in the mid-1990s. These results are congruent with the results of the present study that whatever convergence is underway among the economies is not affected very much by the accession of Mexico to NAFTA. The relatively slow growth of the Mexican GDP per capita helps drive the convergence of the energy and emissions intensity variables and is reflected in the slow rate of technological change estimated in this article.

However, as all three countries' populations have grown strongly, some of the positive trends described above do not carry over to total emission loads. Therefore, environmental change has been more negative. However, assuming that the population growth rate is exogenous to NAFTA, this cannot be blamed on NAFTA.

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Notes

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1. Their article has received three citations in the *ISI Citation Index* compared to hundreds of citations for the various versions of Grossman and Krueger's article.

2. Of course, there was a major devaluation of the Peso in late 1994, which also would have encouraged export growth.
3. This is if traditional fuels and energy carriers are included. When only fossil fuels and other modern energy carriers are included the time profile of emissions intensity tends to be an inverted U.
4. From *IEA* and *World Bank* data collected for Stern (2005).
5. Concentrations of pollution in urban areas do perhaps follow an inverted U shape relation with income because of the tendency to the dispersion of economic activity in the course of economic development through the processes of suburbanization and industrial decentralization (Stern, 2004a).
6. Technique effects as defined by Grossman and Krueger (1995) and Copeland and Taylor (2004), etc. include both technological change and changes in input mix.
7. This result depends on the specific calibration used.
8. A production frontier is a multi-output production function. The term efficient frontier indicates that the production frontier represents the best practice technology available. A firm or country that is using its available inputs efficiently will be producing on the frontier.
9. An alternative approach (e.g., Fernandez, Koop, & Steel, 2002; Lansink & Silva, 2003) would treat any deviation from the carbon-minimizing vector of inputs as an inefficiency.
10. Imposition of zero degree homogeneity means that increasing all outputs proportionally has no effect on emissions. An increase in output holding input constant is an increase in TFP. I assume that this increase in knowledge does not itself change the level of pollution if the level of inputs is held constant. Changing the mix of outputs does, however, affect the level of emissions.
11. As some inputs, such as nuclear power, oil refining, or zinc smelting are zero in some countries in some years, a function that can accommodate zero values for some inputs is needed to introduce the inputs into the model. As in Stern (2002), I use a linear function of the inputs, which is homogenous of degree one and makes the (questionable) assumption that the inputs are infinitely substitutable for each other. As emissions are homogenous in the input aggregate, $\sum_{j=1}^{n} \beta_j x_{jit}$, the model is not identifiable unless a restriction is placed on the parameters, β_j, or on the state of technology. A non-identifiable econometric model is one which cannot be estimated as more than one set of parameter estimates are compatible with the same error terms. Identification ensures that there is a unique vector of regression coefficients. This is the rationale behind the arbitrary restriction that these parameters sum to unity.
12. I also estimated models with a diagonal error covariance matrix and found that this restriction can be easily rejected. (The likelihood ratio statistic is 8.91 which is chi-square distributed with three degrees of freedom and, therefore, $p = 0.03$.)
13. This is a second order integrated process, designated I(2), and is also known as the local linear trend model.
14. Cointegration occurs when variables that contain random walk components or stochastic trends share these components so that some weighted sum of the variables does not contain a random walk. If this does not occur then a regression using these variables will end up with a random walk in the residual term which violates the classical regression assumptions and invalidates any inference based on the the regression results. If a group of variables cointegrate then, despite each following a random walk, the group will tend to move together and following shocks, which push the variables apart, they will tend to converge with each other again.
15. Usually, this test is computed using the average rate of growth over the sample period and the initial level of the indicator, but here there would only be three observations with which to compute the correlation or regression.
16. Mostly 1971 but as late as 1985 in the case of NOx emissions in Mexico.
17. An important caution in interpreting these tests is that two or more stochastic trends can cointegrate to a stationary variable with non-zero mean. For example y and x in the following model:

$$y_t = \beta_0 + \beta_1 x_t + w_t \tag{9}$$

cointegrate if w_t is stationary, but unless $\beta_0 = 0$ and $\beta_1 = 1$ the two series are not equal in the long run. This is termed "conditional convergence" in the growth literature (Strazicich & List, 2003). McKibbin and Stegman (2005) argue that conditional convergence allows a linear time trend to be present as well.

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Appendix: Data Sources

Pollution Emissions

Generally the emissions series I use were developed using bottom up methods, which are described in the sources I cite. I prefer to use the series developed by the governments in question as these generally rely on much more detailed information and more effort than the academic series (LeFohn, Husar, & Husar, 1999; Marland, Boden, & Andres, 2003) which were developed for all countries in the world over 150-year-plus time periods. I also regard more recent estimates to be probably superior due to "learning by doing" at the agencies involved.

Carbon Emissions:

Canada: Data for 1971–89 are based Marland et al. (2003). CO2 emissions for 1990–2002 are from Matin et al. (2004) and updated from the Environment Canada website for 2003. These data include non-energy related industrial emissions as well as energy related emissions but do not include emissions from land use change. The Marland et al. (2003) data for 1971–89 are scaled up to reflect the higher level of emissions in the Marland et al. (2003) data. The OECD (2005) series is within 2–3% of the energy related emissions given by the Matin et al. (2004) series but the Marland et al. (2003) series is 4% below the Matin energy-related series in 1990, rising to a 22% gap in 2000.

Mexico: Data for 1971–89 are from Marland et al. (2003). Data for 1990–2002 are from OECD (2005). No scaling is applied to the earlier data.

USA: Data for 1971–89 are from Marland et al. (2003). CO2 emissions for 1990–2002 are from United States EPA (2005) . Differences between the different data sources are not very large in the case of the USA.

Sulfur Emissions:

Canada: Sulfur emissions for 1971–2002 are from OECD (various years).

Mexico: Data on SOx is available from INEGI (various years) for 1985–2003. For 1971–84 the growth rates in the ASL database (ASL and Associates, 1997; Lefohn et al., 1999) were used to extrapolate back from the INEGI data. This implies that I believe that the INEGI data are more reliable, while I believe that the ASL data reasonably accurately reflects the rates of change of emissions in the earlier years.

United States: Data for 1971–98 are available from United States EPA (2000) and updated to United States EPA (2003) using data available from the EPA website.

NOx Emissions:

Canada: Data for 1980–2002 are from OECD (various years). Over time, earlier estimates of emissions have been increased and so I adjusted upwards the earlier data to splice smoothly to the more recent sources.

Mexico: Data available from INEGI (various years) for 1985–2003.

USA: Data for 1971–98 are available from United States EPA (2000) and updated to United States EPA (2003) from sources available from the EPA website.

Explanatory Variables and Energy Use

Complete series were compiled for all of the following variables for the period 1971-2003 for Canada, Mexico, and the U.S.

Energy Use:
Data are from the International Energy Agency (IEA) OECD (2003) and IEA online data. Data were collected for total primary energy supply of crude oil, refined petroleum products, natural gas, coal, hydropower, nuclear power, and biomass fuels. Other energy use categories were considered small enough to ignore. Primary supply of refined petroleum products is equivalent to actual end use oil consumption in a country while primary supply of crude oil is the quantity of oil refined in a country.

GDP:
I obtained the data from the Penn World Table version 6.1 (Heston et al., 2006). Data for 2001-3 are updated from the *World Development Indicators Online* published by the World Bank (2005).

Population:
Data are from the *World Development Indicators Online*.

Area:
Area data was obtained from *World Development Indicators Online*.

Economic Structure:
The structure of value added by industry was obtained from the *SourceOECD* website and *World Development Indicators Online*. 2001–3 data for Canada was obtained from Statistics Canada (2005) and 2002–3 data for the US was downloaded from the Bureau of Economic Analysis website.

Metal Smelting:
Data on primary production of refined copper, lead, zinc, and nickel for 1980–2000 were received from the United Nations Industrial Development Organization. These data are reported in the *Yearbook of Industrial Statistics*. For copper, lead, and zinc we obtained the same data for 1971–79 from the hardcopy version. For nickel we obtained data for 1971–79 from the US Bureau of Mines *Minerals Yearbook*. The latter source was used to fill any gaps in the UNIDO data, for all data in 2001–3, and for lead data for Mexico in 1990–2003.

Units as Entered into the Econometric Model
Sulfur: Thousands of metric tonnes of sulfur
NOx: Thousands of metric tonnes of nitrogen oxides

Carbon: Millions of metric tonnes of carbon
Energy: Millions of metric tonnes of oil equivalent
GDP and Industry Outputs: Billions of 1995 international US dollars
Population: Thousands
Area: Square kilometers
Metals: Thousands of metric tonnes.