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Theoretical and Empirical Analysis of the Environmental Impact of Kyoto Protocol

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Abstract

This thesis presents both a theoretical and empirical investigation of impact and environmental efficacy of the Kyoto Protocol on climate change. On the theoretical side, the thesis presents a simple four-sector North-South-OPEC model of the world economy where the use of fossil fuel creates greenhouse gas emissions. The model suggests that caps on emissions in industrialized countries lead to reduction of dirty good production in these "clean" countries, but this reduction is picked up on a one-for-one basis by the increase in dirty good production in "dirty" developing countries. Since there is less fuel saving in "dirty" developing countries, an increase in fossil fuel demand from South and OPEC is higher than its decline in the North. Therefore, world emissions rise. An implication of the theoretical model is that if a country does not ratify Kyoto Protocol or fails to meet its commitments, the emission cap does not fall so far and increase in world emissions is mitigated. The Kyoto Protocol also includes a Clean Development mechanism which allows firms in developed countries to purchase emission credits from firms in developing countries if the latter engage in emission reduction activities. The investigation of the impact of the CDM indicates that global emissions will rise if developed countries initially consume a sufficiently large share of world fossil fuel. Finally, increases in OPEC's price of fossil fuel reduce world emissions.

Our empirical investigation aims to answer three questions. First, are there clean and dirty countries in the sense that rich developed countries adopt production techniques with lower CO2 emissions per unit of output? Second, do countries reduce emissions per unit of output of fuel-using goods by direct abatement or indirectly by adopting fuel saving technologies or a combination of the two? Third, what is the direction and magnitude of relocation of emission-intensive activities between developed and developing countries? To shed light on these issues, we estimate the so-called Environmental Kuznets Curve (EKC) regressions. We focus on a four-sector decomposition of GDP into agriculture, manufacturing, other industry and services. We work primarily with a balanced panel which consists of 71 countries, 24 years and 1704 observations. For conventional Kuznets curve regressions with no controls on the output composition of the economy, we find that, as we move to countries with higher per capita GDP, per capita emissions increase at a decreasing rate and eventually decline. The theoretical model predicts that richer countries also invest more heavily in fuel saving technologies leading to lower emissions per unit of output. Consequently, even with controls on the output composition of the economy, per capita emissions will continue to increase at a decreasing rate as per capita GDP rises because rich countries undertake more fuel saving. The empirical evidence strongly confirms this prediction. Both the magnitude of the estimated elasticities and their statistical significance provide suggestive evidence that fuel saving has been more important than direct abatement, at least to this point in time. Finally, our simulations suggests that due to surprising emission intensity reversals, both the Annex and non-Annex countries tend to expand their relatively clean sectors and contract their relatively dirty sectors in response to the Kyoto agreement meeting emission reduction targets. Consequently, in contrast to the theoretical model, world emissions fall in response to tighter emission caps in developed countries.

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Dedication

To Dr. James Gaisford.

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Chapter One: Introduction

This thesis presents both a theoretical and empirical investigation of impact and environmental efficacy of the Kyoto Protocol on climate change. The theoretical model uses a simple four-sector North-South-OPEC model of the world economy, where the use of fossil fuel creates greenhouse gas emissions. To assess the Kyoto agreement we investigate the impact on world emissions as developed countries tighten their emission caps and developing countries introduce emission credits, which can be sold in developed countries.

The model in this thesis suggests that caps on emissions in developed countries lead to a reduction of dirty-good production in these "cleaner" countries, but this reduction is offset on a one-for-one basis by the increase in dirty-good production in "dirtier" developing countries. Since there is less fuel saving in "dirtier" developing countries, there is an increase in fossil fuel demand from the South and OPEC which is of larger magnitude than the decline in the North. Therefore, world emissions rise. Paradoxically, the United States decision not to ratify the Kyoto Protocol and Canada's apparent decision to ignore or delay its commitments imply that the emission cap will not fall so far and the increase in world emissions will be mitigated.

The Kyoto Protocol also includes a Clean Development Mechanism which allows firms in developed countries to purchase emission credits from firms in developing countries if the latter engage in emission reduction activities. To reflect the Kyoto Protocol, we allow for partial or constrained trade in emission credits. The investigation of the impact of the CDM indicates that global emissions will rise if developed countries initially consume a sufficiently large share of world fossil fuel. Finally, increases in OPEC's price of fossil fuel reduce world emissions.

An important take-off point for this theoretical model is a recent article by Copeland and Taylor (2005) which provides a conditional endorsement of the Kyoto Protocol. The authors show that "unilateral emission reductions by the rich North can create self-interested emission reductions by the unconstrained poor South"[1] if the positive income effects in the South are sufficiently strong. This happens because of favorable terms of trade effects which make the South richer whereupon it implements tighter environmental controls.[2]

In Copeland and Taylor there are only dirty and clean goods. Countries use the same production techniques and, due to factor price equalization, have the same emission intensities. Thus, the output composition of the economy determines its emissions. If two countries have the same composition of outputs, they will have the same emission relative to GDP. Developed Northern countries tend to be cleaner than developing Southern countries based only on the fact that their ratio of the clean output relative to the dirty output tends to be larger because of more stringent environmental policies.

[1] Copeland and Taylor (2005), p. 1.
[2] Copeland and Taylor (2005) do not directly assess the Clean Development Mechanism.

Our model has clean and dirty countries as well as clean and dirty goods. Factor price equalization does not occur because the user cost of capital is assumed to be lower in North. Consequently, North is able to accumulate more capital per unit of output making it richer than the South. At the same time, having a lower user cost of capital allows the North to engage in more capital-intensive fuel-saving activity and, thus, generate lower emissions in each good.

Our empirical investigation aims to answer three questions. First, are there clean and dirty countries in the sense that rich developed countries adopt production techniques with lower CO2 emissions per unit of output as suggested in our theoretical model? Second, do countries reduce emissions per unit of output of fuel-using goods by direct abatement, which reduces emissions per unit of fossil fuel, or indirectly by adopting fuel saving technologies as our theory model suggests, or by a combination of the two methods? Third, what is the change in emissions associated with the relocation of emission-intensive activities between developed and developing countries?

To address these questions, we will estimate the so called Environmental Kuznets Curves (EKC's). We focus on a four-sector decomposition of GDP into agriculture, manufacturing, other industry and services. As a principal dependant variable CO2 is chosen since its contribution to GHG constitutes about 72% as shown in Table 1, and since data are readily available. We work primarily with a balanced panel which consists of 71 countries, 24 years and 1704 observations. The independent variables reflect the scale, technique and composition effects of economic activity on emissions, which are discussed by Krueger and Grossman (1995), Antweiler et al. (2001) and others. As in

Antweiler et al. (2001), we consider both fixed effects and random effects specifications of the empirical model.

Table 1 Contribution of GHG to Global Warming. (Analysis Center of the U.S. Department of Energy).

Greenhouse gases	Multiplier (Global Warming Potential)	Total Relative Contribution	Percent of Total (new)
Carbon Dioxide (CO_2)	1	368,400	72.369%
Methane (CH_4)	21	36,645	7.199%
Nitrous Oxide (N_2O)	310	96,720	19.000%
CFC's (and other misc. gases)	various	7,291	1.432%
Total		509,056	100.000%

Source: Adapted from the Analysis Center for the U.S. Department of Energy. http://cdiac.esd.ornl.gov/pns/current_ghg.html.
Note: GWP (Global Warming Potential) is used to contrast different greenhouse gases relative to CO_2.

For conventional Kuznets curve regressions with no controls on the output composition of the economy, both the current theoretical model and that of Copeland and Taylor (2005) suggest that, as we shift attention to countries with higher per capita GDP, per capita emissions will increase at a decreasing rate and may eventually decline. The empirical results provide a strong support for this theoretical prediction. In the Copeland and Taylor model richer countries become greener only by adopting a cleaner mix of outputs whereas in our model richer countries also invest more heavily in fuel saving technologies leading to lower emissions per unit of output. Consequently, with the introduction of controls on the output composition of the economy, the Copeland and

Taylor model suggests that national emissions would increase at a constant rate. In contrast, our Kyoto model suggests that per capita emissions will continue to increase at a decreasing rate as per capita GDP rises because rich countries undertake more fuel saving. Statistically significant regression coefficients imply that conventional EKC results continue to be obtained when controls on output are introduced, providing strong evidence in favour of our model.

As to the second empirical question, both the magnitude of the elasticities and their statistical significance lead to the conclusion that fuel saving has been more important than direct abatement, at least to this point in time.

The empirical evidence suggests a surprising result with respect to the third question. Our regressions suggest the presence of emission intensity reversals where agriculture and services are cleaner than manufacturing at the per capita incomes of most developing countries but manufacturing is cleaner at the per capita incomes of most developed countries. These emission intensity reversals, which are not anticipated by the theoretical model, open up the possibility of a fortuitous positive impact of tighter emissions caps in developed Annex-I counties under the Kyoto Protocol. Our simulations suggest that as developed countries expand their relatively clean manufacturing sectors, developing countries expand their relatively clean service and/or agricultural output. Consequently, in contrast to our theoretical model, our empirical results suggest that global emissions may fall in spite of the flawed structure of the Kyoto Protocol.

both the Annex and non-Annex countries tend to be expanding their relatively clean sectors and contracting their relatively dirty sectors in response to the Kyoto agreement and the world becomes cleaner.

Chapter Two. Climate Change and Kyoto Protocol

There is strong scientific evidence of climate change and mounting evidence of a connection with human economic activity associated with the burning of fossil fuels. The change in climate is likely to have a large and predominantly negative impact on many aspects of life on Earth. [3]

Some of the sunlight that arrives to earth is reflected back into the space, but the rest reaches the surface, warming the land, atmosphere and oceans. The earth re-emits this energy in the form of infrared radiation. However, greenhouse gases such as carbon dioxide, ozone, methane, etc. trap this radiation and prevent its escape, thus causing increases in temperature. Table 1 shows that carbon dioxide (CO2) is responsible for over 70% of the greenhouse effect. The result of the greenhouse effect is a warming of the earth surface. Without these greenhouse gases its surface would be up to 30°C cooler.[4] Thus, we need these gases to an extent sufficient to survive.

Humans contribute to greenhouse gas concentrations and, thus, an even greater radiation trap through manufacturing, power generation, transportation, and livestock farming. The burning of coal, oil and natural gas is the key human factor in increasing greenhouse gas emissions because these fossil fuels are being used at a much faster rate than they

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[3] IPCC, Third Assessment Report of the International Panel on Climate Change – Climate Change 2001, including the contribution from Working Group I Climate Change 2001 – The Scientific Basis. http://www.grida.no/climate/ipcc_tar

[4] See Dalton H. (2006) www.defra.gov.uk/science/how/documents/royalcollege.pdf

were created.[5] What is worrisome is the fact that climate change resulting from the build-up of greenhouse gases appears to be happening at unprecedented speed. According to Stern (2006), "over the past 30 years, global temperatures have risen rapidly and continuously at around 0.2°C per decade, bringing the global mean temperature to what is probably at or near the warmest level reached in the current interglacial period, which began around 12,000 years ago. The decade of the 1990s was the warmest since the mid-1800s, when record-keeping started. Further, the hottest years ever recorded are: 1998, 2002, 2003, 2001, and 1997.[6] Estimates suggest that by the year 2100, the average global temperature will rise by 1.4 to 5.8 degrees Celsius.[7]

The effects of climate change are becoming increasingly evident. Cyclones and hurricanes appear to be more frequent and more powerful. As world temperatures rise, floods and droughts are becoming more severe. Scientists suggest that this is evidence that climate change has already begun. The spring ice thaw in the Northern Hemisphere occurs 9 days earlier than it did 150 years ago, and the fall freeze now typically starts 10 days later. [8] According to a United Nations Framework Convention on Climate Change (UNFCCC), "arctic air temperatures have increased by about 5 degrees C during the 20th century, and in the Russian Arctic, buildings are collapsing because the permafrost under

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[5] IPCC, Third Assessment Report of the International Panel on Climate Change – Climate Change 2001, including the contribution from Working Group I Climate Change 2001 – The Scientific Basis. http://www.grida.no/climate/ipcc_tar
[6] For example, see http://news.nationalgeographic.com/news/2004/12/1206_041206_global_warming.html or Stern (2006).
[7] IPCC, Third Assessment Report of the International Panel on Climate Change – Climate Change 2001, including the contribution from Working Group I Climate Change 2001 – The Scientific Basis. http://www.grida.no/climate/ipcc_tar
[8] See Handwerk (2004) http://news.nationalgeographic.com/news/2004/12/1206_041206_global_warming.html

their foundations has melted."[9] The sea level may rise from 9 to 88 cm due to melting water resulting from reductions in the size of the polar caps.[10] The annual duration of lake and river ice coverage has shortened by about two weeks during the 20th century. In Europe beetles and other insects are living at higher altitudes where previously it was too cold to survive and examples are multiple. [11] Large proportion of the endangered species may become extinct.

Even the minimum predicted shifts in climate change are likely to have significant social and economic effects. A general reduction is expected in potential crop yields in most tropical regions. Stern (2006) states that minimal changes in temperature can cause dramatic reductions in yields leading to disruptions in the food supply. Salt-water intrusion from rising sea level will have a direct impact on the availability and quality of fresh water. Heat waves, such as the one that was experienced in 2003 in Europe when 35,000 people died and agricultural losses reached $15 billion, could be commonplace by the middle of the century.[12] According to Stern (2006) poor developing countries will suffer most from the climate changes. They are the ones with fewer resources for coping with storms, floods, droughts and disruptions in food and water supply. In addition, they are heavily dependant on agriculture, the most climate sensitive economic sector.[13]

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[9] UNFCCC report, retrieved on Jan 10, 2007 from http://unfccc.int/essential_background/feeling_the_heat/items/2904.php
[10] Pancoast (2003, p.15)
[11] UNFCCC report, retrieved on Jan 10, 2007 from http://unfccc.int/essential_background/feeling_the_heat/items/2904.php
[12] Stern's Review on the Economics of Climate Change, (2006, p. 123).
[13] Stern's Review on the Economics of Climate Change, (2006, p. 7).

The important greenhouse gases include methane at 7%, and nitrous oxide at 19% as well as CO2 at 72% as shown previously by Table 1 in the Introduction. While there is a strong connection between methane emissions and livestock operations in agriculture, other greenhouse gases tend to move together with CO2 and are linked with the combustion of fossil fuels. Consequently, carbon dioxide emissions (CO2) are often used as a proxy for overall GHG emissions. It is important to acknowledge that CO2 emissions do not give us a direct measure of damage since CO2 takes long time to decay. Concentrations of greenhouse gases have been increasing rapidly due to the burning of fossil fuels. Every year the burning of fuels adds about 6 billion metric tons of carbon in the form of CO2 to the atmosphere. Since there is no reliable data on the aggregate stock of CO2 in the atmosphere, however, emissions measurable in million metric tons are used as proxy for environmental damage.

CO2 emissions vary widely across countries as shown in Table 2. In Table 2 the Annex-I group of countries are those that were designated to make reduction commitments under the Kyoto Protocol. This group includes all developed countries and most transition countries but not China. Table 2 divides the non-Annex countries, which have no reduction commitments under the Kyoto Protocol into an OPEC and non-OPEC group. It can be observed that developed countries have been historically more responsible for CO2 emissions in absolute terms. [14] Developed countries also obtain the largest share of the worlds' output while developing countries are more heavily populated. Shares of

[14] The UNFCCC's definitions of developed and developing countries as well as Annex and Non-Annex countries are used to sort 173 countries considered in this study. In the Appendix, the two groups of countries are described in detail.

world emissions are generally similar to shares of world output with the exception of the transition countries.

Table 2 Share of emissions, population and output in 2003.

	2003					
	ANNEX-I			NON-ANNEX		
Variable	TOTAL	Developed	Transition	TOTAL	OPEC	Non-OPEC
Share of World Emissions	59%	48%	12%	41%	6%	34%
Share of World Population	20%	15%	5%	80%	8%	72%
Share of World GDP	59%	53%	6%	41%	4%	37%
Emissions to Output Ratio (kg CO2 per dollar of GDP)	0.510467	0.45898	0.99845	0.51304	0.78094	0.48336
Emission per capita (MT CO2 per person)	11.74074	12.66785	8.836283	2.077812	3.100332	1.967275
GDP per capita (constant 2000 US dollars per person; PPP conversions)	23000	27600	8850	4050	3970	4070

Source: Author's calculations based on EIA and WDI databases.

While the data from the U.S. Energy Information Administration in Table 2 indicates that developed countries account for largest share of greenhouse gas emissions, Table 3 suggests that emissions are rising most rapidly in the developing world. Table 3 also shows that between 1990 and 2000 total GHG emissions actually declined for the Annex I countries. This decline was related to the steep drop in economic output of the countries of Eastern Europe and the former Soviet Union, which were shifting from centrally planned to market economies. The decline in emissions of roughly 38% from those counties more than compensated for the increase in emissions from the developed countries as can be observed in Table 3. There has also been significant progress in emissions reductions in some developed countries in Western Europe. Denmark, for example, stabilized emissions between 1990 and 2000 by switching to renewable energy and natural gas. Norway also stands out as a country where climate change was seriously addressed. A tax on CO2 was introduced in 1991 and it covers two-thirds of the country's emissions. This tax attributed to making investments in energy efficient technologies profitable.

Table 3 Emissions Data for 1990 and 2000

Region/Country	Carbon (MMT) 1990	2000	Percentage of 2000 Total	Increase from 1990 to 2000
Canada	478.57	568.23	2.38%	18.73%
Mexico	300.09	379.99	1.59%	26.62%
United States	5,013.45	5,815.50	24.38%	16.00%
North America	**5,793.03**	**6,764.86**	28.36%	16.78%
Brazil	222.66	345.43	1.45%	55.14%
Other	472.883127	645.3133808	2.71%	36.46%
Central & South America	**695.54**	**990.74**	4.15%	42.44%
United Kingdom	598.48	551.02	2.31%	-7.93%
Other	3,901.81	3,875.91	16.25%	-0.66%
Western Europe	**4,500.29**	**4,426.93**	18.56%	-1.63%
Eastern Europe & Former U.S.S.R.	**3,792.16**	**2,321.72**	9.73%	-38.78%
Middle East	**730.99**	**1,086.24**	4.55%	48.60%
Africa	**718.08**	**875.59**	3.67%	21.93%
Australia	262.77	353.20	1.48%	34.42%
China	2,241.17	3,030.88	12.71%	35.24%
India	588.24	1,000.69	4.20%	70.12%
Japan	1,014.85	1,190.06	4.99%	17.26%
Other	1,089.00	1,810.53	7.59%	66.26%
Asia & Oceania	**5,196.03**	**7,385.37**	30.96%	42.13%
World Total	**21,426.12**	**23,851.46**	100.00%	11.32%

Source: Authour's calculations based on data from the International Energy Annual, 2004.

The earliest effort to estimate the effect of greenhouse gases on climate was in 1895 by a Swedish chemist named Svante Arrhenius. With limited data he tried to show that the presence of CO2 in the atmosphere raised global temperature substantially. Arrhenius calculated that the removal of GHG from the atmosphere would lower global temperatures by about 31 degrees Celsius. He also calculated that doubling of carbon dioxide in the atmosphere from pre-industrial levels would raise global temperatures by 4 to 6 degrees Celsius.[15]

In 1988, the World Meteorological Organization and the United Nations Environment Program created an Intergovernmental Panel on Climate Change (UNEP). In 1990 this group issued an assessment report which reflected views of about 400 scientists urging the need to address the issue of climate change. In response to this assessment report, the governments created the United Nations Framework Convention on Climate Change which was ready for signature at the "Earth Summit" in Rio de Janeiro in 1992. It is an international agreement of countries to reduce carbon emissions and sets up the institutional framework for international climate policy. Parties that ratified it have periodic meetings, the Conferences of Parties, aimed at promoting efforts to struggle with global warming and climate change.[16] Worldwide research and regular assessment reports played a major role in the negotiations leading to the Kyoto Protocol.

The Kyoto Protocol was negotiated in 1997 at the Third Conference of Parties to the United Nations Framework Convention of Climate Change. It was adopted unanimously

[15] McKibbin J.W. and Wilcoxen J.W. (2002, p.110)
[16] For more information about UNFCC and the various COP (Conferences of Parties) meetings that followed it, see the UNFCC website: http://www.unfccc.org.

and entered into force on 16 February 2005. Only Parties to the Convention that have also become Parties to the Protocol (i.e. by ratifying and approving it) are bound by the commitments.

At present, the Protocol has been ratified by 163 countries. The Convention on Climate Change divides countries into three main groups according to their differing commitments.[17] Annex I consists of industrialized countries, which for the most part are members of the Organization for Economic Cooperation and Development (OECD), plus countries with economies in transition. The Annex-II countries, which are the OECD members in Annex I, are required to provide financial resources to enable developing countries to undertake emissions reduction activities. Finally, the Non-Annex countries are mostly developing countries. Developing countries are not required to make emissions reductions and they can be classified as non-Annex countries.[18]

Mandatory GHG emissions reductions are required of the world's leading economies in Annex-I under the Kyoto Protocol. For most countries these targets range from reductions of 6% to 10% of their 1990 emissions levels by the commitment period 2008 to 2012. The reduction targets apply with respect to 1990 emission levels and apply only to the following six "Kyoto gases" — carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydro fluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SP6).[19] Thirty-five countries and the EU from Annex-I have ratified the

[17] For more information about UNFCCC and the various COP meetings that followed it, see the UNFCCC website: http://www.unfccc.org.
[18] From press release retrieved from unfccc.int/resource/guideconvkp-p.pdf (2002).
[19] Franck Lecock, Zmarak Shalizi (2004).

Kyoto Protocol. Each individual country is required to reduce its emissions by at least 5% below their 1990 levels.[20] The EU has its own internal agreement to meet its 8% target by distributing different rates to its member states.[21] As an Annex-I country, Canada ratified Kyoto with a commitment to reduce overall level of GHG by 6% below its 1990 level for the period 2008-2012. As an Annex-II country, Canada is also expected to provide support to developing countries which will assist them in lowering their emissions.

The mandatory reduction targets for the Annex-I countries, which have ratified the Kyoto Protocol, are more significant than they first appear. The industrialized countries have experienced substantial overall economic growth since 1990, making targets more difficult to attain. Further, outside of the European Union this growth has been accompanied by increases in emissions. Since the transition countries experienced a substantial recession in the 1990's, their emissions have fallen significantly as we have discussed in relation to Table 3. In effect, therefore, they have been endowed with excess emissions.[22] Consequently, the heaviest burden in the fight against climate change is placed on the industrialized nations that are mostly responsible for the past and current GHG emissions.

The Kyoto Protocol has other important provisions, which include: Emission Trading, Joint Implementation and Clean Development Mechanism. Emission Trading is straightforward; it occurs when one Annex I country buys permits from another. Joint

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[20] From press release from the United Nations Environment Programme at www.unep.org (September 1999)
[21] United Nations Environment Programme at www.unep.org (September 1999)
[22] McKibbin W. J., Wilcoxen P.J. (2003).

Implementation allows one country to undertake an emission reduction project in another one in exchange for permits. The Clean Development Mechanism is similar to Joint Implementation but is designed to include Non-Annex countries as well. Countries can get credits for reducing GHG by planting or expanding forests ("removal units"), for investing in emission reducing projects in other developed countries ("joint implementation") and funding activities associated with emissions reductions in developing countries. Credits that are earned through either of these mechanisms can be traded at the international emission market or "banked" for future use. [23]

History has posed difficulties for the Kyoto Protocol. The Bush administration contended that compliance with Kyoto would have implied high costs to US economy. Consequently, the US decided not to ratify the Kyoto Protocol and Australia followed suite. Since the biggest CO2 emitter withdrew from signing the Protocol, it required approval of most of the remaining major industrialized countries. It was not possible at that time for the Protocol to enter into force without the participation of Russia, Canada, New Zealand and Japan. Interestingly, there is a sense in which the American withdrawal promoted the ratification of the protocol because it reduced the compliance costs for the remaining non-EU Annex-I countries. These countries found themselves with veto power vis-à-vis the EU in the Bonn and Marrakech COP meetings. Consequently, they were able to obtain concessions from EU on the issues of carbon-sink credits and emission trading. The position of the EU was against including carbon-sinks as a means

[23] For more information about UNFCCC and the various COP meetings that followed it see http://www.unfccc.org.

for the fulfillment of reduction targets for 2008-2012. The EU also favoured hard emission caps as opposed to permit trade.[24]

A key premise for the theoretical and the empirical work in this thesis is that an international agreement on climate change is warranted because GHG emissions are a negative global public good, which requires coordinated policy actions across countries to avoid free-riding. Nevertheless, the environmental efficacy of the Kyoto Protocol appears open to question because the non-Annex countries have made no emissions commitments per se and because they are able to engage in credit trade with the Annex-I countries under the Clean Development Mechanism.[25] Much of the debate over climate change policy has focused on questions such as which countries should be held responsible for mitigating climate change. On one hand, since industrialized countries have caused most of the increase in GHG concentrations, there appears to be a strong case for expecting them to significantly reduce emissions. On the other hand, since developing countries account for a large and growing share of emissions, there are serious questions whether global climate change policy can succeed without their participation.[26]

[24] Bohringer C., Loschel A. (2003).

[25] Further, the analysis of the efficacy of the Kyoto Protocol cannot be divorced from questions of international trade and growth. Emission abatement involves sizable costs and Kyoto Protocol is likely to lead to changes in world energy markets and in the location of emission intensive production. CO2 emissions originate mostly from the combustion of fossil fuels to produce energy and heat. Since energy is used in production in industry and also a key factor in household consumption it is reasonable to investigate a link between GDP and CO2 emissions. Of course, the Kyoto agreement has been criticized by many. For example, see Bohringer and Vogt (2004).

[26] In addition, there are distributional aspects of climate change policy which depend on whether countries use tradable permits or emission taxes as instruments. With permits government's have a distributional instrument since political sensitivities can be considered in allocating permits industry. With a Pigouvian tax there may be greater transparency, but determining the tax which is appropriate to the overall target may pose difficulties. See Frank Jotzo (2004).

Chapter Three: Literature Review

A key feature of literature in the relationship between pollution and economic growth has been the investigation of the Environmental Kuznets Curves (EKCs). The EKC hypothesis defines an inverted-U-shaped relationship between pollutants and per capita income. The literature on the EKC developed rapidly over the past ten years. The common point of all studies is that environmental pressure increases faster than income at early stages of development up to a certain income level and then it goes down. Explanations for the EKC center on an income effect whereby with higher income people start valuing more environmental quality. Another dimension is the composition effect, i.e. shifting of output composition of the economy from clean agrarian to polluting industrial to services.

Previous theoretical and empirical studies related to my thesis can be divided into four main areas. The first is related to the question of impact of economic growth on the environment. Another group of studies looks at how trade flows are influenced by changes in pollution regulation. Next, a third group of studies investigates how pollution levels are affected by changes in trade flows or openness to trade over time. Finally, a fourth group of studies addresses the structure of the Kyoto agreement itself.

Examples of the literature with a focus on how economic growth affect the environment include Grossman and Krueger (1991, 1995), and Schmalensee (1997). These studies focus on the relation between growth and pollution and interpret results in terms of scale, composition and technique effects.

Grossman and Krueger (1991, 1995) were the first to document empirically that pollution does not necessarily increase with economic growth. When Grossman and Krueger (1995) examined the relationship between per capita income and various environmental indicators, they found that economic growth is initially accompanied with higher pollution which declines with further income growth. For the most cases the critical turning income point was registered at approximately $8,000 per capita. As the appropriate estimation technique, the authors used random effects model to account for any unobserved characteristics impacting pollution and therefore inducing temporal correlation in the error term.

Grossman and Krueger (1991) explain EKC though scale, composition and technique effects. To allow for the component of the error term that is common to a given year's observations in different countries and to eliminate resulting bias in estimates, the authors used generalized least squares with the inclusion of fixed country effects. Both random and fixed effects specifications yielded an inverted-U-shaped relationship, with emissions initially increasing at a decreasing rate and, finally, declining.

Schmalensee et al. (1997) employ fixed time and country effects with log-linear specification with per capita income in levels and per capita CO2 emissions in logs. The model suggests that for developing countries there is rapid growth of CO2 per capita with per capita GDP and for developed like US and Japan the growth of per capita emissions flattens and may reverse at a high enough income level.

Holtz-Eakin and Selden (1995) suggest that global pollutants like CO2 either increase monotonically with income or have high turning points with large standard errors. It should be noted that empirical support for the existence of EKC for CO2 emissions has not been found though the meaningful relationship has been observed for individual countries. (Dijkgraaf and Vollebergh, 1998).

Perman and Stern (2003) state that employing appropriate econometric techniques and taking into account serial dependence or stochastic trends to suggest that the EKC does not exist. Time related effects reduce environmental impacts in countries at all levels of income. In rapidly growing countries the scale effect outweighs the time effects, leading to higher pollution. In wealthy countries, growth is slower and pollution reduction efforts can overcome the scale effect. This is how they explain the EKC phenomena.

The second group of studies looks at how trade flows are influenced by changes in pollution regulation (Grossman and Krueger (1993)). They present empirical evidence of how trade liberalization or the reduction in trade barriers leads to scale, composition and technique effects pertaining to the environment. There is evidence of EKCs for two local pollutants: sulfur dioxide and "smog". Another study by Tobey (1990) investigates the hypothesis that stringent environmental policy may have caused trade patterns to change in commodities produced by the world's dirty industries. The author finds that "stringent environmental regulations imposed on industries in the late 1960's and early 1970's by most industrialized countries have not measurably affected international trade patterns."[27]

Finally, a third group of studies investigates how pollution levels are affected by changes in trade flows or openness to trade over time. This group includes Copeland and Taylor (1994) and Antweiler, Copeland, and Taylor (2001).

Antweiler, Copeland and Taylor (2001) investigate how trade affects pollution concentrations by decomposing this change in pollution concentrations into scale, technique and composition effects and employing data on sulfur dioxide concentrations for over 40 developed and developing countries. They find that changes in pollution concentrations resulting from output decomposition occurring as a result of trade are small. This work is interesting in that the authors provide separate estimates of magnitudes of scale and technique effect, one increasing pollution and the other reducing it as well as an estimate of composition effect. Pollution concentrations are influenced by the source of economic growth. In particular the authors cover pollution haven hypothesis and factor endowment hypothesis and distinguish between income gains brought by trade which lower pollution and income gains brought by capital accumulation which raise pollution. This work results in conclusion that free trade appears to be good for the environment.

A significant contribution to the literature on trade and environment is made by Copeland and Taylor. Copeland and Taylor (1995) investigate the effect on world pollution of

[27] Tobey (1990, p. 192)

income differences between countries. They find that world pollution rises in case of substantial income differences and international trade in pollution permits can lower global pollution. This model builds on their earlier work (Copeland and Taylor, 1994) where the authors used a two-country general equilibrium model to find whether free trade shifts pollution to human-capital scarce country, South, and whether global pollution is increased. Copeland and Taylor show that trade allows for the migration of polluting industries from rich developed into poor developing countries which in addition to lower income levels have less stringent environmental regulations. Higher income leads to tighter regulation, which in turn lowers pollution. Empirical evidence supports the significance of income effects, but appears to refute the dirty industry migration hypothesis. The increase in global pollution is shown by decomposing total change in pollution into changes coming from scale, composition and technique effects.

The fourth group of studies looks directly at features of the Kyoto agreement. Frank Jotzo (2004) presents an interesting summary/analysis of the politics and economics of participation of developing countries in emission reductions. He highlights the ethical case where developing countries insist on their "right to develop" and that they fear the North is using environmental issues to impede their progress. On the other side, considering the fact that developing countries account for a significant share of annual global emissions, they need to participate in climate change policy. China, India and Brazil, which are the largest emitters among developing countries, form the principal negotiating bloc of the G-77 developing countries. If these countries eventually make commitments, this will put pressure on the US to commit as well.

Frank Jotzo (2004) stresses that "national circumstances differ between groups of countries, and there are conflicting interests among developing countries" (p. 3). Countries most at risk from the sea-level rise demand GHG commitments. OPEC, on the other side, opposes it to protect their interests as oil and gas exporters. Among lower-income countries Indonesia stands out, because though it is a fossil-fuel exporter and member of OPEC, it has an island setting and thus is vulnerable to climate change. In fact, it was the first OPEC country to start Kyoto ratification.

Jotzo (2004) also points out that the uncertainty concerning economic costs helps explain the reluctance of industrialized countries such as US and Australia to join. In fact, Lecocq and Grasous (2003) research the issue of uncertainty about future emissions and abatement costs on commitments decisions by developing countries. They use a partial equilibrium model to simulate the impact of uncertainty on costs for all parties under different rules regarding quota allocation. They confirm that uncertainty in costs is a strong barrier. They demonstrate that rules under which new parties enter the Protocol as well as timing are critical. The analysis shows that when developing countries join, the total costs of climate change decrease significantly.

An interesting research idea is presented by Kavuncu and Knabb (2005). They simulate costs and benefits that current and future generations incur as a result of climate change. The costs of emissions stabilization program are high for current generation and increase over next 100 years for future generations. They calibrate the Diamond (1965) overlapping generations model with an environmental sector, i.e. the emissions stabilization program of Kyoto Protocol. An interesting result is that the first generation to benefit from environmental programs from now is born in the 24th century.

The existing literature offers mixed support for the idea that if countries take unilateral efforts to reduce emission, then global emissions will decline. Hoel (1991) using a game theory approach shows that unilateral reduction of emissions by one country leads to increase in emission in the other country. He further shows that that the outcome of unilateral reductions is the higher total emissions. Costly emissions reductions by a group of countries lead to free-riding by other group.

The primary research which our theoretical model is based on is Copeland and Taylor (2005). The authors employ competitive general equilibrium model with countries grouped into North and South based on the endowments of human capital. They explore whether emission reductions by one group of countries will result in emission increases elsewhere. In contrast to the traditional assumption in the literature that home and rest-of-world emissions are strategic substitutes, in this model they are strategic compliments. If North emits less, then South is going to emit less. The authors examine international trade under Kyoto framework and find "unilateral emission reductions by the rich North can create self-interested emission reductions by the unconstrained poor South"[28]. This happens because favorable terms of trade effects make the South richer where upon it implements tighter environmental controls. The paper also acknowledges free riding, income and carbon leakage effects when countries outside of Kyoto, which specialize in

[28] Copeland and Taylor (2005), p. 1.

dirty goods, increase dirty goods production and hence emissions in response to a change in the world price created by lower emissions of Kyoto countries. Because of these offsetting effects under free trade, it is possible that emissions in South may decline in response to Northern cuts.

The allocation of emission reductions implied by Kyoto Protocol may be efficient if there is no international trade in permits. This is because free trade causes factor prices to converge across countries allowing an efficient allocation of abatement to take place. When trade in permits occurs, however, this may result in increase in global emissions and make both countries worse off. Permit trade creates direct gains but also causes negative terms of trade effect for the North because the world price of the dirty good rises. The, negative terms of trade effect and the combined effects of carbon leakage and bootstrapping may make both countries worse off and lead to higher world emissions.

Copeland and Taylor make two important assumptions. Firstly, prior to Kyoto there is an internal Nash equilibrium to the environmental policy game where both North and South have binding emission caps.[29] Secondly, they assume that North and South have the same technologies and factor price equalization occurs where emissions constitute one of the factors. This means that emissions prices equalize across countries without international permit trade.

[29] In internal Nash Equlibrium in environemental policy game both North and South have binding emissions caps. In boundary Nash Equilibrium in our model only Northern countries have binding caps while South and OPEC remain unconstrained.

In our model we effectively assume a boundary Nash Equilibrium where Southern countries are uncapped. Although we assume a common underlying technology, we take a long-run view where there is a perfectly elastic supply of capital. Further, we assume that the user cost of capital in North is lower than the South and OPEC possibly due to lower risk premium. In contrast to the Copeland and Taylor this means that there will not be factor price equalization and the North will have an advantage in relatively capital intensive production activities including abatement.[30]

Pancoast (2003) formulates a two-country general equilibrium model which is similar in spirit to the model in this thesis. Her model investigates how tightening emissions caps in developed countries affects global emissions. Emissions credits are also introduced to analyze the effect of the CDM. The results of this paper suggest that the ultimate objective of the Kyoto protocol – the reduction of global GHG emissions – may not be achieved. As in the theoretical model in the current thesis but in contrast with Copeland and Taylor (2005), Pancoast (2003) assumes a boundary Nash equilibrium where the South does not have an emissions cap. In the Pancoast (2003) model factor price equalization does not occur because she assumes that technologies differ across countries. In the current theoretical model North-South differences in the user cost of capital rather than technological differences cause international differences in factor prices and emission intensities, but the results are similar to those in the Pancoast model.

[30] A more conventional approach with fixed capital endowments, capital abundant North and capital scarce South and OPEC would render the model less tractable, though would not change the results.

There is a final important difference between the model in this thesis and the models formulated by Copeland and Taylor (2005) and Pancoast (2003). In contrast to previous works with only clean and dirty goods, we have four goods with emissions generated from using fossil fuel. Interestingly, there is little sacrifice in terms of clarity and tractability to achieve this additional realism.

Chapter Four. Theoretical Model

We are considering a world which is divided into three countries: North, N; South, S; and OPEC, O. South and OPEC share the same characteristics except that OPEC sets the world price of fossil fuel. The four production sectors indexed by j consist of fossil fuel, F; electricity, E; dirty goods, D; and clean good, C. Clean good, dirty good and fossil fuel are freely traded, but electricity is assumed to be non-traded so that its price is determined on domestic market.[31] Further, H stands for the "household sector", which consume all four goods.

Inputs are indexed by i. The primary inputs consist of labour, L, and capital, K, which are used in the production of all goods, and a natural resource, R, which is specific to the production of fossil fuel. Electricity is used as an intermediate input in the production of the dirty good and fossil fuel is used as an intermediate input in the production of electricity, the dirty good and fossil fuel itself. North, South and OPEC are assumed to be diversified into the production of all goods and have the same technologies.

A major strength of the model is that GHG emissions come from fossil fuel use. M will represent emissions arising from the use of fossil fuel in the production of the dirty good, electricity, and fossil fuel itself as well as from the consumption of fossil fuel by households. As often considered in the literature emissions are treated as an additional factor of production (Copeland and Taylor, 1995, 2005). One unit of fossil fuel use

[31] Allowing electricity to be tradable would not substantially affect the results.

always generates one unit of emissions since we assume direct abatement is not possible. Emissions can be lessened indirectly, however, by the investment in a fuel saving technology. No emissions are used in clean good production. It is considered environmentally pristine in that it uses no fossil fuel or electricity and, thus, does not cause own emissions directly or indirectly.

Any use of fossil fuel implies the generation of emissions. Emissions from fossil fuel use by households are suggestive of emissions from transportation and home heating. Emissions from fossil fuel use in production of dirty goods are suggestive of emissions from heavy industry. Emissions from fossil fuel use in electricity sector are suggestive of emissions from electricity generation. Finally, emissions from fossil fuel use by itself are suggestive of emissions from energy sector. Therefore, the model is broadly descriptive of the major sources of GHG emissions in the real world.

Table 4 overviews the input output relationships in the markets for clean and dirty good, electricity, fossil fuel in households' or consumers' market. X_{jH}^{h} represents consumer demand for good j by households in country h. X_{ji}^{h} represents the demand for input i by sector j in country h. Y_{j}^{h} denotes the supply of output j by country h. Y_{i}^{h} denotes the supply of input i in country h.

Table 4 Inputs and Outputs in Country h=N,SO.

Outputs	Inputs					
	Electricity E	Fossil Fuel F	Capital K	Labour L	Emissions M	Nat.Res. R
Clean good Y_C^h	n.a.	n.a.	X_{KC}^h	X_{LC}^h	n.a.	n.a.
Dirty good Y_D^h	X_{ED}^h	X_{FD}^h	X_{KD}^h	X_{LD}^h	X_{MD}^h	n.a.
Electricity Y_E^h	n.a.	X_{FE}^h	X_{KE}^h	X_{LE}^h	X_{ME}^h	n.a.
Fossil Fuel Y_F^h	n.a.	X_{FF}^h	X_{KF}^h	X_{LF}^h	X_{MF}^h	X_{RF}^h

In Figure 1, we summarize all the production linkages in the economy and emphasize that all four goods are consumed by households. The North, South and OPEC are all assumed to be fully diversified in production of clean and dirty goods.

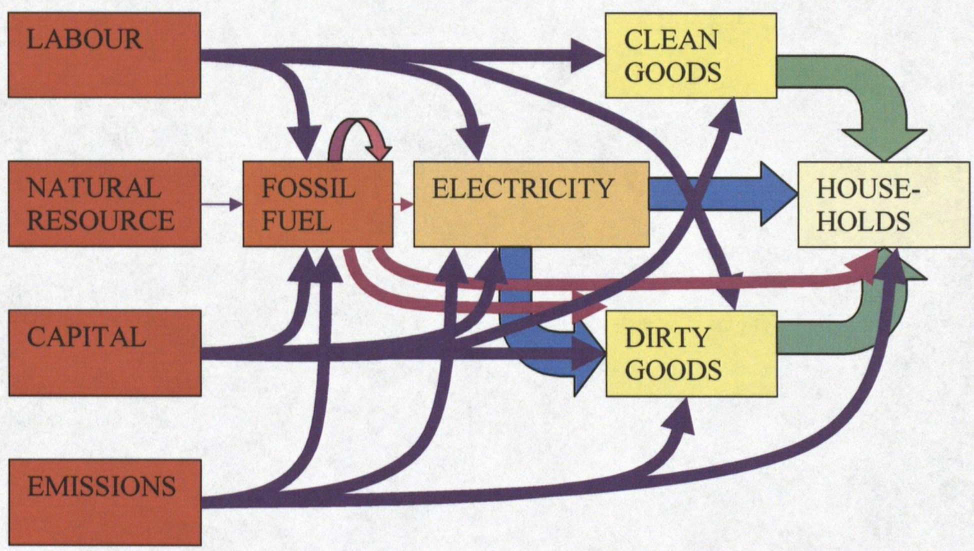

Figure 1 Production linkages in the economy.

The overall utility that country h gets is increasing in the sub-utility from consumables. The sub-utility function from consumables is linear in the clean good and fully separable across goods.

$$U_H^h = U_H^h(u_H^h, Y_M^w) \tag{1}$$

$$where \quad u_H^h = \sum_{j=D,E,F} V_H^h(x_{Hj}^h) + x_{HC}^h \qquad h = N,S,O \quad . \tag{2}$$

Since world emissions lead to climate change, Y_M^w enters negatively into the overall utility function. The clean good is chosen as a numeraire such that $P_C = 1$ for $h = N,S,O$.

By assuming that the sub-utility function is quasi-linear and separable, the demand for each non-numeraire good — the dirty good, electricity and fossil fuel — depends only on its own price. The first order conditions for utility maximization imply equality between prices and marginal utilities giving $P_j = \partial U_H^h(\cdot)/\partial u_H^h)(\partial u_{jH}^h(X_{jH}^h)/\partial X_{jH}^h)$ for $j = D,E,F$. Consequently, the demand functions can be written as follows:

$$X_{EH}^h = X_{EH}^h(p_E^h) \quad h = N,S,O \tag{3}$$

$$X_j^w = \sum_{h=N,SO} X_{jH}^h(p_j^w) \quad j = D,F \tag{4}$$

Here p_j^w is the world price of good j and p_E^h is domestic price of electricity which is non-traded in country h. For simplicity we assume that the clean good, the dirty good and the fossil fuel are freely traded. The structure of the sub-utility function is such that there are no income effects in the demand functions in (3) and (4).

Each country is endowed with a quantity of the natural resource. We assume perfect competition in the markets for natural resource in North and South. Thus, North and South fully utilize their natural resource endowments such that the demand for the natural resource is equal to the endowment, $X_R^h = \overline{Y}_R^h$, h=N,S. However, OPEC is able to set world price of fossil fuel above competitive level by limiting the use of its natural resource to be less than its endowment $p_F^w = \overline{p}_F^O \Rightarrow X_R^O \le \overline{Y}_R^h$.

There are some important features concerning capital. The supply of capital is perfectly elastic with user cost of capital in South and OPEC greater than in the North $p_K^N < p_K^{SO}$ due to lower risk premium and $p_K^{SO} = p_K^S = p_K^O$. There is a capital using fuel saving technology that exhibits increasing total and marginal costs and is common to all users. Though we have an assumption that countries have the same technologies, the lower price of capital in the North is equivalent to technological advantage, which is pronounced in capital-intensive activities including fuel-saving activity. Given the same emission prices, North has comparative advantage in the dirty good which is more capital intensive than the clean good.

In our model we take an initial corner solution where North is bound by cap, but South and OPEC are unconstrained. Therefore, there is zero emission price in South and OPEC, but positive in the North. [32]

$p_M^{SO} = p_M^S = p_M^O = 0,$

[32] A superscript "SO" on a price or technology (e.g. fuel saving) variable denotes that South and OPEC have the same value for the variable.

$Y_M^N = \overline{Y}_M^N \Rightarrow p_M^N \geq 0$.

This assumption of a boundary Nash equilibrium with no emissions cap in the South or OPEC, rather than internal equilibrium as in Copeland and Taylor (2005), is a key driver of differences in our results.

Emissions, Fuel Saving and Credits

In our model all activities associated with use of fossil fuel generate emissions. We assume that emission units are chosen such that one unit of fossil fuel used in production or consumption always generates one unit of emissions. This simplification, which assumes direct abatement is of negligible importance, appears to be largely in accord with the empirical work later in this thesis. Nevertheless, indirect emissions reduction through fuel savings is possible. It is assumed that there exists a fuel savings technology that is common to all uses including consumption as well as production.

The auxiliary fuel saving technology combines $1-\mu^h$ actual units of fossil fuel with $\kappa(\mu^h)$ units of capital to produce one standardized unit of fossil fuel. Consequently, μ^h denotes the fuel saving in the production of one standardized unit of fossil fuel attributable to auxiliary technology.33

The $\kappa(\mu^h)$ function exhibits several important properties. First, we assume that $\kappa'(\mu^h) > 0$, $\kappa''(\mu^h) > 0$, $\kappa'''(\mu^h) > 0$ which means that marginal costs of fuel saving

[33] Basic production and consumption processes will be written in terms of standardized units of fossil fuel.

given by $p_K^h \kappa'(\mu^h)$ are positive, increasing and increasing at an increasing rate. We also assume that $\kappa(0) = 0$, such that there is no capital necessary for fuel savings if there is no fuel savings. We further assume that $\kappa(1) = \infty$, which implies that if all the fuel is saved capital requirement goes to infinity. Thus, it is impossible to entirely escape from fuel use.

The capital requirements for fuel saving are presented on the diagram below, which implies that the fuel saving technology exhibits increasing total and marginal costs.

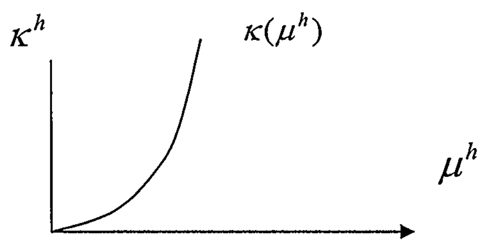

Figure 2 Cost of fuel saving.

The opportunity cost of using a standardized unit of fossil fuel in the North is:

$$\rho_F^N = \kappa(\mu^N) p_K^N + (1 - \mu^N)(\overline{p}_F^O + p_M^N) \tag{5}$$

Firms and consumers in North choose their fossil fuel saving μ^N to minimize the opportunity cost. The first order condition is:

$$p_K^N \kappa'(\mu^N) = \overline{p}_F^O + p_M^N \tag{6}$$

This first order condition implies that marginal benefit of fuel saving is equal to the marginal cost, which in turn implies that the optimal fuel savings is an increasing function of the sum of the prices of fossil fuel and emissions relative to capital, $\pi^N \equiv \overline{p}_F^O + p_M^N / p_K^N$

$$\mu^{*N} = \mu^{*N}\left(\pi^N\right) \tag{6.1}$$

Let us define optimum value function for the opportunity cost of fossil fuel in North.

$$\rho_F^{*N}(p_M^N, \overline{p}_F^O, p_K^N) \equiv p_K^N \kappa \; (\mu^{*N}(\pi^N)) + (p_M^N + \overline{p}_F^O)\left[1 - \mu^{*N}(\pi^N)\right] \tag{7}$$

where:

$$\frac{\partial \rho_F^{*N}}{\partial p_M^N} = (1 - \mu^{*N}(\pi^N)) > 0$$

$$\frac{\partial \rho_F^{*N}}{\partial p_K^N} = \kappa(\mu^{*N}(\pi^N)) > 0$$

$$\frac{\partial \rho_F^{*N}}{\partial \overline{p}_F^O} = (1 - \mu^{*N}(\pi^N)) > 0$$

When any price that is a component of the opportunity cost rises, so does the opportunity cost.

The opportunity cost of fossil fuel in the South and OPEC differs from the North. While agents in the South and OPEC do not have to pay to emit, they may be eligible for emission credits. The Clean Development Mechanism allows firms in developing countries to reduce their emissions below business-as-usual (BAU) levels and sell the corresponding credits to developed countries. International credit trade introduces integration of the South and OPEC into the emission credit market of the North. Recall that μ^{SO} represents the overall fuel savings of the South and OPEC. Let us define $\overline{\mu}^{SO}$ as business-as-usual fuel saving and, thus, emission reduction. Given that μ^{*SO} represents the optimum fuel saving of South and OPEC, under a full credit system, all further fuel savings and emissions reductions given by $\mu^{*SO} - \overline{\mu}^{SO}$ would be eligible for credits. Emission reductions and thus fuel savings eligible for credits however are likely to be constrained. Let θ be maximum credit that can be sold per unit of fossil fuel consumed. Consequently, if $\theta = 0$, then there is no credit market integration; if $0 < \theta < (\mu^{*SO} - \overline{\mu}^{SO})$, then there is partial integration; and if $\theta \geq (\mu^{*SO} - \overline{\mu}^{SO})$, then there is full integration.

North America advocated, for example, for full market integration in which case the emissions credit constraint would have been non-binding and $\theta \geq \mu^{*SO} - \overline{\mu}^{SO}$. Meanwhile, the European Union did not support emissions credits at all, i.e. θ=0. Full integration of the markets is unlikely to take place, but partial integration is possible with

$0 < \theta < \mu^{*SO} - \overline{\mu}^{SO}$. The case of no integration implies that South's and OPEC's fuel saving is equal to the business as usual level $\overline{\mu}^{SO}$. This is the case in an initial pre-Kyoto equilibrium which we will take as the starting point for the analysis of increasing allowable emission credits.

Let us examine the credit revenue of South and OPEC for each case. We assume that economic agents in South and OPEC are able to obtain the Northern price of emissions on their sales of emission credits. With full or unconstrained credit market integration, South's and OPEC's credit revenue is $p_M^N \cdot (\mu^{SO} - \overline{\mu}^{SO})$. With constrained or partial integration, the revenue is $\theta \cdot p_M^N$. More generally, we can write credit revenue as $p_M^N \min\{\mu^{SO} - \overline{\mu}^{SO}, \theta)$. Consequently, opportunity cost of using $1 - \mu^{SO}$ units of fossil fuel in South and OPEC is:

$$\rho_F^{SO} = (1 - \mu^{SO})\overline{p}_F^O + p_K^{SO}\kappa(\mu^{SO}) - p_M^N \min\{\mu^{SO} - \overline{\mu}^{SO}, \theta\} \tag{8}$$

The first term is the direct cost of fossil fuel after accounting for fuel saving. The second term is the capital costs associated with fuel saving. The last term is the negative cost or revenue from sale of emission credits due to fuel savings.

Starting with the case of full or unconstrained credit market integration (i.e., $\theta \rightarrow \infty$), the first order condition for minimizing the opportunity cost of fuel use in the South and OPEC is of the same form as for the North:

$$p_K^{SO}\kappa'(\mu^{SO}) = \overline{p}_F^O + p_M^N \tag{9}$$

South's and OPEC's optimum fuel saving depends positively on sum of OPEC's price of fossil fuel and price of Northern emission relative to its user cost of capital.

$$\mu^{*SO} = \mu^{*SO}(\pi^{SO}) \tag{9.1}$$

$$\pi^{SO} = \frac{\overline{p}_F^O + p_M^N}{p_K^{SO}}$$

Since the user cost of capital is lower in North, optimal fuel saving in North is greater than fully optimum fuel saving in South and OPEC:

$$p_K^{SO} > p_K^N \Rightarrow \frac{\overline{p}_F^O + p_M^N}{p_K^N} > \frac{\overline{p}_F^O + p_M^N}{p_K^{SO}} \Rightarrow \mu^{*N} > \mu^{*SO}.$$

Next consider the case of no integration where emission credits are not allowed (i.e. $\theta = 0$). We will assume that $\overline{\mu}^{SO}$ is set at the level that minimizes costs with no integration or, in other words, it is set at the level which firms would actually choose without Kyoto agreement. In this case opportunity cost of fuel use becomes:

$$\rho_F^{SO} = (1-\mu^{SO})\overline{p}_F^O + p_K^{SO}\kappa(\mu^{SO}) \tag{10}$$

and, the first order condition is:

$$p_K^{SO}\kappa'(\overline{\mu}^{SO}) = \overline{p}_F^{O}. \tag{11}$$

This implies that the business-as-usual level of fuel savings is an increasing function of OPEC's price of fossil fuel relative to South's and OPEC's user cost of capital:

$$\overline{\mu}^{SO} = \overline{\mu}^{SO}\left(\frac{\overline{p}_F^{O}}{p_K^{SO}}\right).$$

The Marginal Benefit for the South and OPEC is smaller with zero credits than with full credits.

$$\overline{p}_F^{O} < \overline{p}_F^{O} + p_M^{N} \Rightarrow \frac{\overline{p}_F^{O}}{p_K^{SO}} < \frac{\overline{p}_F^{O} + p_M^{N}}{p_K^{SO}} < \frac{\overline{p}_F^{O} + p_M^{N}}{p_K^{N}} \Rightarrow \mu^{*N} > \mu^{*SO} > \overline{\mu}^{SO}.$$

Finally, in the case of partial integration the emissions credit constraint is binding such that $0 \leq \theta \leq (\mu^{*SO} - \overline{\mu}^{SO})$. Consequently, the constrained level of fuel saving is:

$$\mu^{SO} = \overline{\mu}^{SO}\left(\frac{\overline{p}_F^{O}}{p_K^{SO}}\right) + \theta. \tag{11.1}$$

The extent of fuel saving by South and OPEC is the BAU level plus allowable credits. Substituting into opportunity cost equation for the South and OPEC (8) we obtain:

$$\overline{\rho}_F^{SO} = (1 - \overline{\mu}^{SO}(\cdot) - \theta)\overline{p}_F^{O} + p_K^{SO}\kappa(\overline{\mu}^{SO}(\cdot) + \theta) - \theta p_M^{N} = \overline{\rho}_F^{SO}(\overline{p}_F^{O}, p_K^{SO}, p_M^{N}, \theta). \tag{12}$$

Now let us examine some key comparative static results for South's and OPEC's fossil fuel saving:

$$\frac{\partial \overline{\rho}^{SO}}{\partial \overline{p}_F^{SO}} = 1 - \mu^{SO} + \left(\kappa'(\overline{\mu}^{SO} + \theta) - \frac{\overline{p}_F^O}{p_K^{SO}} \right) \frac{\partial \overline{\mu}^{SO}}{\partial (\overline{p}_F^O / p_K^{SO})} \geq 1 - \mu^{SO}$$

Notice that, $\kappa'(\overline{\mu}^{SO} + \theta) - \frac{\overline{p}_F^O}{p_K^{SO}}$ is positive if θ is positive and it is equal to zero if θ is equal to zero. Thus, in the vicinity of an initial equilibrium where θ=0 and $\mu^{SO} = \overline{\mu}^{SO}$, we get:

$$\frac{\partial \overline{\rho}^{SO}}{\partial \overline{p}_F^{SO}} = 1 - \overline{\mu}^{SO} > 0. \tag{13}$$

Note that from equation (7) $\frac{\partial \rho_F^{*N}}{\partial \overline{p}_F^O} = (1 - \mu^{*N}) > 0$. Since $\mu^{*N} > \overline{\mu}^{SO}$ implies $1 - \overline{\mu}^{SO} > 1 - \mu^{*N}$, North uses less fossil fuel than South and OPEC. As a result, in the vicinity of an initial equilibrium without credits, and increase in the price of fossil fuel has a bigger impact on the opportunity costs of South than that of North.

An increase in the Northern emission price has no impact on South's and OPEC's opportunity cost of emissions in the initial pre-Kyoto equilibrium where $\theta = 0$ and has a negative impact when credits are present:

$$\frac{\partial \overline{p}^{SO}}{\partial p_M^N} = -\theta . \tag{14}$$

An increase in the user cost of capital in South and OPEC raises the opportunity cost of fossil fuel in the vicinity of pre-Kyoto equilibrium because using the fuel saving technology becomes less economical:

$$\frac{\partial \overline{p}^{SO}}{\partial p_K^{SO}} = \frac{1}{p_K^{SO}} \left(p_K^{SO} \kappa(\overline{\mu}^{SO} + \theta) - \left(\kappa'(\overline{\mu}^{SO} + \theta) - \frac{\overline{p}_F^O}{p_K^{SO}} \right) \frac{\partial \overline{\mu}^{SO}}{\partial (\overline{p}_F^O / p_K^{SO})} \right). \tag{15}$$

An increase in allowable emission credits reduces the opportunity cost of fossil fuel use in South and OPEC:

$$\frac{\partial \overline{p}^{SO}}{\partial \theta} = -[\overline{p}_F^O + p_M^N - p_K^{SO} \kappa'(\overline{\mu}^{SO} + \theta)] \leq 0 \tag{16}$$

Since the emissions constraint is binding, the marginal benefit of reducing emissions, $\overline{p}_F^O + p_M^N$ exceeds the marginal costs, $p_K^{SO}\kappa'(\overline{\mu}^{SO})$, if p_M^N>0.

Figure 3 summarizes the analysis of fuel savings and emissions reductions in a context where GHG emissions come from the combustion of fossil fuel. The marginal cost curves are positively sloped reflecting the fact that fuel savings becomes progressively more costly. North due to a lower user cost of capital has lower marginal costs of fuel saving. The marginal benefit of fuel saving is composed of the price of fossil fuel and the price of emissions which are avoided by reducing fuel use. The intersection of the marginal benefit and the marginal cost curves for North gives the optimal amount of fuel saving in the North and, thus, the reductions in North's emissions. Similarly, the intersection of the marginal benefit and the marginal cost curves for South and OPEC gives the fully optimal or unconstrained amount of fuel saving. The business-as-usual level of emissions for the South OPEC region, $\overline{\mu}^{SO}$, occurs where the fossil fuel price is equal to the marginal cost of South and OPEC. Given that allowable credits are constrained to be no greater than θ, $\widetilde{\mu}^{SO}$ is the chosen amount of fuel saving. The shaded area is the credit revenue that South gets through selling credits.

Figure 3 shows clearly that the optimum level of fuel savings in the North exceeds the fully optimum level of fuel savings in the South and OPEC because North's lower cost of capital implies that its marginal costs curve lies below that of South and OPEC. Since fuel saving in South and OPEC is constrained, there is a larger difference in fuel saving costs. Since such limits can be expected under the Clean Development Mechanism, the North is cleaner than South and OPEC in all fossil fuel using activities.

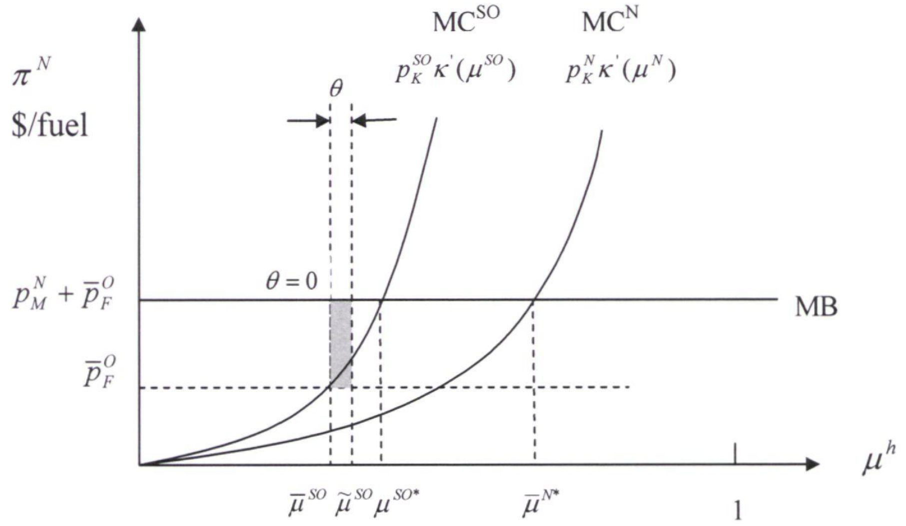

Figure 3. Optimum fuel saving in North, South and OPEC.

Prices and Unit Costs

We now proceed to examine zero-profit or price equal unit cost conditions. For simplicity it will be assumed that there are no tariffs or trade barriers of any kind. Consequently, we will let p_j^w denote world price of goods $j = C, D, F$ and let p_E^h be the domestic price of non-tradable electricity. Similarly, let p_i^h stand for the domestic price of input where $i = K, L, M, R$. Since the clean good is chosen to be the numeraire, $p_C^h = 1$.

The basic production technologies, like the fuel saving technology, are assumed to be uniform across countries. Capital and labour enter into the basic production technologies for all goods and the natural resource enters into the production of fossil fuel. We will assume that fossil fuel is used as an input with a fixed coefficient, a_{Fj}, in the basic production technologies for the dirty good, electricity and fossil fuel. As we have seen above, however, the basic production technologies for these goods can be supplemented using the auxiliary fuel saving technology to reduce fuel use. Electricity also enters with a fixed coefficient, a_{ED}, in the production of dirty good.

For North, and for the South and OPEC, the zero-profit conditions for the clean good, the dirty good, electricity and fossil fuel are:

$$p_C^w = \beta_C(p_K^h, p_L^h) = 1 \qquad h = N, SO \qquad (17)$$

$$p_D^w = \beta_D(p_K^h, p_L^h) + p_E^h a_{ED} + \rho_F^h a_{FD} \qquad h = N, SO \tag{18}$$

$$p_E^h = \beta_E(p_K^h, p_L^h) + a_{FE}\rho_F^h \qquad h = N, SO \tag{19}$$

$$\overline{p}_F^O = \beta_F(p_K^h, p_L^h, p_R^h) + a_{FF}\rho_F^h \qquad h = N, SO \tag{20}$$

The unit costs of each of the goods depend on the wage and user cost of capital and the unit costs of fossil fuel also depend on the rental price of the natural resource, p_R^h. The unit cost of the dirty good also depends on the price of electricity, which is used as an input. The unit costs of the dirty good, electricity and fossil fuel also depend on the opportunity cost of using fossil fuel as an input. Here, recall that ρ_F^h represents the opportunity cost of using one standardized unit of fossil fuel in country h inclusive of OPEC's price of fossil fuel, North's price of emissions and country h's user cost of capital.

Since the clean good is the numeraire, we are able to use the zero profit conditions for the clean good to solve for the equilibrium wage $\tilde{p}_L^h$ given that p_K^h is exogenous. The wage must be higher in the North than in the South and OPEC to offset the lower user cost of capital in the North. Substituting $\tilde{p}_L^h$ and equations (19), (7) and (12) into the zero-profit condition for the dirty good, we obtain the diversified production condition presented below:

$$\begin{aligned} p_D^W &= \beta_D^N(p_K^N, \tilde{p}_L^N) + \beta_E(p_K^N, \tilde{p}_L^N)a_{ED} + \rho_F^{*N}(p_M^N, \overline{p}_F^O, p_K^N)A_{FD} \\ &= B_D^N(\overline{p}_F^O, p_K^N, p_M^N) \end{aligned} \tag{21}$$

$$\begin{aligned} p_D^W &= \beta_D^{SO}(p_K^{SO}, \tilde{p}_L^{SO}) + \beta_E(p_K^{SO}, \tilde{p}_L^{SO})a_{ED} + \overline{\rho}_F^{SO}(p_M^N, p_K^{SO}, \overline{p}_F^O, \theta)A_{FD} \\ &= B_D^{SO}(\overline{p}_F^O, p_K^{SO}, p_M^N, \theta) \end{aligned} \tag{22}$$

where: $A_{FD} = a_{FD} + a_{FE}a_{ED}$.

Here, A_{FD}^h is the number of standardized units of fossil fuel required to produce one unit of dirty good inclusive of the amount required to produce the underlying electricity. When a country's diversification condition holds, it is able to produce both clean and dirty goods because equations (17) and (18) hold simultaneously. The diversification conditions given by equations (21) and (22) are shown as the NN and SO curves in Figure 5.

An increase in either the Northern emissions price or OPEC's price of fossil fuel raises overall costs in the North and requires a higher world price for the dirty good if the sector is to break even:

$$\left.\frac{\partial p_D^w}{\partial p_M^N}\right|_{NN} \equiv A_{MD}^N = A_{FD}\frac{\partial \rho_F^N}{\partial p_M^N} = A_{FD}(1-\mu^{*N}) > 0 \tag{23}$$

$$\left.\frac{\partial p_D^w}{\partial \overline{p}_F^O}\right|_{NN} \equiv A_{MD}^{SO} = A_{FD}\frac{\partial \rho_F^N}{\partial \overline{p}_F^O} = A_{FD}(1-\mu^{*N}) > 0 \tag{24}$$

The NN curve representing Northern diversification is positively sloped and shifts up in response to an increase in the OPEC's price of fossil fuel.

An increase in the North's emissions price has no impact on the price of the dirty good that is consistent with zero profits in the South and OPEC in the absence of credits, but reduces the price of the dirty good when emission credits are present. A reduction in the price of dirty good is possible because an increase in the North's price of emissions increases credit revenue and, therefore, reduces the opportunity cost of fuel and overall costs in South and OPEC.

$$\left.\frac{\partial p_D^w}{\partial p_M^N}\right|_{SO} \equiv A_{\bar{\mu}D}^{SO} = -\theta A_{FD} \tag{25}$$

A higher price of emissions in the North implies greater subsidy for the South and OPEC and also greater fuel saving efforts. The SO curve representing diversification in the South and OPEC is horizontal in a pre-Kyoto equilibrium without credits, but it becomes negatively sloped when credits are allowed.

An increase in the price of fossil fuel necessitates an increase in the price of the dirty good if the South and OPEC are to remain diversified:

$$\left.\frac{\partial p_D^w}{\partial p_F^O}\right|_{SO} = \left(1 - \bar{\mu}^{SO} + \left(\kappa'(\bar{\mu}^{SO} + \theta) - \frac{\bar{p}_F^O}{p_K^{SO}}\right)\frac{\partial \bar{\mu}^{SO}}{\partial(\bar{p}_F^O / p_K^{SO})}\right) A_{FD} > 0 \tag{26}$$

It should be noted that in the vicinity of an initial pre-Kyoto equilibrium with no credits, an increase in the price of fossil fuel would require a bigger increase in the price of the dirty good to allow the South and OPEC, as opposed to the North, to break even because the South and OPEC use more fossil fuel than the North per unit of output of each fuel using good (i.e., $1-\overline{\mu}^{SO} > 1-\mu^{*N}$).

An increase in allowable credits reduces the opportunity cost of fossil fuel in the South and OPEC and, thereby, reduces the price of the dirty good which is consistent with zero-profits:

$$\left.\frac{\partial p_D^w}{\partial \theta}\right|_{SO} = -A_{FD}\left[\overline{p}_F^O + p_M^N - p_K^{SO}\kappa'(\overline{\mu}^{SO})\right] \leq 0 \qquad (27)$$

Such an increase in allowable permits causes a downward pivot in the SO curve.

The analysis of the diversification conditions for North, South and OPEC is presented in Figure 4 below. Along the NN curve for diversification in the production of dirty and clean goods by North, a higher world price of the dirty good is necessary when the Northern price of emissions rises since now costs have risen. For South and OPEC in the initial pre-Kyoto equilibrium when emission credits are not allowed, the world price of dirty good at which South and OPEC break even is independent of the Northern emissions price. SO curve is horizontal.

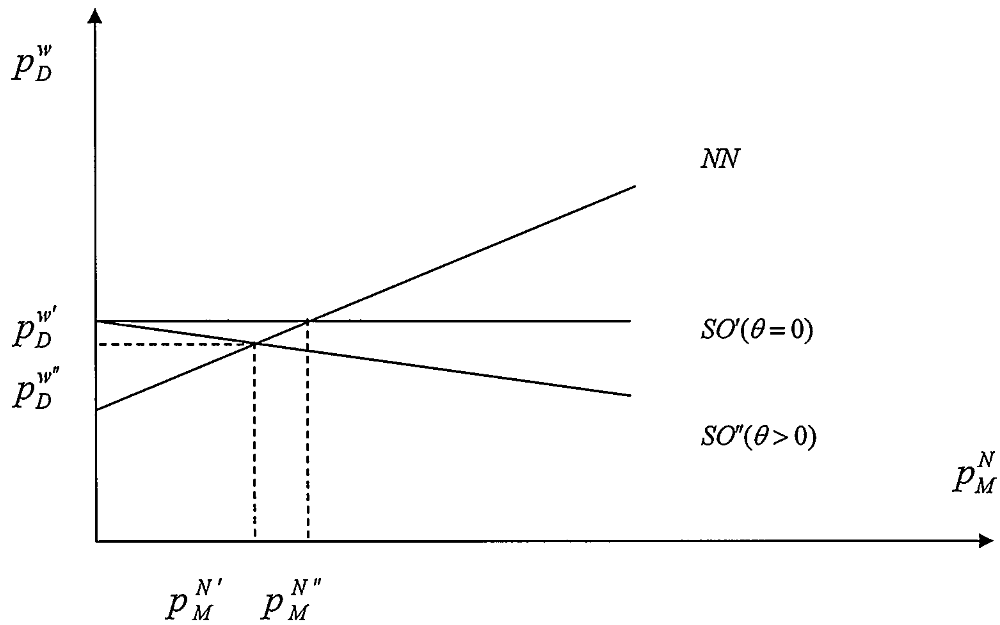

Figure 4. Diversification conditions for North, South and OPEC.

A requirement for an equilibrium with diversified production in both the North and the South and OPEC region is that the intercept of the NN curve lies below SO curve. This will occur if and only if the dirty good is more capital intensive than the clean good when the Northern price of emissions is equal to zero. We have seen that a higher wage in the North is necessary to offset its lower user cost of capital, such that both the North and the South-OPEC region both are in zero profits in clean good. Consequently, when the Northern price of emissions is equal to zero, both countries would have equal unit costs for the dirty good if the clean and the dirty good were equally capital intensive. If the dirty good is more capital intensive when the Northern price of emissions is equal to zero, however, the North will have lower unit costs in the dirty good than the South. Therefore, the world price of dirty good required for North to break even is lower than for the South and OPEC, which is reflected in the lower intercept for the NN curve than for the SO curve. Since emission intensive goods tend to be highly capital intensive, it will be assumed that the dirty good is more capital intensive than the clean good even if the emission prices are equal to zero.

From the diversification conditions for North and for the South-OPEC region given by equations (21) and (22) we can solve for the world price of dirty good and the Northern price of emissions. In Figure 4, the intersection of the NN and SO curves shows these equilibrium prices.34 Further, for both the North, and the South and OPEC we can determine: the fuel saving levels from equations (6.1) and (11.1), the opportunity cost of fossil fuel use from equations (7) and (12), the domestic prices of electricity from equation (19), and natural resource rents from equation (20). Similarly from equations (3) and (4) we can establish consumption levels for dirty goods, electricity and fossil fuel.

Figure 4 provides the basis for some important comparative statics results, which are presented in Table 5. Proofs of these comparative static results are provided in the Appendix. The world price of dirty goods and the price of emissions in the North are independent of Northern emissions cap in equilibrium whenever both regions are diversified. Since diversification conditions shown by the NN and SO curves are independent of emissions cap, change in the cap has no impact whatsoever on endogenous variables, such as the world price of the dirty good, the price of emissions in the North, electricity prices, natural resource rents and consumption levels.

[34] This implies that both the South's supply of dirty goods and emissions credits is perfectly elastic.

Table 5 Comparative Statics starting from a pre-Kyoto Diversified Equilibrium, where $\theta = 0$ and $p_M^N > 0$.

	Decrease in North's emission cap $\overline{Y}_M^N$	Increase in emission credit constraint θ	Increase in OPEC's fossil fuel price $\overline{p}_F^O$
North's emissions price $p_M^N(\theta, \overline{p}_F^O)$	*zero*	(−)	(+)
World dirty-good price $p_D^w(\theta, \overline{p}_F^O)$	*zero*	(−)	(+)
North's fuel saving level $\mu^{*N}(\theta, \overline{p}_F^O)$	*zero*	(−)	(+)
South and OPEC's fuel saving $\overline{\mu}^{SO}(\overline{p}_F^O) + \theta$	*zero*	(+)	(+)
North's opportunity cost of fossil fuel $\rho_F^{*N}(p_M^N(\theta, \overline{p}_F^O), \overline{p}_F^O)$	*zero*	(−)	(+)
South's and OPEC's opportunity cost of fossil fuel $\overline{\rho}_F^{SO}(p_M^N(\theta, \overline{p}_F^O), \theta, \overline{p}_F^O)$	*zero*	(−)	(+)
Electricity prices $p_E^h(p_M^N(\theta, \overline{p}_F^O))\ h = N, SO$	*zero*	(−)	(+)
Dirty good consumption $X_{DH}^h(p_D^N(\theta, \overline{p}_F^O))\ h = N, SO$	*zero*	(+)	(−)
Electricity consumption $X_{EH}^h(p_E^h(p_M^N(\theta, \overline{p}_F^O)))\ h = N, SO$	*zero*	(+)	(−)
Fossil Fuel consumption in North $X_{FH}^N(\rho_F^{*N}(p_M^N(\theta, \overline{p}_F^O), \overline{p}_F^O))$	*zero*	(+)	(−)
Fossil Fuel consumption in South and OPEC $X_{FH}^{SO}(\overline{\rho}_F^{SO}(p_M^N(\theta, \overline{p}_F^O), \theta, \overline{p}_F^O))$	*zero*	(+)	(−)
Natural Resource Rents in North $p_R^N(\rho_F^{*N}(p_M^N(\theta, \overline{p}_F^O), \overline{p}_F^O), \overline{p}_F^O)$	*zero*	(+)	(+)
Natural Resource Rents in South and OPEC $p_R^{SO}(\overline{\rho}_F^{SO}(p_M^N(\theta, \overline{p}_F^O), \theta, \overline{p}_F^O), \overline{p}_F^O)$	*zero*	(+)	(+)

Greater integration of emissions markets through an increase in allowable emission credits that South and OPEC can sell to the North leaves the NN curve unaltered, but the

SO curve pivots down. Greater revenue allows firms in South and OPEC to break even at a lower price of dirty good. Therefore, at the new price of the dirty good the North can break even at the lower emissions price. Fuel saving goes up in the South and OPEC to facilitate the sale of the credits. The opportunity cost of fossil fuel use goes down in the South and OPEC since credit revenue from selling emissions credits outweighs the impact of lower Northern price of emissions in the vicinity of initial pre-Kyoto equilibrium with no emissions credits. In North fuel saving and the opportunity cost of fuel use go down because of lower emissions price. Lower opportunity cost in both regions lead to lower domestic prices of electricity and higher natural resource rents. The lower world price of dirty good means the higher dirty good consumption for the North, and for the South and OPEC. Similarly, lower electricity prices lead to more electricity consumption in both regions. The lower opportunity costs of fossil fuel lead to greater fossil fuel consumption.

In the vicinity of initial equilibrium with no credits $\theta = 0$, an increase in the price of fossil fuel both diversification curves shift up. Recall from equations (24) and (26) that the Northern diversification curve, NN, shifts up to a smaller extent than that of South and OPEC, SO, because the South and OPEC use more fossil fuel than the North per unit of output of each fuel using good in the vicinity of an initial pre-Kyoto equilibrium with no credits. Given that the price of the dirty good rises sufficiently for the firms in the South to break even, Northern firms can afford a higher price of emissions. An increase in the price of fossil fuel leads to increases in: (a) the North's emissions price, (b) the world price of the dirty good, (c) the opportunity cost of fuel use in both the North and the South and OPEC regions, (d) fuel saving in both regions, (e) the price of electricity in both regions and (f) natural resource rents in both regions. Overall fuel savings in the South and OPEC increase because the business-as-usual fuel savings increase with the price of fossil fuel. Fuel saving in the North goes up because of the higher price of emissions and higher price of fossil fuel presented in Figure 5 below. As a result of the price increases, electricity, dirty good and fossil fuel consumption go down.

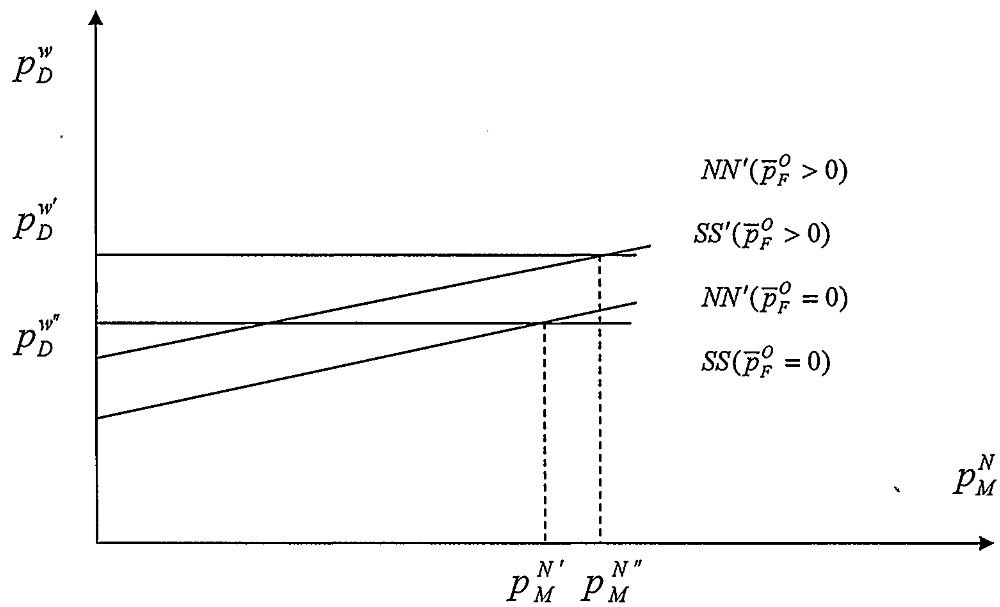

Figure 5. Analysis of shifts in NN and SO when θ becomes positive.

National and International Markets

With prices determined by the zero-profit conditions we can use market equilibrium conditions to determine the quantities. Firstly, we look at three separate national economies.

Equation (21) describes equilibrium in the market for electricity with all electricity input utilization coefficients fixed.

$$Y_E^h = \overline{a}_{ED} Y_D^h + X_{EH}^h \quad h = N,S,O \tag{28}$$

The supply of electricity is equal to its demand by dirty good and fossil fuel sectors and includes demand coming from consumers.

The next equation describes the equilibrium in the labour market.

$$\overline{Y}_L^h = a_{LC}(\cdot)Y_C^h + a_{LD}(\cdot)Y_D^h + a_{LE}(\cdot)Y_E^h + a_{LF}(\cdot)Y_F^h(1-\mu^h) \qquad h = N,S,O \tag{29}$$

The left hand side is labour endowment of the economy or labour supply. The right hand side is the sum of labour demanded to produce clean goods, dirty goods, electricity and fossil fuel considering fuel saving. The conditional demand for labour in each sector is the number of units of labour required to produce one unit of output multiplied by the actual units produced. Note that input utilization coefficients are not fixed but instead vary with cost of capital and labour.

$$\frac{\partial b_j}{\partial p_L^h} = \frac{\partial \beta_j}{\partial p_L^h} = a_{Lj}(\cdot) \qquad j = C, D, E, F$$

where β_j is homogeneous of degree one in primary factor prices, a_{ij} homogeneous of degree zero or conditional demands per unit output depend only on relative prices.

Since the price of capital differs between the North and the South and OPEC region, the input utilization coefficients are also different across the two regions. The ratio of wages to user cost of capital is higher in the North than in the South and OPEC.

A similar aggregation across uses of capital yields the endogenous long-run quantity of capital that is accumulated in each country.

$$Y_K^h = a_{KC}(\cdot)Y_C^h + a_{KD}(\cdot)Y_D^h + a_{KE}(\cdot)Y_E^h + a_{KF}(\cdot)Y_F^h \qquad h = N,S,O \qquad (30)$$

Note that capital utilization coefficients include capital used directly in production and also used in fuel saving.

$$\frac{\partial b_j}{\partial p_K^h} = \frac{\partial \beta_j}{\partial p_K^h} + a_{Fj}\frac{\partial \rho^*}{\partial p_K^h} = a_{Kj}(\cdot) \qquad j = D, E, F$$

The following equation gives the equilibrium in the market for natural resource.

$$X_R^h = a_{RF}(\cdot)Y_F^h \leq \overline{Y}_R^h \qquad h = N,S,O \qquad (31)$$

The right hand side is the available supply of natural resource and the left hand side is the demand generated by the fossil fuel sector. The demand for the natural resource is equal to the output of fossil fuel multiplied by the amount of resource required to produce one unit of fossil fuel output. The resource utilization coefficient is not fixed; instead it is a function of the relative prices of the primary factors.

$$\frac{\partial b_j}{\partial p_R^h} = \frac{\partial \beta_j}{\partial p_R^h} = a_{Rj}(p_R^h(\theta, \overline{p}_F^O)/p_K^h, \widetilde{p}_L^h/p_K^h)$$

Feasibility dictates that the resource use is less than or equal to the endowment. We assume that OPEC sets the world price of fossil fuel above the competitive level. In order to do this, OPEC has to leave some of its natural resource reserves unused such that there is excess supply. OPEC uses less resource than it has available in order to defend the higher price of fossil fuel on the world market. Equation (24) holds with inequality for OPEC which restricts its quantity of fossil fuel produced below the competitive supply, but with equality for North and South which behave competitively.

$$Y_F^h = \frac{X_R^h}{a_{RF}(\cdot)} = Y_F^h(\overline{p}_F^O, \theta), \quad \frac{\partial Y_F^h}{\overline{p}_F^O} > 0, \quad \frac{\partial Y_F^h}{\theta} > 0 \qquad h = N,S \qquad (32)$$

If the price of fossil fuel rises or allowable credits increase, there is an increase in natural resource rents and a reduction in the use of natural resource per unit output of fossil fuel. This implies a greater supply of fossil fuel.

Let us move to the international market for fossil fuel. In order to defend its price of fossil fuel, OPEC must accommodate the residual demand which consists of world demand minus the supply of North and South. [35]

$$Y_F^O = X_F^N + X_F^{SO} - Y_F^N - Y_F^{SO} \tag{33}$$

Alternatively, if we define the output of OPEC and the South to be $Y_F^{SO} = Y_F^S + Y_F^O$, then we can write:

$$Y_F^{SO} = X_F^N + X_F^{SO} - Y_F^N \tag{34}$$

The joint supply of fossil fuel from South and OPEC is equal to demand from South and OPEC and net demand from the North.

The demand for fossil fuel in country h is determined by its use in the dirty sector, electricity, fossil fuel production and household consumption. Considering the fact that there is fuel saving in every sector including households, actual fossil fuel demand is given by:

[35] A superscript "SO" on a quantity variable refers to the sum of the quantities for OPEC and South.

$$X_F^h = (\bar{a}_{FD}Y_D^h + \bar{a}_{FE}Y_E^h + \bar{a}_{FF}Y_F^h + X_{FH}^h)(1-\mu^h) \qquad (35)$$

Substituting for Y_E^h we obtain

$$X_F^h = (A_{FD}Y_D^h + \bar{a}_{FF}Y_F^h + \bar{a}_{FE}X_{EH}^h + X_{FH}^h)(1-\mu^h) \qquad (36)$$

Consequently, $A_{FD} = \bar{a}_{FD} + \bar{a}_{FE}\bar{a}_{ED}$ is the direct use of fossil fuel in the dirty good sector and the indirect use of fossil fuel in producing the underlying electricity for that sector.

Using equation (36) we can write:

$$A_{FD}Y_D^h = \zeta^h X_F^h - \bar{a}_{FF}Y_F^h - \bar{a}_{FE}X_{EH}^h + X_{FH}^h \qquad h = N, SO$$

$\zeta^h \equiv \dfrac{1}{(1-\mu^h)}$ is a standardization coefficient for country h.

Aggregate demand for dirty good across countries is equal to its supply by North, South and OPEC.

$$Y_D^N + Y_D^{SO} = X_{DH}^N + X_{DH}^{SO} \qquad (37)$$

Now, substituting Y_D^h into (37) solves for goods market equilibrium.

$$\left[\frac{1}{(1-\mu^N)A_{FD}}-\frac{A_{FF}}{A_{FD}}\right]X_F^N+\left[\frac{1}{(1-\mu^S)A_{FD}}-\frac{A_{FF}}{A_{FD}}\right]X_F^{SO}+\frac{A_{FF}}{A_{FD}}\frac{Y_R^N}{a_{RF}}-\frac{A_{FF}}{A_{FD}}\frac{Y_R^N}{a_{RF}}=$$

$$=A_{FD}X_{DH}^w+\frac{1}{A_{FD}}(a_{FE}X_{EH}^w+X_{FH}^w)$$

Simplifying the terms results in:

$$\left[\frac{1}{(1-\mu^N)}-A_{FF}\right]X_F^N+\left[\frac{1}{(1-\mu^S)}-A_{FF}\right]X_F^{SO}=A_{FD}X_{DH}^w+a_{FE}X_{EH}^w+X_{FH}^w$$

$$\left[\frac{1-(1-\mu^N)A_{FF}}{(1-\mu^N)}\right]X_F^N+\left[\frac{1-(1-\mu^{SO})A_{FF}}{(1-\mu^{SO})}\right]X_F^{SO}=A_{FD}X_{DH}^w+a_{FE}X_{EH}^w+X_{FH}^w \qquad (38)$$

Let us define $\phi^h \equiv 1-(1-\mu^h)A_{FF}>0$ is a net output coefficient where $(1-\mu^N)A_{FF}$ is fuel use as an input in producing one unit of gross output of fossil fuel.

We can now rewrite equation (38) as:

$$\phi^N\zeta^N X_F^N+\phi^{SO}\zeta^{SO}X_F^{SO}=A_{FD}X_{DH}^w+a_{FE}X_{EH}^w+X_{FH}^w \text{ , or} \qquad (39)$$

$$X_F^N=\frac{1}{\phi^N\zeta^N}Z_F^W-\frac{\phi^{SO}\zeta^{SO}}{\phi^N\zeta^N}X_F^{SO}.$$

Here, $Z_F^w=A_{FD}X_{DH}^w+a_{FE}X_{EH}^w+X_{FH}^w$ is the standardized world demand for fossil fuel by consumers and it includes the direct use of fossil fuel and the imputed use in electricity and dirty goods. All consumption levels are standardized to allow aggregation across countries to the levels that would occur if there were no investment in fuel saving.

Equation (39) represents the combinations of fuel demand by the North and by the South and OPEC region that are consistent with equilibrium in goods markets.

The goods market equilibrium condition represented by equation (39) is shown by the FF curve in Figure 6. It is linear over a range consistent with positive outputs of the dirty and clean good in both countries and it is negatively sloped. Moving down and to the right along the FF curve North reduces its output of the dirty good and increases clean good production while South and OPEC increase their output of the dirty good and reduce clean good production. Every time we transfer production of dirty good from North to the South, emissions in South and OPEC go up by more than they go down in North because South and OPEC invest less in fuel saving, therefore, dirty good production is dirtier in the South and OPEC.[36] Consequently, the magnitude of the slope of the FF curve is less than one.

[36] As $\mu^N > \mu^S \Rightarrow 1-\mu^N < 1-\mu^S \Rightarrow \frac{1}{1-\mu^N} > \frac{1}{1-\mu^S}$ the slope of FF curve above is less than 1. We can conclude $\phi^N > \phi^S$ and $\zeta^N > \zeta^S$.

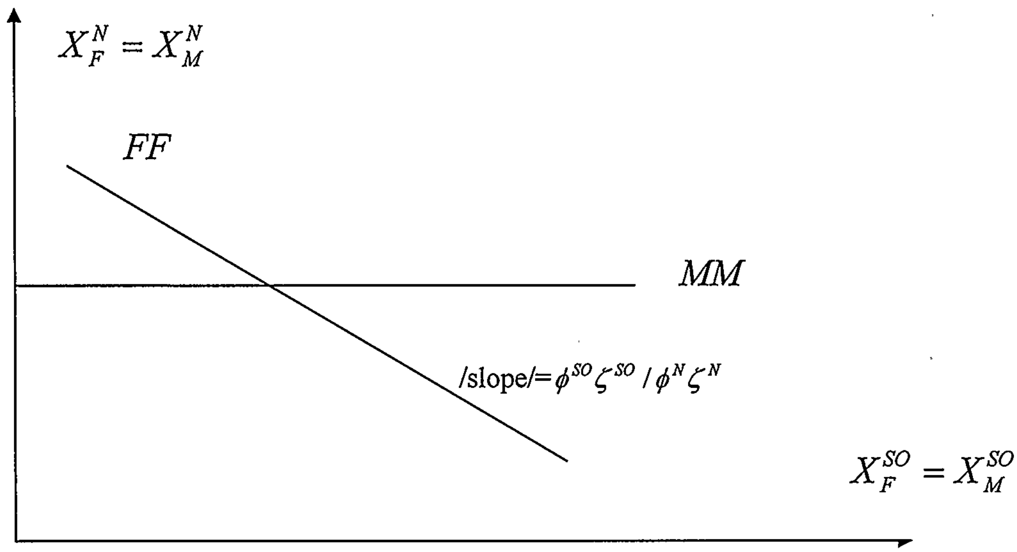

Figure 6. Goods and Emissions Market Equilibrium.

From the above, we can solve for the combinations of X_F^N and X_F^{SO} that are consistent with goods market equilibrium. Since one unit of fossil fuel produces one unit of emissions, we are also solving for combinations of X_M^N and X_M^{SO}.

We then proceed with emission market equilibrium. Northern emissions are equal to Northern cap and credits available from the South.

$$X_F^N = \overline{Y}_M^N + \theta\zeta^{SO} X_F^{SO} \qquad (40)$$

Recall that θ represents extra fuel savings or credits available per standardized unit of fuel use and then $\zeta^{SO} X_F^{SO}$ is the number of standard units of fossil fuel used in South and

OPEC. Equation (40) represents the combinations of fuel use in the North and in the South and OPEC region that are consistent with emissions market equilibrium. The emissions market equilibrium is shown by the linear MM curve in Figure 6. If there are no credits available, the curve is flat as shown in Figure 5 and fuel use is equal to emissions cap given that one unit of fuel use generates one unit of emissions. If credits are introduced and θ becomes positive, the curve pivots upwards. There is no change in the vertical intercept and the curve remains linear.

With two linear equations and two unknowns we are able to solve for fossil fuel demand and emissions in the North, in the South and OPEC, and in the world as a whole.

$$X_F^N = \frac{\phi^{SO}\zeta^{SO}\overline{Y}_M^N + \theta\zeta^{SO}Z_F^W}{\phi^{SO}\zeta^{SO} + \theta\zeta^{SO}\phi^N\zeta^N}, \quad \theta = 0 \Rightarrow X_F^N = \overline{Y}_M^N \tag{41}$$

$$X_F^{SO} = \frac{Z_F^W - \phi^N\zeta^N\overline{Y}_M^N}{\phi^{SO}\zeta^{SO} + \theta\zeta^{SO}\phi^N\zeta^N}, \quad \theta = 0 \Rightarrow X_F^{SO} = \frac{Z_F^W - \phi^N\zeta^N\overline{Y}_M^N}{\phi^{SO}\zeta^{SO}} \tag{42}$$

$$\begin{aligned} X_F^W &= \frac{(1+\theta\zeta^{SO})Z_F^W - (\phi^N\zeta^N - \phi^{SO}\zeta^{SO})\overline{Y}_M^N}{\phi^{SO}\zeta^{SO} + \theta\zeta^{SO}\phi^N\zeta^N}, \\ \theta = 0 \Rightarrow X_F^W &= \frac{Z_F^W - (\phi^N\zeta^N - \phi^{SO}\zeta^{SO})\overline{Y}_M^N}{\phi^{SO}\zeta^{SO}} \end{aligned} \tag{43}$$

Before we look at Kyoto type environmental policy, we need to look at how quantity demanded of fossil fuel responds to change in OPEC's price. Figure 7 shows an impact of an increase of fossil fuel price in the vicinity of pre-Kyoto equilibrium. Since the MM curve does not change with the change in the fossil fuel price, Northern demand for fossil fuel remains the same and is equal to the cap. In other words, in the vicinity of the zero credit equilibrium, North's demand is completely inelastic because the cap is binding, i.e. even if the price of fossil fuel goes up, North will use the same amount of fossil fuel because its original quantity was constrained by a cap. The FF curve shifts inward for two reasons. First, the higher fossil fuel prices leads to more fuel saving in the North and in the South and OPEC. Consequently, less fossil fuel is needed to clear the goods markets and the FF curve shifts in. Second, the higher price of fossil fuel itself reduces fossil fuel consumption by households and the induced increase in the prices of electricity and dirty goods cause reductions in household consumption of electricity and dirty good. With consumption of fossil fuel and fossil fuel using goods declining, the standardized world demand for fossil fuel by households decreases. This reinforces the inward shift in the FF curve. With the quantity of fossil fuel demanded by the North constant, the quantity demanded by the South and OPEC must fall because of the inward shift in FF curve. With demand falling in the South and OPEC and remaining constant in the North, overall world demand for fossil fuel falls. The decline in fossil fuel use is associated with decline in emission of equal magnitude. The Appendix provides a mathematical proof that the world demand for fossil fuel declines as the price rises.

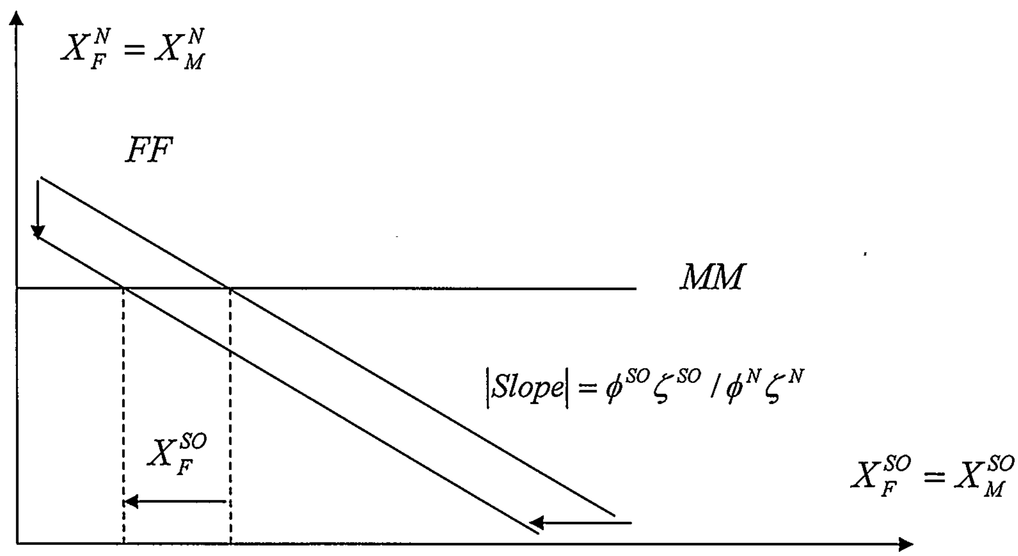

Figure 7. Impact of an Increase in Fossil Fuel Price on Fossil Fuel Demand.

The results of this analysis shows that world demand falls as fuel price increases giving rise to a downward sloping demand curve. Recall that from (32) supply curve for fossil fuel for North and South is increasing in fossil fuel price. With the set world price of fossil fuel, the interaction of the world demand curve and the supply curve of South and North determine what OPEC must produce.

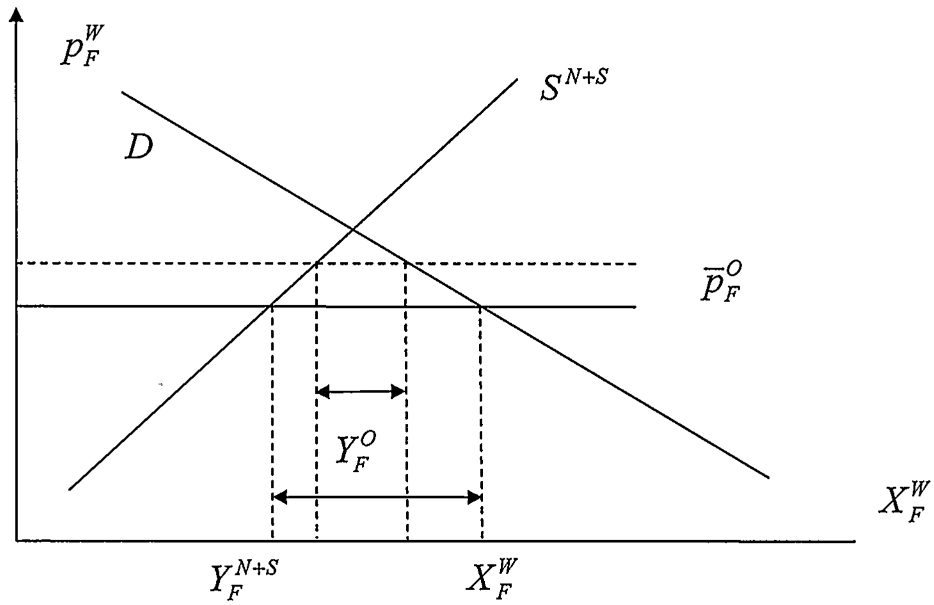

Figure 8. Impact of an Increase in Fossil Fuel Price on World Equilibrium.

With an increase in the price of fossil fuel, there occurs an increase in the quantity supplied from North and South and a decline in the quantity demanded by the world as a whole. Consequently, a lower fossil fuel output is required from OPEC, as shown in Figure 8. This decline in OPEC's output of fossil fuel match exactly the fall in X_F^{SO} in Figure 7.

GHG Emissions and Kyoto-Style Environmental Policy

The first type of environmental policy that we want to consider is what happens when North reduces its emissions cap. In Figure 9 the reduction in the Northern cap shifts the MM curve down from MM' to MM''. As a direct result of the lower cap, fossil fuel demand in the North falls and, thus, the North's emissions fall. By contrast, there is an increase in the South's and OPEC's fossil fuel demand and emissions. As we move along the FF curve, dirty good production in South and OPEC increases by the same magnitude that it declines in the North. The increase in fossil fuel demand in South and OPEC is of larger magnitude than the decline in North because South and OPEC invest less in fuel saving. In the diagram this result arises because the magnitude of the slope of FF curve is less than one. Consequently, there is an overall increase in the world demand for fossil fuel and in world emissions.37 The Appendix provides a mathematical proof that the world demand for fossil fuel declines North's cap is tightened.

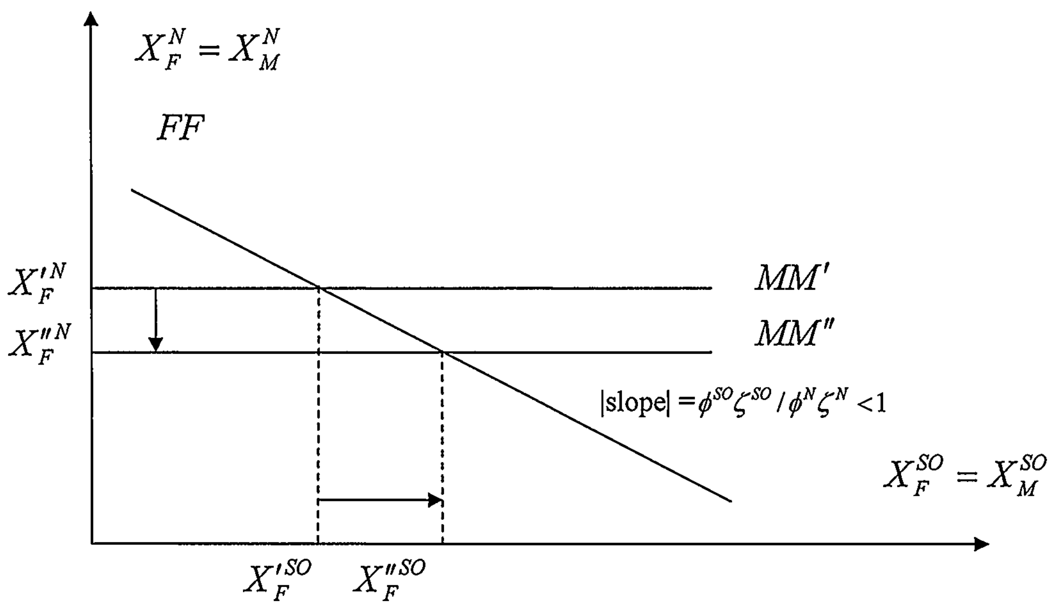

Figure 9. Impact of Tightening the Emissions Cap on Fossil Fuel Demand.

[37] Equivalent results hold when credits are present because there is a parallel downward shift in the MM' curve which in this case is positively sloped.

Figure 10 shows that the world demand shifts outwards in response to tightening of Northern cap. This demand shift is attributable to increased production of dirty goods in the South and OPEC where there is less fuel savings. If OPEC decides to hold constant its price of fossil fuel, then the increase in world demand would require a higher output of fossil fuel from OPEC since the quantities supplied by North and South remain unchanged in the presence of the constant world price. The increase in the OPEC's output matches the increase in world demand for fossil fuel and, thus, is associated with higher emissions.

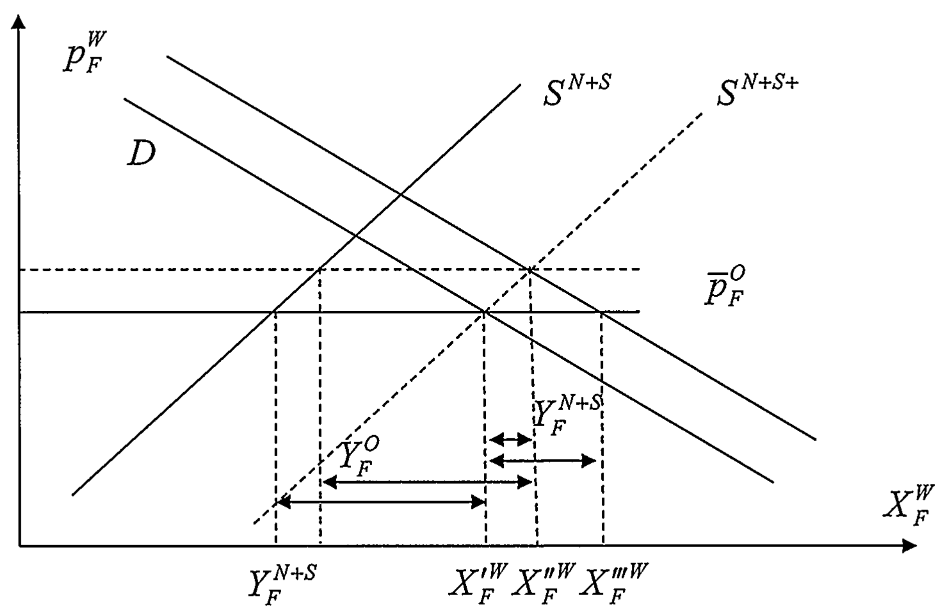

Figure 10. Impact of Tightening the Emissions Cap on World Equilibrium.

There are several implications of the above analysis. Suppose that North is comprised of several technologically equivalent countries one of which decides to avoid participation in global emission reduction program. This suggests that the emissions cap will not fall as far. The implications are if United States does not ratify Kyoto Protocol or Canada does not meet its commitments, MM curve will not shift down as far as in Figure 9 and the shift of fossil fuel use in South and OPEC will be smaller. Thus, world emissions will not rise by as much and there would be net environmental benefits for the world.

In the analysis above in Figure 10 we were assuming that OPEC holds the fossil fuel price constant by increasing its output. Let us now investigate the effect of higher fossil fuel demand when OPEC does not respond by increasing output of fossil fuel but rather lets the price of fossil fuel to rise. Consider the case where OPEC holds its output constant so that the world's supply is given by the SS+N+ curve. The price increases to the point where joint supply of fossil fuel by North and South rises sufficiently to preserve OPEC's initial supply. It is seen from the diagram that a constant price gives a larger increase in world fossil fuel use and emissions than a constant output policy, but world fossil fuel consumption and emissions still rise in the latter case.

Finally, if fossil fuel, electricity and dirty goods are normal goods, the results of tightening the Northern cap are weaker. Tightening the cap will lead to lower income in the world since credit income $p_M^N \overline{Y}_M^N$ goes down. Lower world income leads to lower world demand for electricity, for dirty goods and for fossil fuel, thus, shifting inward the FF curve. The combined effect of shifting down MM curve and shifting in FF curve leads to an unambiguous decrease in fossil fuel use in the North and a likely increase in South and OPEC. Provided that credit income is a negligible proportion of North's income, the inward shift in the FF curve will be negligible and world fossil fuel demand and emission will still rise, i.e. the results will not change. Thus, consideration of income effects mitigates the increase in fossil fuel use in South and OPEC and, as a result, world emissions do not rise by as much.

We should also consider the case of partial specialization. Recall that in the absence of an emissions cap, the North would have a comparative advantage in dirty good, which is capital-intensive. Suppose that either the South and OPEC do not produce the dirty good or North does not produce the clean good, or both are partially specialized. This also weakens the results for the Northern emissions cap. If either region is not diversified, the prices of the dirty good and electricity, as well as the opportunity cost of fossil fuel, will depend on Northern cap. Any tightening of the cap will lead through increase in prices to a fall in fossil fuel demand. Consequently, there will be a smaller increase in the fossil fuel utilization in South and OPEC mitigating the increase in world emissions.

Another caveat concerning the theoretical model is the assumption that clean sector generates no emission. This, by construction, rules out emission intensity reversals. This avoids situation where the good which is cleaner in North is dirtier in South and production shifts due to a tighter Northern cap cause expansion in each country's relatively clean sector.

Finally, let us investigate the case of an increase in emissions market integration on fossil fuel use in the North region, South and OPEC, and world as a whole. Recall that FF curve and MM curve representing goods and emissions market equilibrium are given by equilibrium conditions (40) and (39) respectively.

MM: $$X_F^N = \overline{Y}_M^N + \theta\zeta^{SO} X_F^{SO} \qquad (40)$$

FF: $$X_F^N = \frac{1}{\phi^N \zeta^N} Z_F^W - \frac{\phi^{SO}\zeta^{SO}}{\phi^N \zeta^N} X_F^{SO} \qquad (39)$$

Let us start with analysis by examining what happens to each curve as we introduce greater credit market integration, where θ goes up. The diagrams below present each case.

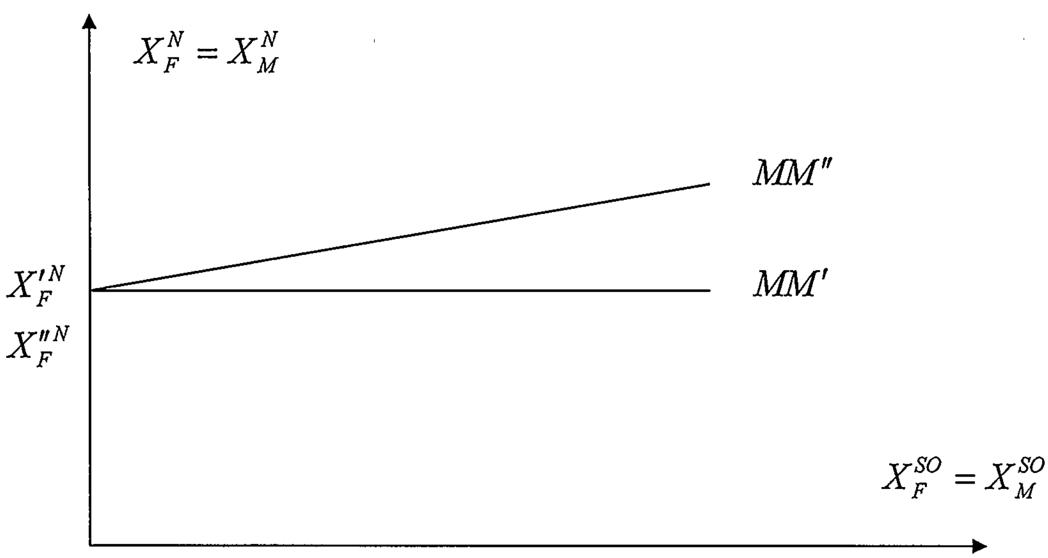

Figure 11. Upward shift in MM curve as θ goes up.

Increasing θ from an initial value of zero introduces an opportunity for South and OPEC to benefit from selling credits. In order to get use of the credits, fuel savings in South and OPEC goes up, South and OPEC emit less and the slope of the MM curve,

$\theta\zeta^{SO} = \theta \cdot \frac{1}{1-\mu^{SO}}$ increases, which is shown by an upward pivot of MM curve. While the intercept determined by emissions cap remains unchanged, higher values of Southern fossil fuel use are associated with a larger increase in credits and, thus, more Northern fossil fuel use.

Higher θ also effects the FF curve in two ways. First, let us see how the vertical and horizontal intercepts of the FF curve change in response to changes in fuel savings. The vertical intercept of FF reflects the maximum fossil fuel use in the North. With higher integration, price of emissions in the North goes down and this in turn leads to lower fuel savings. Since the term $\phi^N\zeta^N$ determining the intercept declines with lower μ^N, the vertical intercept $Z_F^W / \phi^N\zeta^N$ increases. The horizontal intercept of FF reflects the maximum fossil fuel use in the South and OPEC. In order to make use of credits, South and OPEC increase fuel saving. Thus the term $\phi^{SO}\zeta^{SO}$ increases and horizontal intercept given by $Z_F^W / \phi^{SO}\zeta^{SO}$ goes down. From this analysis of fuel saving we can conclude that with vertical intercept going up and horizontal going down, the slope of the FF curve gets steeper.

However, there is a second reason that the FF curve shifts related to changes in consumer demand. With lower price of Northern emissions, the prices of electricity, dirty good, and fossil fuel all go down. Demand for electricity, fossil fuel and dirty good rises and the derived world demand for fossil fuel, Z_{FH}^W, goes up. This accentuates the increase in the vertical intercept, reduces or even reverses the decrease in the horizontal intercept but does not cause further changes in the slope, which remains steeper than it was initially.

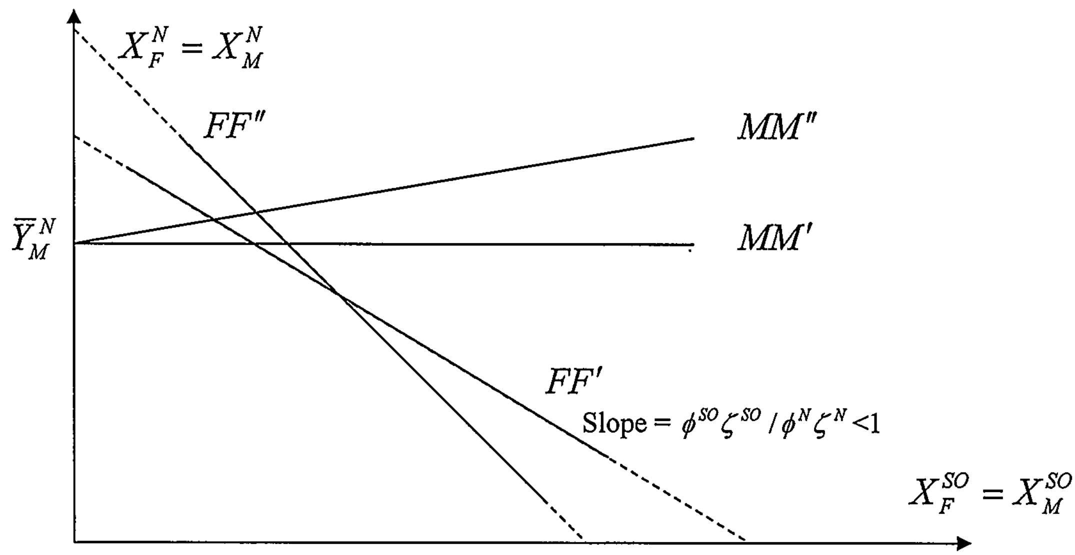

Figure 12. Upward twist in FF curve in the vicinity of initial equilibrium

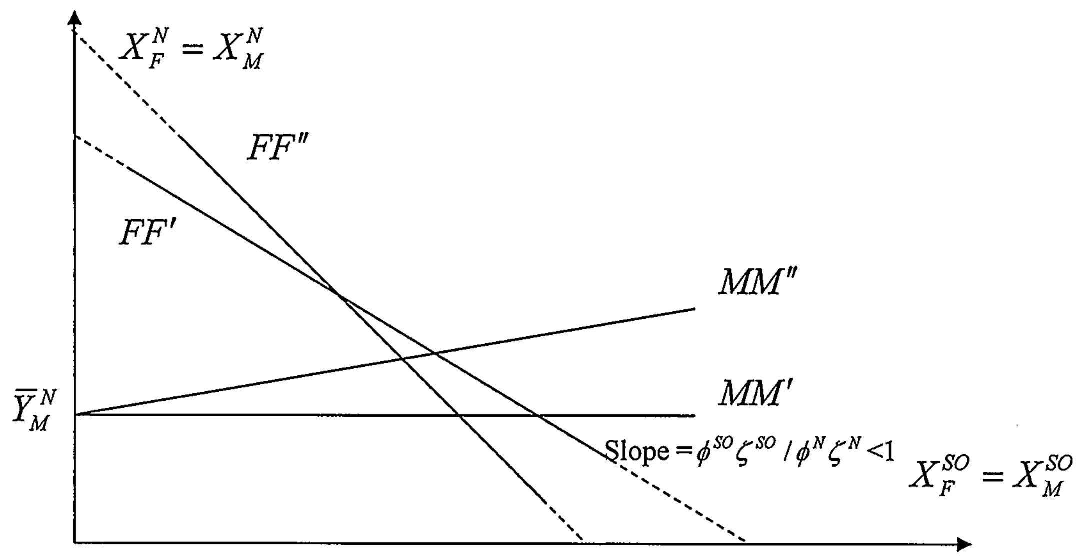

Figure 13. Downward twist in FF curve in the vicinity of initial equilibrium

Increased θ results in a twist of FF curve. The new FF curve is steeper than the old FF curve and may cross the old curve as shown in Figure 12 and Figure 13 . Alternatively, the new FF curve could lie above and to the right of the old FF curve. As can be seen from the diagrams above, the initial equilibrium is determined by the intersection of the FF' and MM' curves. The location of the MM' curve and, thus, the initial equilibrium in relation to any crossover of the initial and final FF curves has an important impact on the final equilibrium.

Let us investigate each case in detail to determine fossil fuel demand and emissions in the North, the South and OPEC and the world as a whole. Recall that the intercept of MM' is equal to the emissions cap, thus, we can alternatively say that initial equilibrium is determined by the relative position of the MM' curve, i.e. the exogenously set emissions cap. Let us look at the case where initial equilibrium occurs close to the MM' pivot point.

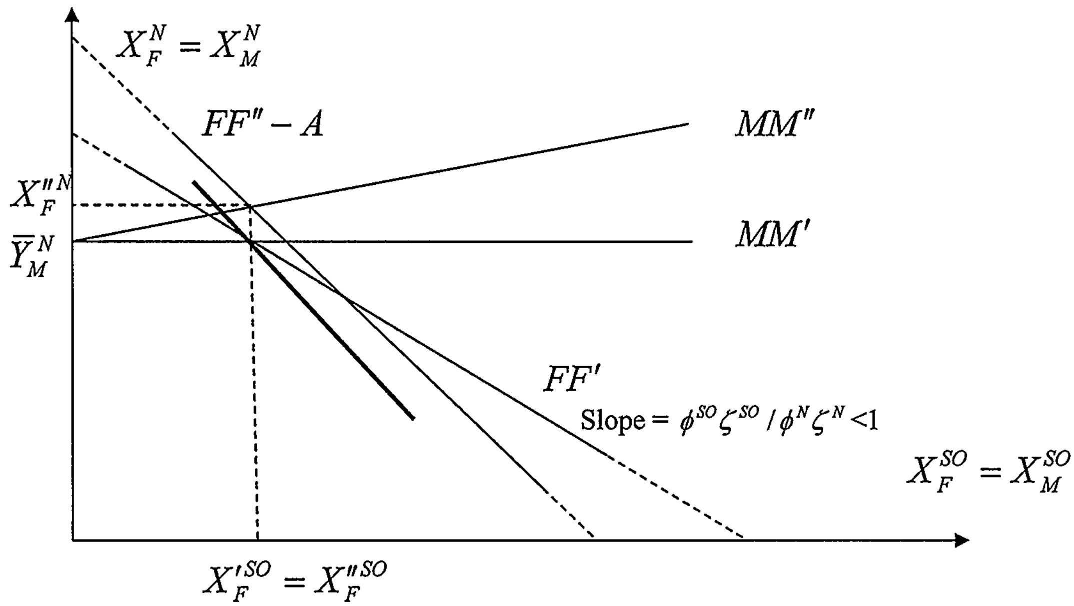

Figure 14. Impact on World Emissions Case 1.

The thick line represents an *isoquant* with slope equal to one, where world fossil fuel use is held constant. Starting from the initial equilibrium, if the vertical shift in *FF* is of the same magnitude as the upward pivot in *MM* curve, as shown in Figure 14, an equilibrium occurs where fossil fuel use in South and OPEC remains unchanged and fossil fuel use in the North unambiguously rises. Thus, world emissions rise. It is also possible that the shift of FF curve is of larger magnitude than that of MM. In this case, in addition to increase in the North, fossil fuel use increases in South and OPEC as seen on the diagram below.

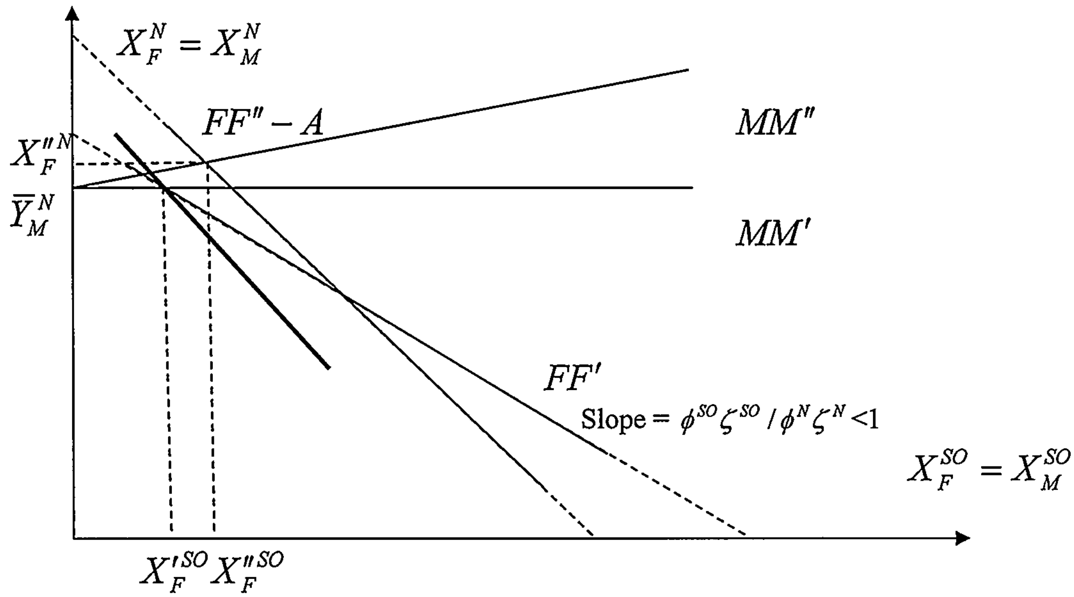

Figure 15. Impact on World Emissions Case 2.

Thus, for the case when the upward shift in FF curve is of the same or larger magnitude as the shift of MM curve in the vicinity of the initial equilibrium, world emissions rise. A natural question arises. Are there any circumstances under which we can definitely say that this conclusion is definitively the case? World emissions unambiguously rise in the case when South and OPEC have initially sufficiently small share of fossil fuel use. Alternatively, the North has larger share of fossil fuel use which is associated with a loose emissions cap. Therefore, the initial equilibrium is close to the vertical intercept of the FF curve.

Now let us consider the case when the emissions cap is not so loose and initial equilibrium occurs further from the vertical intercept of the FF curve. Figure 16 shows the case where there is no shift in the FF curve in the vicinity of the initial equilibrium.

Recall that the thick curve is the reference curve with world consumption of fossil fuel being constant. Higher emissions market integration results in new equilibrium where fossil fuel use in the North rises and its use in South and OPEC falls. Note that the slope of FF curve is less than one and since the reference curve with slope equal to one is to the right of the final equilibrium, the decline of fossil fuel use in the South and OPEC is of larger magnitude than its increase in the North. World emissions fall.

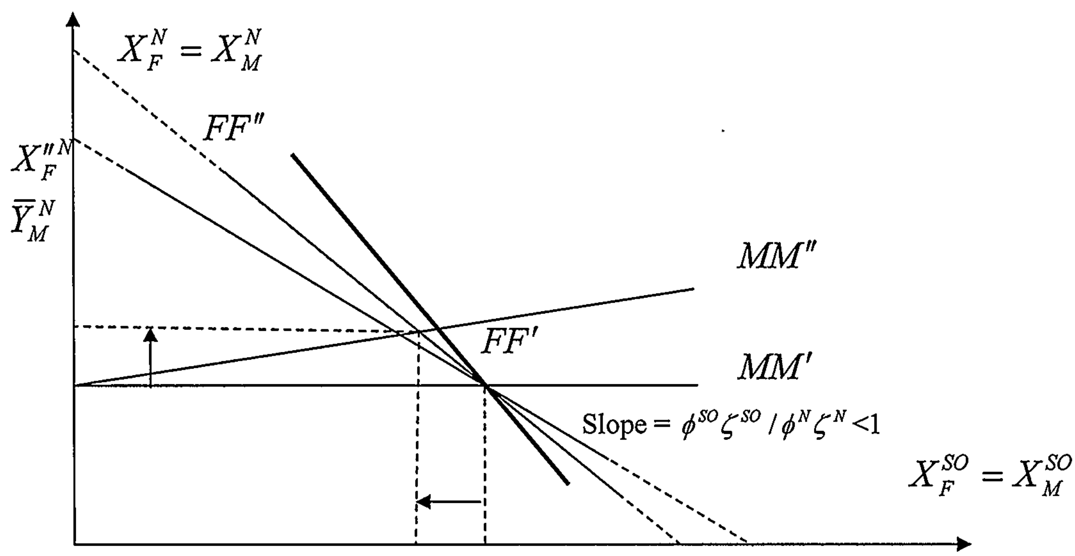

Figure 16. Impact on World Emissions Case 3.

The results become even more pronounced for the case where the FF curve shifts downward in the vicinity of the initial equilibrium. Here, the increase in Northern fossil fuel use is accompanied by a larger decrease in fuel use in South and OPEC. Thus, world emissions fall even more.

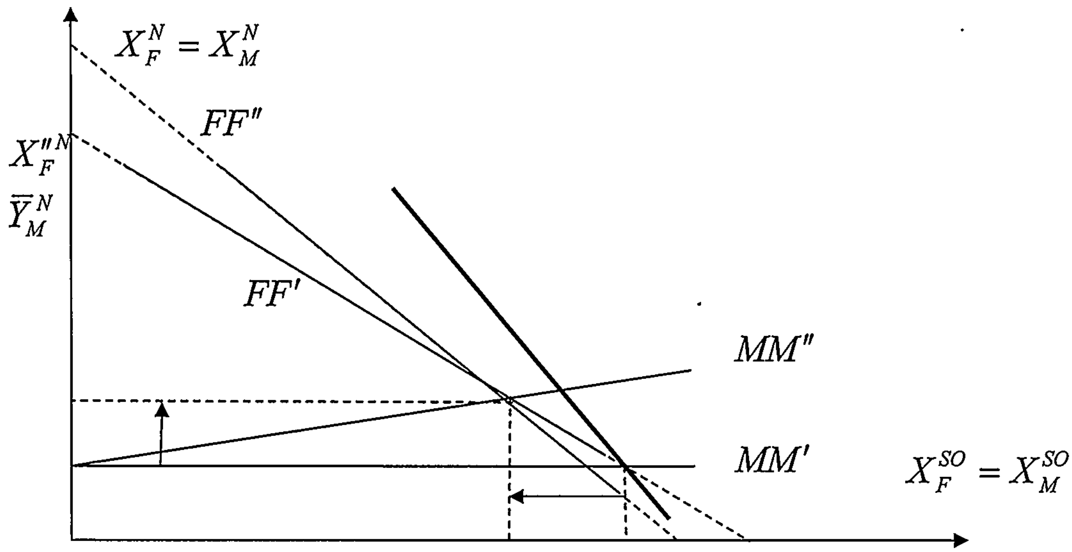

Figure 17. Impact on World Emissions Case 4.

We have considered two possible scenarios which result in higher or lower world emissions. Any case in between these two, i.e. a shift in FF curve less in magnitude than change in MM, implies that a decrease in fossil fuel use in the South and OPEC may or may not be of larger magnitude than an increase in fossil fuel use in the North. World emissions may rise or fall; the result is ambiguous.

Chapter Five: Empirical Investigation

Issues for Empirical Analysis

The theoretical model presented in this thesis suggests some flaws in the Kyoto approach to addressing GHG emissions. There are two issues that we will discuss. The first key issue concerns whether there are dirty and clean countries as well as dirty and clean goods. The second key issue concerns the direction and magnitude of relocation of emission-intensive activities away from developed countries with low emission intensities to developing with higher emission intensities.

The first of these issues is related to recent theoretical work of Copeland and Taylor (2005). Copeland and Taylor say that, due to factor price equalization, there are only dirty and clean goods and countries use the same production techniques, have the same emission intensities and the same fuel savings. Thus, the output composition of the economy determines its emissions. If two countries have the same composition of outputs, they will generate the same emissions relative to GDP. Since in their model factor price equalization occurs, developed Northern countries are cleaner than developing Southern based only on the fact that the share of clean output is larger than dirty output share because of more stringent environmental policies. Our model has clean and dirty countries as well as clean and dirty goods[38]. In our model, factor price equalization does not occur because the user cost of capital is assumed to be lower in North. Consequently, North is able to accumulate more capital and per unit of output it is richer than the South.

[38] By saying that South and OPEC are dirtier than the North we mean that emissions per unit of the dirty good, electricity or fossil fuel output are larger in South and OPEC.

At the same time, having a lower user cost of capital allows the North to engage in more fuel saving activity, which is capital intensive, and generate lower emissions in each good.

Thus, the basic empirical question is whether countries use similar or different production techniques associated with emissions. A related subsequent empirical question arises if different countries adopt different emissions intensities with respect to GHGs. The secondary condition concerns whether countries reduce emissions per unit of output of fuel using goods by direct abatement or indirectly by adopting fuel saving technologies or a combination of the two.[39]

To shed light on these issues, we will estimate so called Environmental Kuznets Curves. For conventional Kuznets curve regressions with no controls on the output composition of the economy, both the current theoretical model and that of Copeland and Taylor suggest that, as we move to countries with higher per capita GDP, per capita emissions will increase at a decreasing rate and may eventually decline. In Copeland and Taylor richer countries become greener only by adopting a cleaner mix of outputs whereas in our model richer countries also invest more heavily in fuel saving technologies leading to lower emissions per unit of output. When controls on the composition of output are introduced to a Kuznets curve regression, therefore, Copeland and Taylor's Kyoto model suggests that per capita emissions should increase at a constant rate as per capita GDP increases. By contrast, our Kyoto model suggests that even with controls on the output

[39] By direct abatement we mean reducing emissions per unit of fossil fuel whereas with fuel saving there is a reduction in fossil fuel use per unit of output.

composition of the economy, per capita emissions will continue to increase at a decreasing rate as per capita GDP rises because rich countries undertake more fuel saving.

The second major empirical issue concerns the magnitude of the sectoral shifts and emission changes associated with the implementation of the Kyoto protocol. We can use the estimated coefficients from the Kuznets curve regressions relating to the sector shares to investigate what happens when the Annex I countries meet their emission targets by adopting a greener mix of outputs. After allowing for an increase in the production of dirty goods in the non-Annex countries, it is possible to calculate a provisional estimate of the change in world emissions.

Data Description

The raw dataset covers 173 countries including developed countries, developing countries and economies in transition, spanning 24 years from 1980 to 2003. By focusing on a four-sector decomposition of GDP into agriculture, manufacturing, other industry and services, the number of countries is reduced. We work primarily with a balanced panel which consists of 71 countries, 24 years and 1704 observations. We also consider an unbalanced panel consisting of 159 countries and 2925 observations since it has more transition and developing countries.

The greenhouse gas used for estimation is carbon dioxide. Data for CO2 emissions are available across many developed and developing countries from the Energy Information

Agency (EIA).[40] It is important to note that, consistent with previous EKC studies, we use most variables including CO2 in per capita terms as per capita income determines the wealth of country.[41] In addition to annual data on CO2 emissions measured in millions of metric tons, the Energy Information Agency (EIA) provides data on coal, gas, oil and overall fossil fuel consumption measured in Quadrillion BTU. To control for the fact that coal is generally dirtier than oil and natural gas is generally cleaner than oil, we calculate the ratios of coal use to overall fossil fuel use and natural gas use to overall fossil fuel use. The ratio of oil use to overall fossil fuel use is always the omitted category. We also calculate per capita fossil fuel consumption and CO2 emissions relative to fossil fuel consumption for use as alternative dependant variables.[42]

The remainder of the economic data was obtained from the World Development Indicators database. This database provided series on land area, population, real GDP and sector shares of GDP in various forms. The per capita land endowment measured as sq. km per person was calculated dividing total land area by population. For each country per capita GDP was measured in constant 2000 US dollars using purchasing-power-parity conversions. The rest of the variables obtained from the WDI were used to control for the composition of the output of the economy. These variables include the

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[40] The correlation of 0.9 between per capita CO2 and per capita fossil fuel use suggest that there is an almost one-for-one dependence between the two and CO2 was most likely measured on the basis of fossil fuel use.

[41] Since the EKC relationship includes standard of living of a country as an important factor, the proxy of standard of living is per capita GDP.

[42] The World Development Indicators database also provides series similar to the EIA data on CO2 emissions, but it does not include data on fossil fuel consumption. Further, there is data available from the WDI database for two other Kyoto gases, methane and nitrous oxide. However, data are only available for 1990, 1995 and 2000 for 54 countries. Therefore, we focused on CO2 where much larger panel was available.

GDP shares of agriculture, services, manufacturing and other industry.[43] For a restricted unbalanced panel consisting of 99 countries and 1315 observations, it was possible to decompose the manufacturing sector into the GDP shares of chemicals; machinery and transportation equipment; food and beverages; textiles and clothing and other manufacturing.

Figure 18 shows the relationship between two key variables, namely per capita CO2 emissions and per capita income. Further details concerning the data together with a table reporting means, standard deviations and units of measurement are provided in the Appendix.

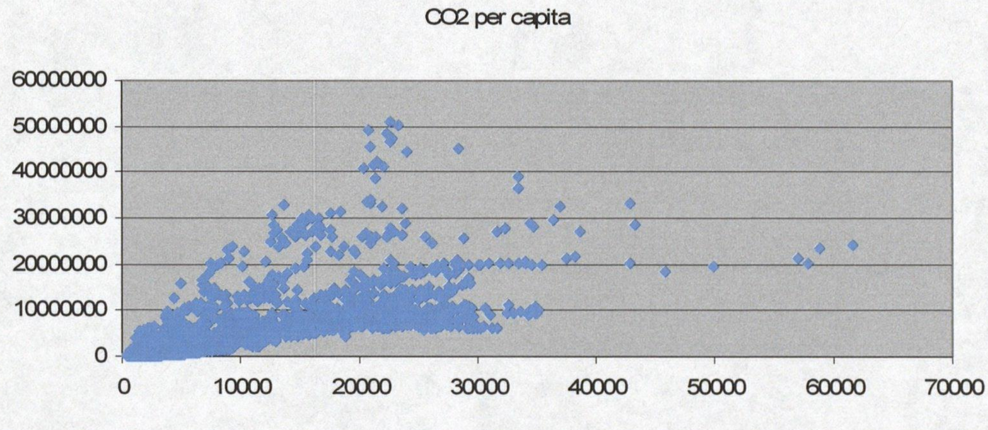

Figure 18 Relationship between CO2 per capita and GDP per capita

[43] The share of other industry in GDP was calculated as a difference between the share of industry in GDP and the share of manufacturing in GDP. The share of manufacturing in GDP is calculated as the share of manufacturing in industry multiplied by the share of industry in GDP.

Methodology

Model Specification.

Our Environmental Kuznets Curve (EKC) regressions can be written as:

$$Y_{it} = \alpha + X_{it}\beta + \varepsilon_{it}$$

where Y_{it} is the dependant variable connected with green house gas emissions for country i at time t, X_{it} is a vector of EKC explanatory variables, α represents the intercept, β represents a vector of slope coefficients and ε_{it} is the error term which will be discussed in depth below. A complete list of variables used in the various model specifications is presented in the table below, and the variables themselves are described in greater depth in the Appendix:

In our initial regressions the dependant variable is CO2 emissions per capita, but we also consider formulations where the dependant variable is the natural logarithm of CO2 emissions per capita, the log of fossil fuel use per capita or the log of the ratio of CO2 emissions to fossil fuel use.

We start by including in the X_{it} control variables and the basic Environmental Kuznets Curve (EKC) variables and then we add Sectoral EKC variables. The control variables include the ratio of coal use to total fossil fuel use, the ratio of natural gas to total fossil fuel use and the per capita land endowment. The coefficient on coal to total fuel use variable is expected to be positive because coal is a dirtier fuel than oil, which is the

Table 6 List of Variables.

Principal Dependant Variable

- log (CO2 per capita)

Alternative Dependant Variables

- CO2 per capita
- Log (Fossil Fuel Use per capita)
- Log (CO2/Fossil Fuel Use)

Basic Control Variables in All Regressions

- Coal/Fossil Fuel
- Gas/Fossil Fuel
- Oil/Fossl Fuel - omitted category
- Land/Population

Environmental Kuznetz Variables

- GDP per capita
- (GDP pc)*(GDP pc)

Sectoral EKC Variables

- (Services/GDP)*(GDP/POP)=Services/POP
- (Services/GDP)*(GDP/POP)2=(Services/POP)*(GDP/POP)
- (Agriculture/GDP)*(GDP/POP)=Agriculture/POP
- (Agriculture/GDP)*(GDP/POP)2=(Agriculture/POP)*(GDP/POP)
- (Other Industry/GDP)*(GDP/POP)=Other Industry/POP
- (Other Industry/GDP)*(GDP/POP)2=(Other Industry/POP)*(GDP/POP)
- (Manufacturing/GDP)*(GDP/POP)=Manufacturing/POP - omitted category
- (Manufacturing/GDP)*(GDP/POP)2=(Manufacturing/POP)*(GDP/POP)-omitted category

Additional 9-sector EKC Variables

- (Chemicals/GDP)*(GDP/POP)=Chemicals/POP
- (Chemicals/GDP)*(GDP/POP)2=(Chemicals/POP)**(GDP/POP)
- (Machinery/GDP)*(GDP/POP)=Machinery/POP
- (Machinery/GDP)*(GDP/POP)2=(Machinery/POP)*(GDP/POP)
- (Food/GDP)*(GDP/POP)=Food/POP
- (Food/GDP)*(GDP/POP)2=(Food/POP)*(GDP/POP)
- (Textiles/GDP)*(GDP/POP)=Textiles/POP
- (Textiles/GDP)*(GDP/POP)2=(Textiles/POP)*(GDP/POP)
- (Other Manufacturing/GDP)*(GDP/POP)=Other Manufacturing/POP - omitted category
- (Other Manufacturing/GDP)*(GDP/POP)2=(Other Manufacturing/POP)*(GDP/POP) - omitted category

omitted category. By contrast, the coefficient on natural gas to total fossil fuel use ratio is expected to be negative because natural gas is cleaner than oil. The coefficient on the per capita land endowment is expected to be positive. Greater per capita land endowments may lead to greater emissions through greater use of transportation services. Further, larger per capita land endowments, which imply lower population density, may be associated with less stringent environmental regulations.

The basic EKC variables are per capita GDP and per capita GDP squared. The coefficient on per capita GDP is expected to be positive and for the per capita GDP squared it is expected to be negative. When the dependant variable is the level of per capita CO2 emissions, this implies that per capita emissions will increase at a decreasing rate as we move to countries with higher per capita GDP and will eventually decline giving rise to a classic inverted "U-shape". With the logarithmic specification of the dependant variable, per capita CO2 emissions initially increase at an increasing rate as we move to countries with higher per capita GDP and then increase at a decreasing rate and finally decline at sufficiently high levels of per capita GDP.

We introduce sector variables to help determine whether there are clean and dirty countries as well as clean and dirty goods. Due to data limitations, we focus on four-sector specifications where economy is divided into services, agriculture, manufacturing and other industry to control for the composition of economy. The GDP share of agriculture, services and other industry are interacted first with per capita GDP and then also with per capita GDP squared. Manufacturing is the omitted category. In the Appendix, we estimate a nine-sector specification of the model for a smaller unbalanced panel, which includes countries of a Former Soviet Union and additional developing countries. This specification divides manufacturing into chemicals, machinery and transportation equipment, food and beverages, textiles and clothing and other manufacturing to see if decomposition of manufacturing matters.

When we add only the interactions of the sector shares with per capita GDP, we can draw straightforward conclusions concerning clean and dirty sectors. For example, if there is a statistically significant negative (positive) coefficient on the GDP share of services interacted with per capita GDP, then the service sector is cleaner (dirtier) than the manufacturing sector. Analogous conclusions could be drawn for agriculture and other industry. In these model specifications, which interact sector shares with per capita GDP, if the coefficient on per capita GDP squared remains statistically significant and negative, then rich countries adopt cleaner production techniques then poor countries. On the other hand, if the coefficient on per capita GDP squared is equal to zero, rich countries would not be cleaner than poor countries; there would only be clean and dirty goods as in Copeland and Taylor (2005).

The addition of interactions between sector shares and per capita GDP squared allows for further complications. A sector which is initially cleaner than manufacturing may converge on manufacturing as per capita GDP rises and may even become dirtier at sufficiently high levels of per capita GDP as a result of features of underlying production technologies. In other words, emission intensity reversals are possible in these model specifications.[44] If the coefficient on per capita GDP squared and the interactions between the sector shares and per capita GDP squared are all statistically insignificant, then we would have only clean and dirty goods and not clean and dirty countries. If the coefficient on per capita GDP squared and/or any of the sector interactions with per capita GDP squared are statistically significant, however, there will be clean and dirty countries as well as clean and dirty goods.

The independent variables reflect the scale, technique and composition effects discussed by Krueger and Grossman (1995), Antweiler et al. (2001) and others. Per capita GDP captures the scale effect because higher per capita GDP is associated with a greater scale of economic activity and, thus, higher per capita emissions. Controls on output are introduced to reflect the composition effect. Differences in sector shares are associated with differences in the output composition of the economy and, as a result, differences in emissions from production. The per capita land endowment and the shares of gas and coal in total fossil fuel use are meant to control for different production techniques and, thus, differences in emissions. The square of per capita GDP captures another facet of differences in techniques across countries. The idea is that richer countries will implement stricter environmental policies and adopt cleaner production techniques.

[44] Emission intensity reversals can arise if fuel savings can be more easily implemented in a sector that is initially dirtier. Thus, sector which is initially dirtier may become cleaner at a sufficiently high per capita income.

Pooled vs. Panel Models.

We start by testing whether or not the data can be pooled across groups. I employed a Chow test. This test compares the sum of squared errors (SSE) generated by the pooled model to the SSE's summed across separate unpooled regressions for each country. Then pooled and unpooled SSE's are tested with F-test. The Chow test was performed on a balanced paned for a regression containing the basic variables, EKC and EKC output control variables with dependent variable being the level of per capita CO2 emissions.

The null hypotheses is that the pooled and unpooled models represent the same data generating process or in other words that there is no statistically significant difference between coefficients in two models. The F-stats of 7.53 for the group was compared to the critical F-stats of 1.45. Thus, one can reject the null hypothesis that the data is suitable for pooling across countries.

Fixed vs. Random Effects.

Therefore, we proceed by following the methodology used in Antweiler et al. (2001), which considers both fixed and random effect approaches. The discussion of econometric methodology inclusive of equations follows Green (1951). The fixed effects specifications can be summarized as:

$$Y_{it} = \alpha_i + X_{it}\beta + \varepsilon_{it},$$

where the intercept α_i is the individual effect for each country i. It is also called the within estimator or Least Squares Dummy Variables (LSDV) model.

Individual fixed effects can be eliminated by differencing the sample by subtracting away group means from each of group observations.

Let $\overline{Y}_i = \frac{1}{T}\sum_t Y_{it}$, $\overline{X}_i = \frac{1}{T}\sum_t X_{it}$ be the group means for Y and X over the T time periods for group i.

$$Y_{it} = \alpha_i + X_{it}\beta + \varepsilon_{it}$$

$$\overline{Y}_i = \alpha_i + \overline{X}_i\beta + \overline{\varepsilon}_i$$

If we take the differences between the two equations, we obtain

$$Y_{it} - \overline{Y}_i = (\alpha_i - \alpha_i) + (X_{it}\beta - \overline{X}_i\beta) + (\varepsilon_{it} - \overline{\varepsilon}_i) \text{ or}$$

$$Y_{it}^* = X_{it}^*\beta + \varepsilon_{it}^*$$

where $Y^* = Y_{it} - \overline{Y}_i$, $X^* = X_{it} - \overline{X}_i$, $\varepsilon^* = \varepsilon_{it} - \overline{\varepsilon}_i$

The unbiased estimator of β in the presence of fixed effects is obtained by OLS and is called the within estimator since it uses the time variation within each country.

Alternatively, if we assume that the differences across countries can be captured in changes of the intercept α_i and it is treated as a parameter to be estimated. Thus, we can rewrite the model as:

$$Y_{it} = d_i\alpha_i + X_{it}\beta + \varepsilon_i$$

where d_i is the dummy variable for country i which captures country-specific effects.[45] This can be presented as:

$$y = [d_1 \quad \ldots \quad d_N \quad X][\alpha \quad \beta]' + \varepsilon$$

Applying matrix algebra it can be shown that derived unbiased estimator of β is the same as within estimator, but this formulation is called LSDV model.[46]

Thus, fixed effects estimation allows us to control for unmeasurable country-specific fixed effects that can cause bias in estimation. Some fixed effects may be country-specific but constant over time, while others may vary over time but be common to all countries. Still other fixed effects may vary across both countries and time such as:

$$\varepsilon_{it} = \theta_i + v_{it}$$

---

[45] In our subsequent modeling we also introduce year dummies to take into account differences in prices, technologies and environmental policies. This allows intercepts to change from year to year.

[46] Green, W. H., (1951). Econometric Analysis, fifth edition, New York, Prentice-Hall.

where the first term is a country-specific effect representing excluded variables and the second term is an idiosyncratic measurement error for observation in group i in time t.

As can be seen from above, in the fixed effects model we do not directly estimate the fixed effects and there might be information in those fixed effects. This lost information might lead to loss of efficiency. In the LSDV model fixed effects are estimated at a cost of sacrificing degrees of freedom.

To solve this problem we can alternatively use the random effects model. In this model country effects α_i are assumed to be random draws from an overall distribution of possible country effects. The benefits of random effects model is that there are fewer parameters to estimate and the estimator could be efficient. However, it could be biased and inconsistent.

In the fixed effects model the fixed effects are estimated as parameters in the model, while in random effects they are combined in the error term. Since in this case error term is typically non-spherical due to country-specific effects included in it, Generalised Least Squares approach is applied.[47] Let $\alpha_i = \alpha + \tau_i$, then our model takes the following form:

$$Y_{it} = \alpha + X_{it}\beta + \varepsilon_{it} + \tau_i$$

[47] In random effects the country-specific effect is part of the error term rather than an intercept as in fixed effects. Therefore, this country-specific effect which is different across countries introduces hereroscedasticity or non-spherical error terms. Nonconstant error variance can be shown mathematically (see Green (1951)).

Here α is the mean intercept, $\varepsilon_{it} + \tau_i$ is the composite error term, τ_i represents the country-specific effect which is fixed over time and ε_{it} represents the effect of omitted variables. Thus, similarities with the fixed effects approach are evident, but now τ_i is modeled as part of the error term.

For each version of the model we consider both fixed and random effects specifications. The random effects model produces estimates that are more efficient under the important assumption that excluded country-specific effects included in the error-term are uncorrelated with the rest of regressors. Otherwise, fixed effects model is preferred. It produces estimates less efficient but consistent.

In order to determine whether the fixed or random effects model is appropriate, the Hausman test is used. The basic idea of the Hausman test is that if we consider random and fixed effects estimators, the null hypothesis is that both are consistent but random effects is efficient. The alternative is that random effects estimator is inconsistent and fixed effects estimator is consistent.

H_O : β_{FE} is consistent but inefficient
β_{RE} is consistent and efficient

H_α : β_{FE} is consistent
β_{RE} is not consistent

This test checks the null hypothesis that the coefficients estimated by the efficient random effects estimator are the same as the ones estimated by the consistent fixed effects estimator. Under the null hypothesis, two parameter vectors should not differ very much. If they indeed do not differ (insignificant P-value, Prob>chi2 larger than .05) then it is safe to use random effects. If P-value is significant, however, fixed effects should be used.[48]

Heteroscedasticity and Autocorrelation.

Autocorrelation and heteroscedasticity of the error term are common problems in panel data models. In the presence of first-order autocorrelation and heteroscedasticity the Gauss-Markov assumptions are violated and usual OLS estimators, although unbiased and consistent, are no longer efficient (the standard errors are incorrect). We apply Wooldridge test for autocorrelation in panel-data models. The null hypothesis in this test is that there is no serial correlation of residuals from the regression of the first-differenced variables. The critical F-statistics at 95% 125.541 is greater than the critical of 5.12. We therefore reject the null hypothesis of no first-order autocorrelation.[49] A likelihood ratio test was performed in Stata to test for the presence of heteroscedasticity across groups. The F-statistic resulted in 4.81 which is less than the critical Chi squared value of 23.59, allowing one to reject the null hypothesis of homoscedasticity in favour of alternative of heteroscedasticity. The heteroscedasticity bias is easily corrected to

[48] In practice if the Hausman test is inconclusive, it is common to present both fixed and random effects results.

[49] It should be noted that there are potential problems of non-stationarity of some variables. Further research to address this issue more formally would be useful.

produce heteroscedasticity robust standard errors with the "robust" option available in STATA. Moreover, GLS approach in the random effect model, which was usually selected by the Hausman test, mitigates the autocorrelation issue.

Results

Dirty vs. Clean Countries?

The first empirical question that we want to address is whether there are clean and dirty countries. Results for a series of EKC regressions are presented in the two tables below. In Table 7 the dependent variable is the level of CO2 emissions per capita and in Table 8 the dependant variable is the natural logarithm of CO2 emissions per capita. Strong results are obtained for both specifications, though log specification appears to generate better fit with the data based on cursory inspection of the R-squared.[50] We start with basic regressions with no sectoral variables in regressions 1A and 2A, then we add sector shares interacted with per capita GDP in regressions 1B and 2B, and, finally, we add sector shares interacted with per capita GDP squared as well in regression 1C and 2C. In each of the regression we also include year dummies which account for differences in prices, technologies and environmental policies across time. In all cases, we report random effects regressions results. For the four of six regressions for which the Hausman test can be employed, it selects random effects model. However, the fixed effects results for the specification of log CO2 as a dependant variable are reported in the Appendix.

The qualitative results for the control variables are consistent across all six specifications. The results indicate a significant and large positive effect of the land to population ratio. A larger per capita land endowment may be associated with greater internal

[50] The summary statistics reported in Section A.3 in Appendix suggests that the distribution of a log of CO2 per capita may more closely approximate normal distribution.

transportation needs. The coefficients on the shares of both natural gas and coal in overall fossil fuel use are both positive. Since oil is the omitted category, these results seem to suggest that both coal and gas are dirtier than oil. This result is surprising for the case of natural gas although it should be noted that the coefficients are not statistically significant for regressions 2A and 2C in Table 7. One possible explanation for the positive coefficient is related to the indirect nature of pre-Kyoto limits on CO2 emissions. It appears that in most developed countries CO2 emissions may have been indirectly limited through measures aimed at reducing other air pollutants such as sulfur dioxide and smog. If a country used a cleaner fuel such as natural gas, it might meet its emission requirements for smog and sulfur dioxide more easily allowing more fuel use and more CO2 emissions. Also larger relative endowments of natural gas can be an explanation for this result.

Now let us consider regressions 1A in Table 7 and 2A in Table 8 where there are no sectoral variables. For regression 1A the positive significant coefficient on per capita GDP coupled with the negative coefficient on per capita GDP squared implies a typical inverted "U-shape" relationship. As one shifts attention to countries with high per capita GDP, per capita emissions initially rise at a decreasing rate and eventually fall. As shown in Table 9, the per capita income at which per capita emissions reach their peak is $22,866. For regression 2A the log form of the dependant variable in conjunction with the positive coefficient on per capita GDP and the negative coefficient on per capita GDP squared give rise to a more complex EKC. At low levels of per capita GDP, per capita CO2 emissions increase at an increasing rate with per capita GDP. Then, at medium

Table 7 EKC regression with the level of co2 emissions per capita as a dependent variable.

	CO2 per capita		
	1A	1B (1)	1C
GDP per capita (pc)	7.94E+02*** [0.000]	4.53E+02*** [0.001]	7.73E+02*** [0.001]
(GDP pc)*(GDP pc)	-1.74E-02*** [0.000]	-2.02E-02*** [0.000]	-4.90E-02 *** [0.004]
(% Agriculture)*(GDP pc)		-7.71E+02*** [0.003]	-1.29E+03*** [0.000]
(% Agriculture)*(GDP pc)2			8.03E-02 [0.188]
(% Services)*(GDP pc)		5.89E+02** [0.014]	-2.45E+02 [0.346]
(% Services)*(GDP pc)2			4.99E-02** [0.019]
(% Other Industry)		4.72E+02 * [0.074]	7.53E+02* [0.050]
(% Other Industry)*(GDP pc)2			1.21E-02*** [0.434]
Gas/Fossil Fuel	3.68E+06*** [0.000]	4.15E+06*** [0.000]	4.16E+06*** [0.000]
Coal/Fossil Fuel	3.14E+05 [0.447]	6.48E+05* [0.074]	9.96E+05** [0.011]
Land/Population	6.56E+06*** [0.000]	4.22E+06*** [0.004]	1.89E+06 [0.332]
Observations	1704	1704	1704
Countries	71	71	71
Panel Type	Balanced	Balanced	Balanced
Random vs Fixed	Random	Random	Random
R-squared within	0.293	0.315	0.344
R-squared between	0.506	0.549	0.615
R-squared overall	0.496	0.538	0.601

Robust p values in brackets; * significant at 10%, ** significant at 5%, *** significant at 1%.
(1) Asymptotic properties for Hausman test of random vs. fixed effects not satisfied.
(2) Hausman test indicates fixed effects.

levels of per capita GDP, emissions increase at a decreasing rate and, finally, at high levels of per capita GDP, per capita emissions decrease. The inflection point at which the slope of the EKC begins to decrease rather then increase is at a per capita income of $13,928. The per capita GDP where per capita emissions reach their peak is $25,881.[51]

Table 8 EKC regression with the natural logarithm of co2 emissions per capita as a dependent variable.

	ln (CO2 per capita)		
	2A (1)	2B	2C
GDP per capita (pc)	1.81E-04*** [0.000]	2.00E-04*** [0.000]	3.01E-04*** [0.000]
(GDP pc)*(GDP pc)	-3.50E-09*** [0.000]	-3.82E-09*** [0.000]	-1.16E-08*** [0.000]
(% Agriculture)*(GDP pc)		3.83E-06 [0.945]	-2.13E-04** [0.011]
(% Agriculture)*(GDP pc)2			1.78E-08*** [0.008]
(% Services)*(GDP pc)		-2.97E-05 [0.187]	-1.07E-04** [0.011]
(% Services)*(GDP pc)2			8.09E-09*** [0.000]
(% Other Industry)		2.42E-05 [0.312]	-1.57E-04*** [0.000]
(% Other Industry)*(GDP pc)2			9.84E-09*** [0.000]
Gas/Fossil Fuel	1.08E-01 [0.325]	2.16E-01* [0.054]	1.66E-01 [0.120]
Coal/Fossil Fuel	1.56E+00*** [0.000]	1.55E+00*** [0.000]	1.41E+00*** [0.000]
Land/Population	1.22E+00*** [0.004]	1.22E+00*** [0.004]	1.43E+00*** [0.001]
Observations	1704	1704	1704
Countries	71	71	71
Panel Type	Balanced	Balanced	Balanced
Random vs Fixed	Random	Random	Random
R-squared within	0.491	0.501	0.514
R-squared between	0.67	0.706	0.711
R-squared overall	0.658	0.691	0.697

Robust p values in brackets; * significant at 10%, ** significant at 5%, *** significant at 1%.
(1) Asymptotic properties for Hausman test of random vs. fixed effects not satisfied.
(2) Hausman test indicates fixed effects.

[51] Grossman and Krueger (1995) find the critical turning income point at approximately $8,000 per capita. For some pollutants in Grossman and Krueger (1991) peak points were registered between $4,000 and $5,000. Schmalensee et al. (1997) suggest growth of per capita emissions flattens and may reverse at an income level of $10,000 per capita suggested by their model.

Table 9 Peak points comparison

1A		2A	
Inflection Point	Peak Point	Inflection Point	Peak Point
n.a.	$22,866	$13,928	$25,881

Next, consider the addition of sector shares interacted with per capita GDP in regressions 1B in Table 7 and 2B in Table 8. In regression 1B, the negative coefficient for agriculture indicates that this sector is cleaner than manufacturing at the 99% confidence interval. By contrast, the positive coefficients for services and other industry indicate that these sectors are dirtier than manufacturing at the 95% and 90% confidence intervals respectively. These results are consistent with the theoretical and econometric analysis of Antweiler et al. (2001) which suggests that the output composition of an economy matters.

In regression 2B, the coefficient on services is now negative and the coefficient on agriculture is now positive, but the coefficients on all three of the sector variables are statistically insignificant. The statistical insignificance of the sectoral variables in regression 2B may not indicate that sector shares are unimportant. Rather, it may be the case that the degree to which these sectors are relatively dirty or relatively clean varies with per capita income. Consequently, in regressions 1C in Table 7 and 2C in Table 8 we include sector shares interacted with per capita income squared as well as per capita income itself. In these regressions, the EKC results depend on the sector composition of an economy. Table 10 presents peak and inflection points for income level for various types of economies.

Table 10. EKC Results with Sectoral Variables.

Economy type	1C		2C	
	Inflection Point	Peak Point	Inflection Point	Peak Point
pure manufacturing	n.a.	$7,881	$6,373	$12,927
pure agriculture	n.a.	$8,204	n.a.	n.a.
pure services	n.a.	n.a	$15,483	$27,350
pure other industry	n.a.	$20,684	$23,385	$40,052
"mixed" economy	n.a.	$18,739	$11,701	$22,061

Note: The "mixed" economy shares are 30% for manufacturing, 10% for agriculture, 40% for services and the remaining 20% for other industry.

The first four rows in Table 10 correspond to hypothetical economies which specialize completely in one sector. For example, in the case of a pure manufacturing economy, the share of manufacturing in GDP is equal to 100% and the shares of the other sectors are equal to zero. The fifth row in Table 10 provides an example for a diversified or a mixed economy where the shares are 30% of economy for manufacturing, 10% for agriculture, 40% for services and the remaining 20% for other industry.

Based on regression 1C in Table 7, emissions would always be increasing at an increasing rate for pure service economy and, similarly, based on regression 2C in Table 8 emissions would always be increasing at an increasing rate for a pure agricultural economy. All of the other hypothetical pure economies have conventional inverted "U-shape" EKCs. The results for agriculture suggest one possible explanation for the absence of EKC results for CO2 emissions for developing countries elsewhere in empirical literature. Schmalensee et al. (1997) suggest that for developing countries there is rapid growth of CO2 per capita with per capita GDP. For highly developing like US and Japan, however, the growth in emissions flattens and may reverse at high enough income level. Perman and Stern (2003) also state that in rapidly growing countries the scale effect outweighs the time effects, leading to higher emissions in developing countries. Since developing countries are predominantly oriented towards agriculture, this may explain the absence of an EKC relationship.

Next consider the mixed economy. The results of regression 1C in Table 10 imply that the EKC has a peak at $18,739. In the case of regression 2C emissions increase at an increasing rate until per capita GDP reaches a level of $11,701 and the EKC reaches its peak at per capita GDP of $22,061.

The econometric results also suggest the presence of emissions intensity reversals. For example, in regression 2C in Table 8, agriculture, services and other industry are all initially cleaner than manufacturing, which is the omitted sector. Nevertheless, as per capita GDP rises, these sectors become progressively less clean relative to manufacturing and eventually become dirtier.[52] We can calculate the switching point or per capita income level at which the reversal occurs. The per capita income level at which the increase in the sector size at the expense of manufacturing leads to higher emissions is $12,001 for agriculture, $13,195 for services and $15,929 for other industry for regression 1C.

[52] Consider the impact on per capita CO2 emissions from a marginal increase in the share of a sector such as services that comes at the expense of manufacturing. A negative coefficient on the share of services interacted with per capita GDP suggests that the service sector is initially relatively clean compared to manufacturing. Increasing the size of the service sector reduces per capita emissions when per capita GDP is low. A positive coefficient on the share services interacted with GDP per capita squared implies that the sector becomes dirtier relative to manufacturing as per capita GDP gets larger. Increasing the size of the service sector has a smaller favourable effect on emissions as per capita GDP rises and eventually at sufficiently high levels of per capita GDP emissions rise. Note that the results are similar for regression 1C in Table 8 except that other industry is initially dirtier than manufacturing and becomes dirtier still as per capita income rises.

Fuel Saving vs. Abatement

Our theoretical model focuses on fuel saving rather then direct abatement as the primary mechanism by which countries can reduce their CO2 emissions. Consequently, an important empirical question concerns the relative importance of fuel saving vs. direct abatement. Recall that fuel saving investment reduces fuel use per unit of output in a sector and, thereby, reduces emissions. Direct abatement relates to reducing the ratio GHG emission to fossil fuel use. On an aggregate or economy-wide basis, fuel saving corresponds with per capita fuel use increasing at a decreasing rate and eventually declining as per capita GDP increases. On the other hand, direct abatement corresponds to reductions in the ratio of aggregate CO2 emissions to aggregate fossil fuel use as per capita GDP rises.

In order to address this issue we use three regression results with dependant variables being natural logarithm of emissions per capita, natural logarithm of fossil fuel use per capita and natural logarithm of emission to fossil fuel use ratio. The explanatory variables are the basic and sectoral EKC variables. Using coefficients from these regressions and the explanatory variables calculated at their mean values, we report the partial elasticities of emissions per capita, fuel use per capita and emissions per fuel use related to each variable. The results are presented in Table 11.

Table 11. Partial elasticities calculated at the variable mean values.

	2C	3C – Fuel Saving	4C – Direct Abatement
	LN(CO2/POP)	LN(USE/POP)	LN(CO2/USE)
GDP per capita (pc)	2.34E+00***	2.35E+00***	-5.84E-02
	[0.000]	[0.000]	[0.499]
(GDP pc)*(GDP pc)	-1.49E+00***	-1.31E+00***	-1.57E-01*
	[0.000]	[0.000]	[0.079]
(% Agriculture)*(GDP pc)	-1.34E-01**	-1.37E-01***	-1.34E-02
	[0.011]	[0.005]	[0.655]
(% Agriculture)*(GDP pc)2	9.95E-02***	8.66E-02**	3.89E-02
	[0.008]	[0.014]	[0.070]
(% Services)*(GDP pc)	8.09E-09**	-3.17E-01*	-1.11E-01*
	[0.011]	[0.064]	[0.085]
(% Services)*(GDP pc)2	6.03E-01***	4.22E-01***	1.64E-01**
	[0.000]	[0.010]	[0.012]
(% Other Industry)	-1.72E-01***	-2.08E-01***	5.04E-02***
	[0.000]	[0.000]	[0.005]
(% Other Industry)*(GDP pc)2	1.71E-01***	1.53E-01***	1.25E-02
	[0.000]	[0.000]	[0.312]
Gas/Fossil Fuel	2.23E-02	9.82E-02***	-6.47E-02***
	[0.120]	[0.000]	[0.000]
Coal/Fossil Fuel	1.57E-01***	1.22E-01***	2.70E-02***
	[0.000]	[0.000]	[0.000]
Land/Population	8.77E-02***	1.27E-01***	-1.51E-02
	[0.001]	[0.000]	[0.306]
Observations	1704	1704	1704
Countries	71	71	71
Panel Type	Balanced	Balanced	Balanced
Random vs Fixed	Random	Random	Random
R-squared within	0.514	0.555	0.115
R-squared between	0.711	0.772	0.125
R-squared overall	0.697	0.759	0.112

Robust p values in brackets; * significant at 10%, ** significant at 5%, *** significant at 1%.

These are partial elasticities calculated at the mean values of the variables.

The elasticities are reported with the appropriate level of significance related to each variable. The second column with LN(USE/POP) as the dependant variable provides a fuel saving focus, while the third column with LN(CO2/USE) as the dependant variable provides a direct abatement focus.

It is evident that the fuel saving regression, 3C, very closely reflects the overall emissions regression, 2C, both in terms of the signs and magnitudes of the elasticities and their statistical significance. On the other hand, the elasticities in regression 4C tend to be smaller in magnitude and are frequently not statistically significant. Thus, both the magnitude of the elasticities and their statistical significance provide strong circumstantial evidence suggesting that fuel saving has been more important than direct abatement, at least to this point in time.[53]

[53] Section A.7. of the Appendix shows that similar results are obtained for standardized regression coefficients 2C, 3C and 4C.

Simulation Results

Let us now proceed to investigate the model predictions concerning the magnitude of changes in CO2 emissions with respect to Kyoto agreement. Recall that:

> "*The Kyoto Protocol is an agreement under which industrialised countries will reduce their collective emissions of* greenhouse gases *by 5.2% compared to the year 1990 (but note that, compared to the emissions levels that would be expected by 2010 without the Protocol, this target represents a 29% cut). The goal is to lower overall emissions of six greenhouse gases - carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, HFCs, and PFCs - calculated as an average over the five-year period of 2008-12. National targets range from 8% reductions for the European Union and some others to 7% for the US, 6% for Japan, 0% for Russia, and permitted increases of 8% for Australia and 10% for Iceland.*"[54]

Our theoretical section produced ambiguous results as to rise or fall in world CO2 emissions in response to the emission reduction commitment of developed countries. To provide insight on the likely magnitude of the impact of the Kyoto Protocol on world emissions, we developed a simple simulation methodology using the estimated regression coefficients from model 2C. Table 12 presents the simulation results.

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[54] From press release from the United Nations Environment Programme.

Table 12. Simulation Results.

	Naïve Prediction	Model Prediction Regression 2C
Adjustment between Manufacturing and Services (1993 Levels)		
US Included	-3.58%	-3.76%
US Excluded	-1.85%	-1.96%
Adjustment between Manufacturing and Agriculture (1993 Levels)		
US Included	-3.58%	-3.82%
US Excluded	-1.85%	-2.04%
Adjustment between Manufacturing and Both Agriculture and Services (1993 Levels)		
US Included	-3.58%	-3.79%
US Excluded	-1.85%	-2.00%
Adjustment between Manufacturing and Services (2001 Levels)		
US Included	-5.40%	-6.35%
US Excluded	-3.85%	-4.76%
Adjustment between Manufacturing and Agriculture (2001 Levels)		
US Included	-5.40%	-6.06%
US Excluded	-3.85%	-4.49%
Adjustment between Manufacturing and Both Agriculture and Services (2001 Levels)		
US Included	-5.40%	-6.20%
US Excluded	-3.85%	-4.63%

Note: The naïve prediction is based on the agreed reductions in the Annex-I countries and the assumption of no changes in the emissions in the non-Annex countries.
Source: Author's calculations.

Due to the limitations in the available data from transition countries for 1990, the baseline year for the Kyoto agreement, emission reductions for each Northern or, using the language of the Kyoto Protocol, Annex-I country were calculated taking 1993 as the baseline.

The simulations rely on important assumption that each country's GDP stays the same for the year in question. We then construct a counterfactual where the Annex I countries achieve their commitments to reduce CO2 emissions to their target levels by moving their economies' output composition from dirty polluting sectors to relatively clean sectors. Of course, if permit revenue is a significant share of income, then GDP may fall in the Annex countries as a result of their caps. As discussed previously, this would be good for the environment due to reduced scale effects. Consequently, having constant rather than reduced GDP represents a worst case scenario for the environment, but a best case scenario for economic welfare.

The naïve approach assumes that there is only change in the output composition and, therefore, emissions in Annex-I countries in response to tighter emissions cap, while no changes occur for non-Annex countries. For model prediction we use the relevant regression coefficients and account for changes in the output composition in Annex countries that results in production shifts to the Southern or non-Annex countries. As a consequence of changes in the output mix in non-Annex countries, the emissions they produce change as well. Thus, overall composition of world output stays the same but the output composition of Annex and non-Annex countries changes as sectors expand and contract.

Consider the case where the sector adjustments involve only manufacturing and services. The relevant part of regression 2C can be summarized as:

$$\ln(CO2/POP) = \ldots \gamma \cdot SER/GDP \cdot GDP/POP + \mu \cdot SER/GDP \cdot (GDP/POP)^2 \ldots$$

Therefore, holding GDP constant, the required change in service output at the expense of manufacturing is:

$$dSER = -dMAN = \frac{1}{(CO2/POP)(\gamma + \mu \cdot GDP/POP)} dCO2$$

Since the service sector is generally dirtier than the manufacturing sector in Annex-I countries, the changes in the value of output are negative for services and positive for manufacturing. The decline in the service sector is offset by an exactly equal increase in the manufacturing sector to preserve GDP. We then aggregate these service sector declines across all Annex-I countries.

As service sector contracts in Annex-I countries, it is picked up one-for-one by non-Annex countries. We assume that each non-Annex country picks up a share of the service sector output in proportion to its GDP. Changes in emissions by non-Annex countries arise due to the changes in service sector vs. manufacturing output:

$$dCO2 = (\gamma + \mu \cdot GDP/POP)(CO2/POP)dSER$$

Here again, γ and μ represent the estimated coefficients from regression 2C. Then, we aggregate our estimates of changes in CO2 emissions in Annex-I and non-Annex countries to obtain a model prediction for the change in world emissions. We also use an analogous procedure to conduct a second simulation for sectoral shifts between manufacturing and agriculture. In a third simulation half of the changes in manufacturing are taken up by the service sector and the other half by agriculture.

For the three simulations of sectoral shifts, we examine counterfactuals for both 1993 and 2001 where the Annex-I countries are at their Kyoto targets for CO2 emissions. While this procedure provides insight into the likely order of magnitude of the impact of the Kyoto agreement on emissions, it should be noted that we do not forecast changes in output or emissions out to 2008-2012 period where countries are actually expected to achieve their targets.

The results for all three sectoral simulation procedures for both 1993 and 2001 suggest that world emissions would fall and would fall by more if the US was part of the Kyoto Protocol. Further, the model based predictions all show somewhat more favourable reduction in emissions than a naïve prediction based on the agreed reductions in Annex-I countries and no changes in emissions in the non-Annex countries.

The economic reason that world emissions fall depends critically on the presence of emissions intensity reversals. In almost all Annex-I countries the service and agriculture sectors are dirtier than manufacturing because these countries have higher per capita GDP's than the threshold levels of $12,001 for agriculture and $13,195 for services which were discussed above. Therefore, in order to meet Kyoto commitment, Annex countries would contract dirty services and agriculture sectors while expanding relatively clean manufacturing sector. On the other hand, for many non-Annex countries the regression results suggest that services and agriculture sectors are relatively clean. Therefore, as developed countries are moving away from these sectors, developing would expand these sectors while contracting the manufacturing sector. Thus, relatively clean services and agriculture sectors will be growing at the expense of manufacturing in developing countries. Due to emission intensity reversals, therefore, both the Annex and non-Annex countries tend to be expanding their relatively clean sectors and contracting their relatively dirty sectors in response to the Kyoto agreement.

Of course, reality is more complex than our model. As development proceeds, there tends to be long-term trend away from agricultural production and towards services with manufacturing first increasing but later declining. In developed countries where the service sector tends to be growing at the expense of both manufacturing and agriculture, the model suggests that the Kyoto agreement may speed up both the move out of agriculture and slow down the move into services. In developing countries where there tends to be a trend into both manufacturing and services and away from agriculture, the model suggests the move away from agriculture may slow down due to the Kyoto agreement but the growth of the service sector may accelerate. Indeed a small part of the rapid growth in communications and information services in India might be attributable to world-wide sectoral adjustments arising from the Kyoto agreement.

Conclusions

Our theoretical model suggests that caps on emissions in industrialized countries lead to reduction of dirty good production in these "clean" countries, but this reduction is picked up by the increase in dirty good production in "dirty" developing countries. Since there is less fuel saving in "dirty" developing countries, the increase in fossil fuel demand from South and OPEC is higher than its decline in the North. Therefore, the model suggests that the world emissions will rise. The implications are that if United States does not ratify Kyoto Protocol or Canada fails to meet its commitments, the emission cap does not fall so far and increase in world emissions is mitigated. Investigating the impact of the CDM on global emissions, we find world emissions collapse if developed countries use a sufficiently large share of world fossil fuel. Finally, increases in the price of fossil fuel reduce world emissions.

Our theoretical and empirical models distinguish between clean and dirty countries as well as between clean and dirty goods. In contrast to Copeland and Taylor, in our model factor price equalization does not occur because the user cost of capital is assumed to be lower in North. Consequently, North is able to accumulate more capital and became richer than the South. At the same time, having a lower user cost of capital allows the North to engage in more fuel saving activity and generate lower emissions in each good, because fuel saving is assumed to be capital-intensive.

Our theoretical model has some caveats. If fossil fuel, electricity and dirty good are normal goods, the results of tightening the Northern cap are weaker. They are weakened if there are income effects associated with household demand for dirty goods, electricity and/or fossil fuel. Tightening the cap acts like losing some factor income and world income goes down. Lower world income leads to lower overall world demand for fossil fuel. Provided that credit income is a negligible proportion of North's income, however, the demand reduction will be negligible and world emissions will still rise.

We should also consider the case of partial specialization. Recall that in the absence of an emissions cap, the North would have a comparative advantage in dirty good, which is capital-intensive. Suppose that either the South and OPEC do not produce the dirty good or North does not produce the clean good, or both are partially specialized. This also weakens the results for the Northern emissions cap. If either region is not diversified, the prices of the dirty good and electricity, as well as the opportunity cost of fossil fuel, will depend on Northern cap. Any tightening of the cap will lead through increase in prices to a fall in fossil fuel demand. Consequently, there will be a smaller increase in the fossil fuel utilization in South and OPEC mitigating the increase in world emissions.

Another caveat concerning the theoretical model is the assumption that clean sector generates no emissions. This, by construction, rules out emission intensity reversals. This avoids the situation where the good which is cleaner in North is dirtier in South and production shifts due to a tighter Northern cap cause expansion in each country's relatively clean sector.

Our empirical investigation aims to answer three questions. First, are there clean and dirty countries in the sense that rich developed countries adopt production techniques with lower CO2 emissions per unit of output? Second, do countries reduce emissions per unit of output of fuel using goods by direct abatement or indirectly by adopting fuel saving technologies or a combination of the two? Third, what is the direction and magnitude of relocation of emission-intensive activities between developed and developing countries?

To shed light on these issues, we will estimate so called Environmental Kuznets Curve curves. We focus on a four-sector decomposition of GDP into agriculture, manufacturing, other industry and services. We work primarily with a balanced panel which consists of 71 countries, 24 years and 1704 observations. For conventional Kuznets curve regressions with no controls on the output composition of the economy, both the current theoretical model and that of Copeland and Taylor suggest that, as we move to countries with higher per capita GDP, per capita emissions will increase at a decreasing rate and may eventually decline. The empirical results provide a strong support for this theoretical prediction. In Copeland and Taylor richer countries become greener only by adopting a cleaner mix of outputs whereas in our model richer countries also invest more heavily in fuel saving technologies leading to lower emissions per unit of output. Consequently, in their model national emissions are increasing at a constant rate, but our Kyoto model suggests that even with controls on the output composition of the economy, per capita emissions will continue to increase at a decreasing rate as per capita GDP rises because rich countries undertake more fuel saving. Statistically significant regression coefficients imply that conventional EKC results continue to be obtained when controls on output are introduced.

Our theoretical model focuses on fuel saving rather then direct abatement as the primary mechanism by which countries can reduce their CO2 emissions. Both the magnitude of the elasticities and their statistical significance provide strong circumstantial evidence suggesting that fuel saving has been more important than direct abatement, at least to this point in time.

We can use the estimated coefficients from the Kuznets curve regressions relating to the sector shares to investigate what happens when the Annex I countries meet their emission targets by adopting a greener mix of outputs. After allowing for increase in production of dirty goods in the non-Annex countries, it is possible to calculate a provisional estimate of the change in world emissions. To provide insight on the likely magnitude of the impact of the Kyoto Protocol on world emissions, we developed a simple simulation methodology, which makes use of estimated regression coefficients. By contrast with our theoretical model, our empirical results suggest the presence of emission intensity reversals. Therefore, both the Annex and non-Annex countries tend to expand their relatively clean sectors and contract their relatively dirty sectors in response to the Kyoto agreement. In developed countries where the service sector tends to be growing at the expense of both manufacturing and agriculture, the model suggests that the Kyoto agreement may speed up both the move out of agriculture and slow down the move into services. In developing countries where there tends to be a trend into both manufacturing and services and away from agriculture, the model suggests the move away from agriculture may slow down due to the Kyoto agreement but the growth of the service sector may accelerate. The final simulation results suggest that world emissions would go down due to declines in both regions.

Looking at orthodox environmental policy compared to Kyoto-style environmental policy achieves interesting conclusions. Either a global cap-and-trade program or Pigouvian tax will lead to reductions in global emissions. Any agreement between North and South that allows permit trade under an overall cap reduces global emissions automatically. Under a worldwide Pigouvian tax, the emissions prices in North and South will be equal to each other and can be set at a sufficiently high level to generate greater fuel saving and lower emissions. Both of these policies, by equalizing emission prices, result in partial specialization in the model where all dirty good firms in South and OPEC exit or clean good firms exit from North or both. The reason is that Northern firms are always more competitive than Southern in dirty good sector due to lower user cost of capital if they both pay the same world price of emissions. The direction of change in specialization is more important than the magnitude. With orthodox policy fossil fuel use shifts to the clean country which is North and leads to greater efficiency, but under the Kyoto Protocol fossil fuel use shifts to the dirty region which is South and OPEC.

In the analysis of theoretical model if OPEC holds constant the price of fossil fuel, there is no increase in the price of dirty good, and, therefore, no incentive for countries to seek technological improvement. If OPEC lets the price of fossil fuel rise holding output constant, that leads to increase in price of dirty good and firms have incentives to invest in technologies. Thus, technological progress is possible under Kyoto framework, but would be more beneficial if Kyoto turned out to be a sound agreement.

There are many issues that remain unexplored with respect to linkages between environmental change and income growth. One concerns the issue that CO2 is a global pollutant rather than local. Stern (2006) states that:

> *with CO2, the global nature of the externality means that people in any particular high-income country cannot by themselves significantly affect global emissions and hence their own climate. This contrasts with the situation for the local pollutants for which environmental Kuznets curves have been estimated. It is easier than with greenhouse gases for the people affected to set up abatement incentives and appropriate political and regulatory mechanisms.*[55]

Therefore, further investigation of the EKC relationship is warranted considering impact of energy saving technologies and including various functional form specifications and estimation techniques. A further extension of the theoretical model might also explicitly introduce income effects. It would also be worthwhile to develop a computational general equilibrium model to provide an alternative empirical test in multi-sector model.

[55] Stern's 2006 Review on the Economics of Climate Change, p. 191.

The present structure of the Kyoto agreement suggests that since historically developed countries accounted for larger share of emissions combined ,with their economic prosperity, they are now being held responsible for meeting Kyoto commitments while the developing countries have no binding commitments. As to policy conclusions based on the theoretical framework, caps on emissions for only the developed countries are insufficient to guarantee the success of the Kyoto Protocol. Moreover, the theoretical model suggests that Kyoto Protocol may even be harmful for environment when no caps for developing countries are introduced. In any case, with US, Australia, China, and India not subject to Kyoto commitments, the agreement is of very limited value. Given the fact that the majority of countries are unlikely to meet their Kyoto obligations, a global cap on emissions is warranted and presents a further step in climate change policy suggested by the second round of Kyoto agreement. Fortunately, if emission intensity reversals suggested by the empirics turn out to be valid, the current Kyoto agreement might be beneficial to the environment.

Appendix:

A.1. Theoretical Proofs

Requirements for diversification in both the North and the South and OPEC.

In this section of the Appendix we establish that the dirty good must be more capital intensive than the clean good if both the North and the South and OPEC region are diversified in the production of the clean and the dirty good. Setting the North's emissions price equal to zero in equation (21) and (22) so as to rule out any capital use in fuel saving, yields the intercepts of the NN and SO curves:

$$\beta_D^N(p_F^w, p_K^N, 0) = \beta_D(p_K^N, p_L^N) + \beta_E(p_K^N, p_L^N)a_{ED} + (p_F^w(1-\mu^N) + p_K^N\kappa(\mu^N))A_{FD},\ and$$
$$\beta_D^{SO}(p_F^w, p_K^{SO}, 0, \overline{\mu}^{SO}) = \beta_D(p_K^{SO}, p_L^{SO}) + \beta_E(p_K^{SO}, p_L^{SO})a_{ED} + (p_F^w(1-\mu^{SO}) + p_K^{SO}\kappa(\mu^{SO}))A_{FD}$$

As indicated by Figure 4, an internal solution consistent with diversification both in North and in the South-OPEC region requires that the intercept of the NN curve is less than that of the SS curve such that

$\beta_D(p_K^N, p_L^N) + \beta_E(p_K^N, p_L^N)a_{ED} + (p_F^w(1-\mu^N) + p_K^N\kappa(\mu^N))A_{FD} <$

$\beta_D(p_K^{SO}, p_L^{SO}) + \beta_E(p_K^{SO}, p_L^{SO})a_{ED} + (p_F^w(1-\mu^{SO}) + p_K^{SO}\kappa(\mu^{SO}))A_{FD}$. Recall that

$p_K^N < p_K^{SO}$ and that $p_L^N > p_L^{SO}$. Further, from equation (17), $b_C^N(p_K^N, p_L^N) = b_C^{SO}(p_K^{SO}, p_L^{SO})$.

Consequently in the absence of factor intensity reversals, the costs of the dirty good can then be higher in South than North only if the overall production of the dirty good inclusive its underlying electricity is more capital intensive than the clean good such that:

$$\frac{\alpha_{KD}(\cdot)+\alpha_{KE}(\cdot)a_{ED}}{\alpha_{LD}(\cdot)+\alpha_{LE}(\cdot)a_{ED}} > \frac{\alpha_{KC}(\cdot)}{\alpha_{LC}(\cdot)},$$

where $\alpha_{ij}(p_K^h, p_L^h) \equiv \frac{\partial \beta_j(p_K^h, p_L^h)}{p_i^h}$ is the requirement of input i=K,L in the production of one unit of j=C,D,E excluding fuel saving.

The impact of changes in allowable credits and fossil fuel prices on fuel saving and other endogenous price variables.

Differentiation of the diversified production conditions given by (21) and (22) reveals that the slopes of the NN and SS curves are $\partial p_D^W / \partial p_M^N\big|_{NN} = (1-\mu^N)A_{FD} > 0$ and $\partial p_D^W / \partial p_M^N\big|_{SS} = -\theta A_{FD} \leq 0$ respectively. Total differentiation of (21) and (22) in the vicinity of an initial zero-credit equilibrium yields:

$$\begin{bmatrix} 1 & -(1-\mu^N)A_{FD} \\ 1 & 0 \end{bmatrix}\begin{bmatrix} dp_D^w \\ dp_M^N \end{bmatrix} = \begin{bmatrix} A_{FD}(1-\mu^N) & 0 \\ A_{FD}(1-\overline{\mu}^{SO}) & -p_M^N A_{FD} \end{bmatrix}\begin{bmatrix} dp_F^O \\ d\theta \end{bmatrix}$$
$$\Delta = (1-\mu^N)A_{FD} > 0$$

For row one in Table 5, which pertains to North's emissions price, we obtain:

$dp_M^N / d\theta = -p_M^N /(1-\mu^N) < 0$, $dp_M^N / d\overline{p}_F^O = (\mu^N - \overline{\mu}^{SO})/(1-\mu^N) > 0$.

For row two, which pertains to the price of the dirty good:

$dp_D^w / d\theta = -p_M^N A_{FD} \leq 0$ and $dp_D^w / d\overline{p}_F^O = (1-\overline{\mu}^{SO})A_{FD} > 0$.

The results for Northern fuel saving in row three are obtained by differentiating equation (6.1) and using row one:

$d\mu^N / d\theta = d\mu^N / dp_M^N \cdot dp_M^N / d\theta = -((1-\mu^N)p_K^N \kappa''(\mu^N))^{-1} p_M^N = \psi_\theta^N < 0$ and

$d\mu^N / d\overline{p}_F^O = d\mu^N / d\overline{p}_F^O + d\mu^N / dp_M^N \cdot dp_M^N / d\overline{p}_F^O = ((1-\mu^N)p_K^N \kappa''(\mu^N))^{-1}(1-\overline{\mu}^{SO}) = \psi_F^N > 0$

The results for fuel saving in the South and OPEC in row four are obtained by differentiating equation (6.1) and using row one: $d\mu^{SO} / d\theta = 1 > 0$ and

$d\mu^{SO} / d\overline{p}_F^O = 1/\kappa''(\overline{\mu}^{SO})p_K^{SO} == \psi_F^{SO} > 0$.

The results for row five on the fuel saving for the North is obtained by differentiating (7) and using the results from row one:

$d\rho^{*N} / d\theta = \partial\rho^{*N} / \partial p_M^N \cdot \partial p_M^N / \partial\theta = -p_M^N < 0$ and

$d\rho^{*N} / d\overline{p}_F^O = \partial\rho^{*N} / \partial\overline{p}_F^O + \partial\rho^{*N} / \partial p_M^N \cdot \partial p_M^N / \partial\overline{p}_F^O = 1-\overline{\mu}^{SO} > 0$

The results for row six on the fuel saving of South and OPEC are obtained by differentiating (12) and using the results from row one:

$d\overline{\rho}^{SO} / d\theta = \partial\overline{\rho}^{SO} / \partial p_M^N \cdot \partial p_M^N / \partial\theta + \partial\overline{\rho}^{SO} / \partial\theta = -p_M^N < 0$ and

$$d\overline{\rho}^{SO} / d\overline{p}_F^O = \partial\overline{\rho}^{SO} / \partial\overline{p}_F^O + \partial\overline{\rho}^{SO} / \partial p_M^N \cdot \partial p_M^N / \partial\overline{p}_F^O = 1 - \overline{\mu}^{SO} > 0$$

The results for electricity prices on row seven are obtained by differentiating equation (19) and using row one: $dp_E^h / d\overline{p}_F^O = a_{FE} d\rho_F^h / d\overline{p}_F^O = a_{FE}(1 - \overline{\mu}^{SO}) > 0$ and $dp_E^h / d\theta = a_{FE} d\rho_F^h / d\theta = -a_{FE} p_M^N < 0 \quad h = N, S$.

For dirty-goods consumption on row eight, we differentiate (4) and use row two to get: $(1/X_D^h)(dX_D^h / d\theta) = -p_M^N A_{FD} \varphi_{FD}^h \varepsilon_{DD}^h > 0$ and $(\overline{p}_F^O / X_D^h)(dX_D^h / d\overline{p}_F^O) = \varphi_{FD}^h \varepsilon_{DD}^h < 0$ where $\varepsilon_{DD}^h \equiv -(p_D^w / X_D^h)(\partial X_D^h / \partial p_D^w) < 0$ is the own price elasticity of demand for dirty goods by households in country h.

For electricity consumption on row nine, we differentiate (3) and use row seven to obtain: $(1/X_E^h)(dX_E^h / d\theta) = -p_M^N \varphi_{FE} \varepsilon_{EE}^h A_{FD} > 0$ and $\varepsilon_{EE}^h \equiv -(p_E^h / X_E^h)(\partial X_E^h / \partial p_E^h) < 0$ $(\overline{p}_F^O / X_E^h)(dX_E^h / d\overline{p}_F^O) = \varphi_{FE}^h \varepsilon_{EE}^h < 0$ where $\varepsilon_{EE}^h \equiv -(p_E^h / X_E^h)(\partial X_E^h / \partial p_E^h) < 0$ is the own price elasticity of demand for dirty goods by households in country h.

For fossil fuel on rows ten and eleven, equation (4) alone implies: $(\overline{p}_F^O / X_F^h)(\partial X_F^h / \partial\overline{p}_F^O) \equiv \varepsilon_{FF}^h < 0$ where ε_{FF}^h is the own price elasticity of demand for fossil fuel by households in country h. Further, using row five and six implies:

$$dX_F^h / \partial\overline{p}_F^O = \partial X_F^h / \partial\rho_F^h \cdot \partial\rho_F^h / \partial p_M^N \cdot \partial p_M^N / \partial\overline{p}_F^O + \partial X_F^h / \partial\overline{p}_F^O = \varepsilon_{FF}^h + \varepsilon_F^h (\mu^N - \overline{\mu}^{SO}) / (1 - \mu^N) < 0$$

where $\varepsilon_F^h = \partial X_F^h / \partial\rho_F^h < 0$.

$$\partial X_F^N / \partial\theta = \partial X_F^N / \partial\rho_F^N \cdot \partial\rho_F^N / \partial\theta = -\varepsilon_F^N p_M^N > 0,$$

$$\partial X_F^{SO} / \partial\theta = \partial X_F^{SO} / \partial\rho_F^{SO} \cdot \partial\rho_F^{SO} / \partial\theta = -\varepsilon_F^{SO} p_M^N > 0$$

For natural resource rents we differentiate (20) to get:

$dp_R^h / d\theta = -(a_{FF} / a_{RF})(d\rho_F^h / d\theta) = p_M^N a_{FF} / a_{RF} > 0$ and

$dp_R^h / d = \left[1 - a_{FF}(d\rho_F^h / d\overline{p}_F^O)\right] = (1-(1-\overline{\mu}^{SO})a_{FF}) / a_{RF} > 0 \quad h = N,S$

The impact of changes in the fossil fuel price, the emissions cap and allowable credits on fossil fuel demand and emissions.

We have two linear equations (39) and (40) which we solve applying the Cramer's Rule.

$$\begin{bmatrix} 1 & -\theta^{SO}\zeta^{SO} \\ \phi^N\zeta^N & \phi^{SO}\zeta^{SO} \end{bmatrix} \begin{bmatrix} X_F^N \\ X_F^{SO} \end{bmatrix} = \begin{bmatrix} \overline{Y}_M^N \\ Z_F^W \end{bmatrix}$$

$$\Delta = \phi^{SO}\zeta^{SO} + \theta\zeta^{SO}\phi^N\zeta^N$$

$$X_F^N = \frac{\phi^{SO}\zeta^{SO}\overline{Y}_M^N + \theta\zeta^{SO}Z_F^W}{\phi^{SO}\zeta^{SO} + \theta\zeta^{SO}\phi^N\zeta^N}, \quad \theta = 0 \Rightarrow X_F^N = \overline{Y}_M^N \tag{41}$$

$$X_F^{SO} = \frac{Z_F^W - \phi^N\zeta^N\overline{Y}_M^N}{\phi^{SO}\zeta^{SO} + \theta\zeta^{SO}\phi^N\zeta^N}, \quad \theta = 0 \Rightarrow X_F^{SO} = \frac{Z_F^W - \phi^N\zeta^N\overline{Y}_M^N}{\phi^{SO}\zeta^{SO}} \tag{42}$$

$$X_F^W = \frac{(1+\theta\zeta^{SO})Z_F^W - (\phi^N\zeta^N - \phi^{SO}\zeta^{SO})\overline{Y}_M^N}{\phi^{SO}\zeta^{SO} + \theta\zeta^{SO}\phi^N\zeta^N},$$
$$\theta = 0 \Rightarrow X_F^W = \frac{Z_F^W - (\phi^N\zeta^N - \phi^{SO}\zeta^{SO})\overline{Y}_M^N}{\phi^{SO}\zeta^{SO}} \qquad (43)$$

Recall that $\zeta^h = (1-\mu^h)^{-1}$ and $\partial\zeta^h / \partial\mu^h = \zeta^{h^2}$, $d\mu^N / d\overline{p}_F^O == \psi_F^N > 0$, $d\mu^{SO} / d\overline{p}_F^O == \psi_F^{SO} > 0$. Consequently, differentiating (41), (42) and (43) with respect to the price of fossil fuel in the vicinity of a pre-Kyoto equilibrium yields.

$$\frac{\partial X_F^{SO}}{\partial \overline{p}_F^O} = 0,$$

$$\frac{\partial X_F^{SO}}{\partial \overline{p}_F^O} = (\phi^{SO}\zeta^{SO})^{-1}(\partial Z_{FH}^W / \partial \overline{p}_F^O - X_F^N\psi_F^N\zeta^{N^2} - X_F^{SO}\psi_F^{SO}\zeta^{SO^2}) < 0,$$

$$\frac{\partial X_F^W}{\partial \overline{p}_F^O} = (\phi^{SO}\zeta^{SO})^{-1}(\partial Z_{FH}^W / \partial \overline{p}_F^O - X_F^N\psi_F^N\zeta^{N^2} - X_F^{SO}\psi_F^{SO}\zeta^{SO^2}) < 0.$$

Differentiating (41), (42), (43) with respect to a reduction in North's emissions' cap in the vicinity of an initial pre-Kyoto equilibrium yields:

$$-\frac{\partial X_F^N}{\partial \overline{Y}_M^N} = -\frac{\phi^{SO}\zeta^{SO}}{\phi^{SO}\zeta^{SO} + \theta\zeta^{SO}\phi^N\zeta^N} < 0, \quad \theta = 0 \Rightarrow -\frac{\partial X_F^N}{\partial \overline{Y}_M^N} = -1 < 0,$$

$$-\frac{\partial X_F^{SO}}{\partial \overline{Y}_M^N} = \frac{\phi^N\zeta^N}{\phi^{SO}\zeta^{SO} + \theta\zeta^{SO}\phi^N\zeta^N} > 0, \quad \theta = 0 \Rightarrow -\frac{\partial X_F^{SO}}{\partial \overline{Y}_M^N} = \frac{\phi^N\zeta^N}{\phi^{SO}\zeta^{SO}} > 1,$$

$$-\frac{\partial X_F^W}{\partial \overline{Y}_M^N} = \frac{(\phi^N\zeta^N - \phi^{SO}\zeta^{SO})}{\phi^{SO}\zeta^{SO} + \theta\zeta^{SO}\phi^N\zeta^N} > 0, \quad \theta = 0 \Rightarrow -\frac{\partial X_F^W}{\partial \overline{Y}_M^N} = \frac{\phi^N\zeta^N - \phi^{SO}\zeta^{SO}}{\phi^{SO}\zeta^{SO}} > 0.$$

Note that $\partial\zeta^h / \partial\mu^h = \zeta^{h^2}$ and $d\mu^N / d\theta = \psi_\theta^N > 0, d\mu^{SO} / d\theta = 1$. Differentiating (41), (42), (43) with respect to allowable emission credits in the vicinity of an initial pre-Kyoto equilibrium yields:

$$\frac{\partial X_F^N}{\partial \theta} = \zeta^{SO} X_F^{SO} > 0$$

$$\frac{\partial X_F^{SO}}{\partial \theta} = (X_F^W / \zeta^{SO}\phi^{SO})\left[\left[\psi_\theta^N \zeta^{N^2} + (1/X_F^W)(\partial Z_{FH}^W / \partial\theta\right] - \left[\psi_\theta^N \zeta^{N^2} + \zeta^{SO^2} + \zeta^{SO}(\zeta^N \phi^N)\right](X_F^{SO} / X_F^W)\right]$$

$$\frac{\partial X_F^W}{\partial \theta} = (X_F^W / \zeta^{SO}\phi^{SO})\left[\left[\psi_\theta^N \zeta^{N^2} + (1/X_F^W)(\partial Z_{FH}^W / \partial\theta\right] - \left[\psi_\theta^N \zeta^{N^2} + \zeta^{SO^2} + \zeta^{SO}(\zeta^N \phi^N - \zeta^{SO}\phi^{SO})\right](X_F^{SO} / X_F^W)\right]$$

A.2. Variables Definitions and Sources

Variables	Definition	Unit	Source
CO2 emissions per capita	CO2 emissions per capita	Million metric tons per person	EIA
Fossil Fuel Use per capita	Combined Oil, Dry Natural Gas and Coal Consumption divided by population	Quadrillion BTU per person	EIA
CO2 emissions/Fossil Fuel Use	Ratio of CO2 emissions to total fossil fuel use	Emissions per BTU	EIA
Oil/Fossil Fuel - omitted category	Oil Consumption divided by total population	Quadrillion BTU per person	EIA
Gas/Fossil Fuel	Share of gas consumption in total fossil fuel consumption	%	EIA
Coal/Fossil Fuel	Share of coal consumption in total fossil fuel consumption	%	EIA
Land/Population	Land area divided by total population	sq. km per person	WDI
GDP per capita	GDP per capita PPP	constant 2000 US$ per person	WDI
Agriculture/POP =(Agriculture/GDP)*(GDP/POP)	Agriculture, value added (% of GDP)	constant 2000 US$ per person	WDI
Services/POP =(Services/GDP)*(GDP/POP)	Services, value added (% of GDP)	constant 2000 US$ per person	WDI
Other Industry/POP=(Other Industry/GDP)*(GDP/POP)	Industry, value added (% of GDP) minus Manufacturing, value added (% of GDP)	constant 2000 US$ per person	WDI
Manufacturing/GDP - omitted category	Manufacturing, value added (% in GDP)	%	WDI

Variables	Definition	Unit	Source
Machinery/POP= (Machinery/Manufacturing)*(Manufacturing/GDP)*(GDP/POP)	Machinery and transport equipment (% of value added in manufacturing)	constant 2000 US$ per person	WDI
Food/POP= (Food/Manufacturing)*(Manufacturing/GDP)*(GDP/POP)	Food, beverages and tobacco (% of value added in manufacturing)	constant 2000 US$ per person	WDI
Textiles/POP= (Textiles/Manufacturing)*(Manufacturing/GDP)*(GDP/POP)	Textiles and clothing (% of value added in manufacturing)	constant 2000 US$ per person	WDI
Other Manufacturing/GDP - omitted category	Other manufacturing (% of value added in GDP)	%	WDI

A.3. Summary Statistics

Variables	Observations	Mean	Std. Dev.	Min	Max
CO2 per capita	3449	4375569	6.22E+06	21740.46	5.10E+07
Fossil Fuel Use pc	3552	61077.73	92670.72	0	811497.8
CO2/Fossil Fuel Use	3850	74.27153	34.03235	25.45865	830.2251
ln (CO2 per capita)	3449	14.19304	1.736435	9.98693	17.74675
ln(Fossil Fuel Use pc)	3449	9.916628	1.750084	5.766412	13.60664
ln(CO2/Fossil Fuel Use)	3850	4.277064	0.19503	3.237056	6.721697
Gas/Fossil Fuel	3850	0.134106	0.200845	0	0.95136
Coal/Fossil Fuel	3850	0.111530	0.002975	7.9E-05	0.804
Land/Population	3801	0.061309	0.115801	0.00016	0.941973
GDP per capita (pc)	3552	7768.01	8199.963	466.1686	61641.15
(GDP pc)*(GDP pc)	3.55E+03	1.28E+08	2.54E+08	217313.2	3.80E+09
Agriculture pc	3400	630.2646	391.7879	18.52097	3104.92
Services pc	3041	4294.619	5484.278	60.01623	48584.3
Other pc	3041	1099.241	1803.652	7.486124	31769.22
(Agr pc)*(GDP pc)	3400	5598481	8.23E+06	48599.8	8.29E+07
(Ser pc)*(GDP pc)	3.04E+03	7.45E+07	1.80E+08	27977.68	2.99E+09
(Oth pc)*(GDP pc)	3.04E+03	1.74E+07	5.33E+07	7856.312	1.37E+09
Chemicals pc	1429	19694.97	46703.04	7.84953	587716.4
Food pc	1584	31598.26	30570.95	104.958	391508.3
Machinery pc	1473	37478.71	57870.93	4.515883	339646.8
Textiles pc	1593	15989.51	21676.49	1.049.24	221424.2
(Chem pc)*(GDP pc)	1.43E+03	3.45E+08	1.00E+09	26118.5	1.43E+10
(Food pc)*(GDP pc)	1.58E+03	4.55E+08	8.05E+08	101235.3	1.36E+10
(Mach pc)*(GDP pc)	1.47E+03	7.48E+08	1.40E+09	3150.042	8.23E+09
(Text pc)*(GDP pc)	1.59E+03	2.33E+08	4.77E+08	512.163	7.71E+09

A.4. List of Countries

Developed Countries (28):

Australia, Austria, Belgium, Canada, Cyprus, Denmark, Finland, France, Germany, Greece, Hong Kong, Iceland, Ireland, Italy, Japan, Luxembourg, Malta, Netherlands, New Zealand, Norway, Portugal, Singapore, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.

Developing Countries (145):

Albania, Algeria, Angola, Antigua and Barbuda, Argentina, Armenia, Azerbaijan, Bahrain, Bangladesh, Barbados, Belarus, Belize, Benin, Bhutan, Bolivia, Bosnia and Herzogovina, Botswana, Brazil, Bulgaria, Burkina Faso, Burundi, Cambodia, Cameroon, Cape Verde, Central African Republic, Chad, Chile, China, Colombia, Comoros, Congo, Costa Rica, Cote d'Ivoire, Croatia, Cuba, Czech Republic, Djibouti, Dominica, Dominican Republic, Ecuador, Egypt, El Salvador, Equatorial Guinea, Eritrea, Estonia, Ethiopia, Fiji, Gabon, Gambia, Georgia, Ghana, Grenada, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, Hungary, India, Indonesia, Iran, Iraq, Jordan, Kazahstan, Kenya, Kiribati, Korea, Kuwait, Kyrgyz Republic, Lao PDR, Latvia, Lebanon, Lesotho, Liberia, Libya, Lithuania, Macedonia, Madagascar, Malawi, Malaysia, Mali, Mauritania, Mauritius, Mexico, Moldova, Mongolia, Morocco, Mozambique, Myanmar, Namibia, Nepal, New Caledonia, Niger, Nigeria, Oman, Pakistan, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Poland, Puerto Rico, Romania, Russian Federation, Rwanda, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Samoa, Sao Tome and Principe, Saudi Arabia, Senegal, Serbian and Montenegro, Seychelles, Sierra Leone, Slovak Republic, Slovenia, South Africa, Sri Lanka, Sudan, Suriname, Swaziland, Syrian Arab Republic, Tajikistan, Tanzania, Thailand, Togo, Tonga, Trinidad and Tobago, Tunisia, Turkmenistan, Uganda, Ukraine, United Arab Emirates, Uruguay, Uzbekistan, Vanuatu, Venezuela, Vietnam, Yemen, Zambia, Zimbabwe.

A.5. Calculation of Peak, Inflection and Switching Points

Calculation of peak points.

$$\ln(CO2/POP) = \alpha \cdot GDP/POP + \beta \cdot (GDP/POP)^2$$

In order to find the peak we need to find a slope and set it equal to zero:

$$\frac{1}{CO2/POP} dCO2/POP = (\alpha + 2\beta \cdot GDP/POP) dGDP/POP$$

$$\frac{dCO2/POP}{dGDP/POP} = (\alpha + 2\beta \cdot GDP/POP) \cdot CO2/POP$$

Setting the slope equal to zero allows to solve for the peak income level:

$$\frac{dCO2/POP}{dGDP/POP} = 0 \quad \Rightarrow (\alpha + 2\beta \cdot GDP/POP) = 0 \quad \Rightarrow GDP/POP = -\frac{\alpha}{2\beta}.$$

Calculation of inflection points.

The slope of the EKC is:

$$\sigma = \frac{dCO2/POP}{dGDP/POP} = (\alpha + 2\beta \cdot GDP/POP) \cdot CO2/POP$$

Changes in the slope of EKC are given by:

$$\frac{d\sigma}{dGDP/POP} = (\alpha + 2\beta \cdot GDP/POP)\frac{dCO2/POP}{dGDP/POP} + 2\beta \cdot CO2/POP =$$
$$= (\alpha + 2\beta \cdot GDP/POP)^2 \cdot CO2/POP + 2\beta \cdot CO2/POP =$$
$$= ((\alpha + 2\beta \cdot GDP/POP)^2 + 2\beta) \cdot CO2/POP$$

$$\frac{d\sigma}{dGDP/POP} = 0 \quad \Rightarrow (\alpha + 2\beta \cdot GDP/POP)^2 + 2\beta = 0$$
$$\Rightarrow GDP/POP_1 = \frac{\alpha - \sqrt{-2\beta}}{2\beta},\ GDP/POP_2 = \frac{\alpha + \sqrt{-2\beta}}{2\beta}$$

Calculation of switching points.

$$\ln(CO2/POP) = \gamma \cdot SER/GDP \cdot GDP/POP + \mu \cdot SER/GDP \cdot (GDP/POP)^2$$

$$\frac{1}{(CO2/POP)} d(CO2/POP) = (GDP/POP)(\gamma + \mu \cdot (GDP/POP)) \cdot d(SER/GDP)$$

$$\frac{dCO2/POP}{dSER/GDP} = 0 \quad \Rightarrow (\gamma + \mu \cdot GDP/POP) = 0 \quad \Rightarrow GDP/POP = -\frac{\gamma}{\mu}$$

A.6. Sensitivity Tests

	ln (CO2 per capita)		ln (CO2 per capita)	ln (CO2 per capita)
Gas/Fossil Fuel	0.216012*	0.473168***	0.855197***	0.647247***
	[0.075]	[0.000]	[0.000]	[0.000]
Coal/Fossil Fuel	1.487948***	1.592745***	1.796225***	1.6395***
	[0.000]	[0.000]	[0.000]	[0.000]
Land/Population	0.202639	0.082	2.522732***	4.063162***
	[0.622]	[0.829]	[0.000]	[0.000]
GDP per capita (pc)	0.000152***	0.000175***	0.000157***	0.000234***
	[0.000]	[0.000]	[0.000]	[0.000]
(GDP pc)*(GDP pc)	-2.99E-09***	-3.41E-09***	-2.89E-09***	-6.86E-09***
	[0.000]	[0.000]	[0.000]	[0.006]
Agriculture pc			0.000156***	-0.000084
			[0.002]	[0.356]
(Agr pc)*(GDP pc)				1.37E-08***
				[0.005]
Services pc			-0.000023	-0.000142**
			[0.328]	[0.022]
(Ser pc)*(GDP pc)				5.01E-09*
				[0.055]
Other pc			0.000027**	-0.000171***
			[0.317]	[0.004]
(Oth pc)*(GDP pc)				6.65E-09***
				[0.009]
Chemicals pc			-5.78E-07***	-2.35E-06
			[0.110]	[0.162]
(Chem pc)*(GDP pc)				8.07E-11
				[0.196]
Food pc			9.62E-07**	1.81E-06*
			[0.019]	[0.062]
(Food pc)*(GDP pc)				-2.41E-11
				[0.570]
Machinery pc			5.00E-07	7.70E-07
			[0.104]	[0.477]
(Mach pc)*(GDP pc)				1.31E-11
				[0.777]
Textiles pc			1.57E-06***	2.13E-06*
			[0.002]	[0.079]
(Text pc)*(GDP pc)				3.77E-12
				[0.942]
Observations	3389	3389	1315	1315
Countries	160	160	99	99
Panel Type	Unbalanced	Unbalanced	Unbalanced	Unbalanced
Random vs Fixed	Fixed	Random	Random	Fixed
R-squared within	0.335	0.332	0.542	0.571
R-squared between	0.683	0.712	0.727	0.593
R-squared overall	0.692	0.718	0.719	0.627

Robust p values in brackets; * significant at 10%, ** significant at 5%, *** significant at 1%.
(1) Asymptotic properties for Hausman test of random vs. fixed effects not satisfied.
(2) Hausman test indicates fixed effects.

	ln (CO2 per capita)	ln (Fossil Fuel Use pc)	ln (CO2/Fossil Fuel Use) (1)
Gas/Fossil Fuel	0.647247***	0.922342***	-0.275096***
	[0.000]	[0.000]	[0.000]
Coal/Fossil Fuel	1.6395***	1.341857***	0.297644***
	[0.000]	[0.000]	[0.000]
Land/Population	4.063162***	3.281297***	0.781866
	[0.000]	[0.000]	[0.002]
GDP per capita (pc)	0.000234***	0.000276***	-0.000042
	[0.000]	[0.000]	[0.083]
(GDP pc)*(GDP pc)	-6.86E-09***	-7.50E-08***	6.42E-10
	[0.006]	[0.002]	[0.503]
Agriculture pc	-0.000084	-0.000182**	0.0000978
	[0.356]	[0.032]	[0.061]
(Agr pc)*(GDP pc)	1.37E-08***	1.41E-08***	-3.31E-10
	[0.005]	[0.002]	[0.890]
Services pc	-0.000142**	-0.000162***	0.0000201
	[0.022]	[0.007]	[0.458]
(Ser pc)*(GDP pc)	5.01E-09*	5.37E-09**	-3.55E-10
	[0.055]	[0.036]	[0.734]
Other pc	-0.000171***	-0.000183***	0.0000116
	[0.004]	[0.002]	[0.635]
(Oth pc)*(GDP pc)	6.65E-09***	6.54E-09***	1.08E-10
	[0.009]	[0.009]	[0.911]
Chemicals pc	-2.35E-06	-2.07E-06	-2.80E-07
	[0.162]	[0.189]	[0.585]
(Chem pc)*(GDP pc)	8.07E-11	6.06E-11	2.01E-11
	[0.196]	[0.298]	[0.296]
Food pc	1.81E-06*	1.99E-06**	-1.88E-07
	[0.062]	[0.035]	[0.607]
(Food pc)*(GDP pc)	-2.41E-11	-3.88E-11	1.47E-11
	[0.570]	[0.348]	[0.367]
Machinery pc	7.70E-07	5.39E-07	2.31E-07
	[0.477]	[0.615]	[0.530]
(Mach pc)*(GDP pc)	1.31E-11	-7.92E-12	-5.19E-12
	[0.777]	[0.862]	[0.732]
Textiles pc	2.13E-06*	2.11E-06*	1.42E-08
	[0.079]	[0.075]	[0.978]
(Text pc)*(GDP pc)	3.77E-12	-7.41E-13	4.52E-12
	[0.942]	[0.988]	[0.838]
Observations	1315	1315	1315
Countries	99	99	99
Panel Type	Unbalanced	Unbalanced	Unbalanced
Random vs Fixed	Fixed	Fixed	Fixed
R-squared within	0.571	0.641	0.113
R-squared between	0.593	0.701	0.187
R-squared overall	0.627	0.71	0.158

Robust p values in brackets; * significant at 10%, ** significant at 5%, *** significant at 1%.

(1) Asymptotic properties for Hausman test of random vs. fixed effects not satisfied.

(2) Hausman test indicates fixed effects.

	ln (CO2 per capita)		
	5A (2)	5ab (1)	5B (2)
GDP per capita (pc)	1.52E-04***	1.54E-04***	2.17E-04***
	[0.000]	[0.000]	[0.000]
(GDP pc)*(GDP pc)	-3.00E-09***	-2.80E-09***	-6.00E-09***
	[0.000]	[0.000]	[0.000]
Agriculture pc		1.06E-04**	-7.75E-05
		[0.021]	[0.277]
(Agr pc)*(GDP pc)		-2.48E-05	1.52E-08***
		[0.129]	[0.000]
Services pc		1.35E-05	-9.79E-05***
		[0.390]	[0.002]
(Ser pc)*(GDP pc)			3.70E-09**
			[0.016]
Other Industy pc			-7.60E-05**
			[0.019]
(Oth pc)*(GDP pc)			3.80E-09***
			[0.005]
Gas/Fossil Fuel	2.16E-01*	2.33E-01***	1.99E-01*
	[0.075]	[0.045]	[0.083]
Coal/Fossil Fuel	1.49E+00***	1.32E+00***	1.27E+00***
	[0.000]	[0.000]	[0.000]
Land/Population	2.03E-01	5.73E-01	5.86E-01
	[0.622]	[0.231]	[0.221]
Observations	3389	2925	2925
Countries	160	159	159
Panel Type	Unbalanced	Unbalanced	Unbalanced
Random vs Fixed	Fixed	Fixed	Fixed
R-squared within	0.335	0.36	0.364
R-squared between	0.335	0.36	0.364
R-squared overall	0.683	0.695	0.676

A.7. Partial elasticities with standardized coefficients

	ln (CO2 pc) 2C	ln (USE pc) 3C	ln (CO2/USE) 4C
GDP per capita (pc)	0.16471***	0.23656***	-0.01366
	[0.000]	[0.000]	[0.499]
(GDP pc)*(GDP pc)	-0.10495***	-0.13208***	-0.03667*
	[0.000]	[0.000]	[0.079]
(% Agriculture)*(GDP pc)	-0.00947**	-0.01382***	-0.00313
	[0.011]	[0.005]	[0.655]
(% Agriculture)*(GDP pc)2	0.00593***	0.00738**	0.00768*
	[0.008]	[0.014]	[0.070]
(% Services)*(GDP pc)	-0.0323**	-0.03201*	-0.02593*
	[0.011]	[0.064]	[0.085]
(% Services)*(GDP pc)2	0.03752***	0.03754**	0.03381**
	[0.000]	[0.010]	[0.012]
(% Other Industry)	-0.01214***	-0.021***	0.01178***
	[0.000]	[0.000]	[0.005]
(% Other Industry)*(GDP pc)2	0.01157***	0.01479***	0.00282
	[0.000]	[0.000]	[0.312]
Gas/Fossil Fuel	0.00169	0.01068***	-0.0163***
	[0.120]	[0.000]	[0.000]
Coal/Fossil Fuel	0.01045***	0.01159***	0.00596***
	[0.000]	[0.000]	[0.000]
Land/Population	0.00538***	0.01115***	-0.00307
	[0.001]	[0.000]	[0.306]
Observations	1704	1704	1704
Countries	71	71	71
Panel Type	Balanced	Balanced	Balanced
Random vs Fixed	Random	Random	Random
R-squared within	0.514	0.555	0.115
R-squared between	0.711	0.772	0.125
R-squared overall	0.697	0.759	0.112

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