Consulting Assistance on Economic Reform II

# DISCUSSION PAPERS

The objectives of the Consulting Assistance on Economic Reform (CAER II) project are to contribute to broad-based and sustainable economic growth and to improve the policy reform content of USAID assistance activities that aim to strengthen markets in recipient countries. Services are provided by the Harvard Institute for International Development (HIID) and its subcontractors. It is funded by the U.S. Agency for International Development, Bureau for Global Programs, Field Support and Research, Center for Economic Growth and Agricultural Development, Office of Emerging Markets through Contracts PCE-C-00-95-00015-00 and PCE-Q-00-95-00016-00. This paper is funded by Contract PCE-Q-00-95-00016-00, Delivery Order 15.

## Developing Countries and the Control of Climate Change: Empirical Evidence

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CAER II Discussion Paper No. 45
November 1999

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# DEVELOPING COUNTRIES AND THE CONTROL OF CLIMATE CHANGE:

## Empirical Evidence

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# Developing Countries and the Control of Global Climate Change: Empirical Evidence

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# I. Executive Summary[1]

This paper aims to advance our understanding of several dimensions of a complicated problem. It is a part of a two-paper set with its companion "Developing Countries and The Control of Climate Change: Theoretical Perspective and Policy Implications." That paper is intended to be read first as a overview of the theoretical considerations that underpin the empirical investigation performed here. In this paper, we begin by using historical data and econometric evidence to assess the contributions of individual regions to the evolution of atmospheric concentrations of the main greenhouse gas (GHG), carbon dioxide, on a historical basis and on a prospective basis to the year 2050 assuming a "business as usual" scenario. Second, we use Nordhaus' (1998) estimates of regional damage functions to assess how various regions would be affected by global climate change according to these projections. Using these estimates, we then measure the proportionate contribution of each region to the overall rise in atmospheric carbon and the share of each region in the global damages resulting from rising carbon concentrations. On the basis of the methodology developed in the companion paper to this work, we calculate the optimal inter-regional transfers that would be required to compensate regions that suffer net damage as a result of the forecast pattern of temperature change and concentrations.

### *Empirical evidence on GHG emissions*

In this section, we introduce some scientific background and review the historical contributions of nine regions of the globe from rising atmospheric carbon, first from fossil fuels and then from land use on an annual basis from 1860. The data that we use for this calculation come from time series that are available for emissions on a country basis for fossil fuel emissions and a regional basis for land use change emissions. We summarize this data, and then model emissions using a panel data econometric model for fossil fuel emissions and a cross-sectional model for land use change emissions. This model serves as the means of predicting emissions.

### *Historical contributions of rising atmospheric carbon from fossil fuels*

These data show that the developed countries contributed more than 85 percent of the atmospheric concentrations of $CO_2$ from anthropogenic sources over the past 130 years. Contributions from the developing world were negligible until the 1930s. While China has contributed about a third of the balance, it has done so mostly during the past 30 years. The evidence suggests that, as theory would predict, the main drivers of $CO_2$ emissions are income growth and population growth. We estimate this relationship econometrically and use the resulting equation to forecast emissions as income per capita

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[1] This research was begun with support from the Office of Emerging Markets, Center for Economic Growth and Agricultural Development, Bureau for Global Programs, Field Support and Research, U.S. Agency for International Development (USAID) under the Consulting Assistance on Economic Reform (CAER) II Project (Contract PCE-C-0095-00015-00, Task Order no. 26). It was completed with support from the AVINA Foundation. The views and interpretations in this paper are those of the authors and should not be attributed to USAID. We thank participants in the HIID Climate Change and Development Workshop and at seminars at USAID, the Kennedy School of Government, and Stanford University. We are particularly grateful to Orest Koropecky and David Hales of USAID, Roy Darwin of the US Department of Agriculture, Martin Weitzman, and Larry Goulder for their careful reading and insightful comments. All remaining errors are the responsibility of the authors.

changes.

Our findings suggest an inverted U-relationship between income per capita and $CO_2$ emissions per capita. As income increases from very low levels, emissions increase at an increasing rate; they reach a plateau at an intermediate level of income beyond which additional increases in comes result in smaller additions to $CO_2$ emissions until they turn negative. This is significant since it suggests that $CO_2$ emissions will not continue growing linearly with income but will slow down, level off, and even decline once a certain level of economic development is attained. The intuition for this finding is discussed in detail in the companion paper.

### *Historical contributions of rising atmospheric carbon from land use changes*

The burning of fossil fuels for energy is the main but not the only source of $CO_2$ emissions. Land use changes, mainly in the form of deforestation and forest land conversion to other uses contribute currently about 20 percent of the global $CO_2$ emissions from anthropogenic sources. In contrast, land use change was the dominant source of $CO_2$ emission during the mid-1800s. Another important change is the geographical shift of the sources of emissions from land use change: in the nineteenth century deforestation, and therefore $CO_2$ emissions from land use change, was nearly twice as high in the temperate countries of the developed world as in the rest of the world. Today, the tropics are responsible for almost all land use change emissions and deforestation in concentrated in a few major countries.

In order to project $CO_2$ emissions in the future we must understand the factors behind the dramatic shift in rates of deforestation and hence forest cover between regions and over time. Unfortunately, reliable time series on deforestation and forest area are not available. Emissions at the country level are not available on an annual basis either, though World Resources Institute (1997) offers estimations of these flows for 1991, for developing countries only. We have therefore limited ourselves to cross-section analysis of 1991 emissions. We model land use change emissions as a function of population density and use the resulting equation to forecast land use change emissions.

Since this equation, and its prediction, is certain to be quite imprecise, and since the data on deforestation is so spotty, we perform a calculation to determine the upper limit on the error that we introduce into our forecast of total emissions. While it is certainly not a policy prescription, we estimate what the total carbon stock would be if the entire tropical forest were cut down, at a linear rate, by 2050. We estimate the additional stock *above the 1990 level* to be approximately 85 GtC under this worst case scenario, a number small enough that it would not alter significantly our predictions regarding temperature increase. While the loss of the forest would be disastrous for many reasons, it would not significantly affect the stock of atmospheric $CO_2$ as of the middle of the next century.

### *Projections of $CO_2$ emissions to 2050*

Having explained historical emissions, we use the econometric estimates to project emissions and concentrations to 2050 and to calculate baseline flows and stocks. In projecting $CO_2$ emissions from fossil fuels, we use the equation discussed above. For population, we use the UN population projections and for income we construct our own projections based on a convergence equation. We forecast that U.S. emissions decline steadily from 1.4 billion tons of C in 1990 to 0.85 by 2050. Chinese emissions increase from 0.92 billion tons to 1.79 in the same period. Globally, emissions increase from 6.18 in 1990 to 7.01 billion tons of carbon equivalent in 2050. As discussed in the companion paper to this empirical discussion, the use of an inverted "U-shaped" relationship between income and emissions is an important difference between our predictions and that used in other work.

$CO_2$ emissions from land use sources are projected to the year 2050 using a population density equation. Developed countries continue to act as a net sequesterer of carbon through reforestation at the rate of about 200 million tons a year while the rest of the world reduces its emissions from land use change from about 1.5 billion tons in 1990 to less than 1 billion tons annually by 2050.

### *Some empirical evidence on damages from climate change*

We did not carry out any original research in this paper regarding the damages from rising GHG concentrations. Our findings, therefore, rely on the literature, specifically Nordhaus (1998). Nordhaus posits, then calibrates a damage function that is quadratic in temperature, making separate calibrations for major sub-regions of the world economy. He also distinguishes between non-catastrophic and catastrophic impacts, where the latter are measured as "insurance premiums" on the avoidance of catastrophic outcomes. Among the non-catastrophic damages, Nordhaus includes estimates of the costs of climate change on health, amenities (e.g. recreation), coastal flooding, and agricultural productivity. Our estimates of the stock of $CO_2$ in 2050 imply a 1.3 C degree increase in global mean temperature over 1990 levels and we apply his damage equation accordingly. There is a great deal of uncertainty surrounding these calculations.

We find that the U.S. economy is essentially unaffected by global warming, with a loss of just 0.05% of its own GDP. China is actually a beneficiary, because of presumed *improvements* in crop productivity as a result of temperature change. Europe is moderately affected, losing 1.54% of its own GDP, mainly because of the presumed coast of sea level rising to coastal environments in Western Europe. The big losers, clearly, are the poorer countries, which generally experience major losses from agriculture, health, and rising sea levels. Africa, already the world's poorest region, is estimated to lose 3.75% of its own GDP, and India is estimated to lose 3.35% of its own GDP.

Using the information regarding regional impacts (and assuming no catastrophic events which currently seem highly unlikely to occur at temperature increases below 2.5 degrees C) we obtain an estimate of the likely contributions of each region to the global damages and their share of these damages. The balance between the two will provide an indication of the direction of compensation flows that are explained in detail in the theoretical companion paper. Most of Annex 1 and China are seen to contribute significantly to the global damages, while they suffer very little or even benefit. India and Africa suffer a much bigger share of the damages than their contributions to the problem, and thus would receive compensation.

*Policy implications*

We stress the following policy implications as a result of the empirical discussion in this paper. (1) Developing countries are likely to increase significantly the rate of GHG emissions, and the proportion of atmospheric GHG stocks for which they are responsible while developed countries are in the process of stabilizing or even reducing their levels of GHG emissions in the future. (2) The stock of GHG emissions due to land use changes (especially deforestation) are unlikely to be highly significant for climate change in the long term. (3) For non-catastrophic damages (i.e., damages that are a continuous function of $CO_2$ concentrations), it appears that the brunt of the damages are borne by the tropical countries, while temperate countries are not significantly affected. This implies that compensation should flow from rich to poor countries and from temperate to tropical countries. (4) The level of uncertainty associated with the estimation of damages is so high that much more work is needed, on a high priority basis, to assess possible damages, and thereby to calibrate better the appropriate levels of societal response.

## II. Introduction

The global control of anthropogenic climate change will require a complex cooperative effort among a large number of individual nations. This cooperative effort will have to be based on a thorough understanding of how the various participating nations contribute to the process of global climate change, and how they are affected by that process. On both dimensions—contributions to climate change and effects from climate change—there are huge uncertainties. The scientific understanding of climate change is itself at a very early stage. While the basic fact of the potential for anthropogenic climate change as a result of greenhouse gas (GHG) emissions is generally accepted, there are large disagreements among scientists about the sensitivity of average global temperature to changes in atmospheric GHG concentrations. Moreover, there are even larger unknowns about how individual countries and. regions might be affected by global climate changes, since the implications of rising global mean temperature for local climate patterns (including temperature, precipitation, storm patterns) and for material well-being (agricultural production, public health, physical comfort) are poorly understood. Finally, there are important quantitative uncertainties about how countries have contributed in the past to changes in stocks of GHGs, and how they are likely to contribute in the future.

This paper aims to advance our understanding of several dimensions of this complicated problem. First, we use historical data and econometric evidence to assess the contributions of individual regions to the evolution of atmospheric concentrations of the main GHG, carbon dioxide ($CO_2$), on a historical basis and on a prospective basis to the year 2050 assuming a “business as usual” scenario. Second, we use Nordhaus’ (1998) estimates of regional damage functions to assess how various regions would be affected by global climate change according to these projections. Using these estimates, we then measure the proportionate contribution of each region to the overall rise in atmospheric carbon and the share of each region in the global damages resulting from rising carbon concentrations.

Our main conclusion can be put simply. For the temperate-zone economies, the contribution to rising carbon concentrations is much larger than the share of global damages, while the reverse is true for the tropics. In effect, the temperate-zone economies are likely to impose severe net costs on the tropical regions. Since the temperate-zone economies tend to be rich, and the tropical-zone economies tend to be poor, global climate change represents a burden imposed on the poorer countries by the richer countries (this point was stressed earlier by Schelling (1992), but without detailed quantitative estimates). Equitable solutions to the control of global climate change should take this inter-regional pattern into account.

We must stress again, however, that both the projections of carbon concentrations and their effects on individual regions are fraught with large uncertainties. The tracking of global carbon concentrations in the atmosphere is itself subject to scientific unknowns. When scientists have attempted to track the global carbon cycle by measuring emissions of carbon into the atmosphere and the re-absorption of carbon in various natural "sinks" (especially oceans and forests), there has been a large amount of "missing carbon." By this we mean that atmospheric carbon concentrations are considerably below what would be expected given the observed emissions of carbon into the atmosphere. (Fan et al 1998)

There is at least as much uncertainty concerning the possible damages from a given change in carbon concentrations. Global climate models do not have enough resolution at the regional scale to assess the effects of global climate change on local patterns of rainfall, temperature, cloud cover, and storm patterns. Furthermore, even if these things were known, their costs (or benefits) for human society would be extremely difficult to assess. Some aspects of rising carbon concentrations may provide net benefits to society. For example, higher atmospheric carbon concentrations may help to fertilize crops in some regions. Rising temperatures may also extend growing seasons in some regions. In other parts of the world, however, the carbon fertilization effect may be small or non-existent, and higher temperatures may directly damage crop productivity. All of these costs and benefits will depend on the evolution of future technologies (e.g. the development of new crop varieties that are adapted to changing climatic conditions). Nordhaus' damage functions are heroic attempts to estimate the balance of these effects. They are very valuable as a first try, but they are undoubtedly very crude.

We proceed as follows: Section III presents empirical evidence on past trends of GHG emissions, both from fossil fuels and land use change (i.e., deforestation). Using the historical data, we develop econometric estimates to model emissions. In Section IV these estimates are used to make baseline forecasts for future emissions. Section V reviews some of the evidence, incomplete as it is, about the relevant damages from climate change, again disaggregated among the developed and developing countries. Section VI offers some concluding observations.

## III. Empirical evidence on GHG emissions

In this section, we introduce some scientific background and review the historical contributions from rising atmospheric carbon, first from fossil fuels and then from land use on an annual basis from 1860 to the 1990s. Time series are available for emissions on a country basis for fossil fuel emissions and on a regional basis for land use change emissions. We summarize this data, and then model emissions using a panel data econometric model for fossil fuel emissions and a cross-sectional model for land use change emissions. This model serves as the means of predicting emissions, as explained in sections IV and V.

*Scientific background*

The main sources of anthropogenic $CO_2$ emissions are energy use and land use change, particularly deforestation. In 1996, emissions from fossil fuel use totaled 6.18 billion tons of carbon (Marland et al 1999). Emissions from land use change in the tropical world—including non-replacement timber harvesting, shifting and sedentary agriculture, and cattle ranching—have been estimated to be 1.6 billion tons in 1990 (Houghton and Hackler 1995). There is a great deal more uncertainty surrounding the measurement of emissions from land use relative to fossil fuels, and even greater uncertainty regarding other sources of $CO_2$. Other greenhouse gases contribute to global warming besides $CO_2$, including $N_2O$ and $CH_4$, but these emissions and their contributions are poorly understood. Chlorofluorocarbons (CFCs) may also contribute to global warming but their emissions have largely been controlled and are no longer considered a significant source of concern. Because of the uncertainty surrounding non-$CO_2$ sources of global warming, as well as data limitations, we limit our analysis to $CO_2$ related to fossil fuels and $CO_2$ emissions from land use change.[2] Table 1 offers a summary of the data available for our study.

**Table 1. Summary of data used in econometric analysis.**

| Data Available | Annex I | Non-Annex I | Temperate | Non-Temperate | World |
|---|---|---|---|---|---|
| YEARS | | | | | |
| Carbon Emissions from Fossil Fuels (annual) | 1960-92 | 1960-92 | 1960-92 | 1960-92 | 1960-92 |
| Carbon Emissions from Land Use Change | 1991 | 1991 | 1991 | 1991 | 1991 |
| | | | | | |
| COUNTRIES | | | | | |
| General Information (Population, GDP, etc.) | 33 | 97 | 43 | 87 | 130 |
| Carbon Emissions from Fuel Combustion | 42 | 113 | 65 | 90 | 155 |
| Carbon Emissions for Land Use Change | 30 | 91 | 42 | 79 | 121 |
| | | | | | |
| OBSERVATIONS | | | | | |
| Fossil Fuel Combustion Regressions (No Price) | 1102 | 3749 | 1630 | 3221 | 4851 |

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[2] This reasoning follows Nordhaus (1998) who limits his analysis to industrial $CO_2$ only, and assumes a constant exogenous level of emissions from land use change.

| | | | | | |
|---|---|---|---|---|---|
| Fossil Fuel Combustion Regressions (With Price) | 344 | 458 | 423 | 379 | 802 |
| Land Use Change Regressions (Cross Section) | 30 | 91 | 42 | 79 | 121 |

To model the process by which emissions are translated into atmospheric $CO_2$ concentrations, we follow Nordhaus (1998) closely. A system of equations (1-3) describes the "mixing" process by which the global stock of $CO_2$ cycles between the atmosphere ($M_{AT}(t)$), the upper reservoirs ($M_{UP}(t)$) and the deep oceans ($M_{LO}(t)$), where Em(t) is emissions at time t. At any point in time, atmospheric concentrations above the pre-industrial level of $M_{AT}$* (approximately 590 GtC) lead to increased global surface warming through increased radiative forcing F(t) (equation 4). Finally, equations 5 and 6 model the process by which increased radiative forcings lead to temperature increases of the global surface and upper oceans ($T_{UP}(t)$) and the lower oceans ($T_{LO}(t)$) with lags resulting from thermal inertia.[3] These equations are as follows:

(1) $M_{AT}(t) = Em(t) + c_{11} M_{AT}(t-1) + c_{21} M_{UP}(t-1)$.

(2) $M_{UP}(t) = c_{22} M_{UP}(t-1) + c_{12} M_{AT}(t-1) + c_{32} M_{LO}(t-1)$.

(3) $M_{LO}(t) = c_{33} M_{LO}(t-1) + c_{23} M_{UP}(t-1)$.

(4) $F(t) = n\{\ln[M_{AT}(t) / M_{AT}^*]/\ln(2)\} + \text{Other Gas}(t)$

(5) $T_{UP}(t) = T_{UP}(t-1) + s_1\{F(t) - \lambda\, T_{UP}(t-1) - s_2[T_{UP}(t-1) - T_{LO}(t-1) - T_{LO}(t-1)]\}$.

(6) $T_{LO}(t) = T_{LO}(t-1) + s_3[T_{UP}(t-1) - T_{LO}(t-1)]$.

Ultimately, damages result from the level of $T_{UP}$ at any time t. To model these damages, we use the quadratic specification developed by Nordhaus (1998b). He posits a relationship between $T_{UP}(t)$ and income loss of the form

(7) $DJ(t) = \theta_{1,j}\, T_{UP}(t) + \theta_{3j}\, T_{UP}(t)^2$,

where $\theta_{i,j}$ is a region-specific parameter reflecting differential impacts of climate change. The regions for which this equation has been calibrated form the units of our own analysis. These regions are: Japan, USA, European Union (EU), "Other High Income," High Income Organization of Petroleum Exporting Countries (OPEC), Middle Income Countries, Russia, Lower Middle Income Countries, Eastern Europe, Low Income Countries, China, India, and Africa.[4] This equation and its parameterization are discussed in detail in section V.

We stress that the Nordhaus system of equations concerning the carbon cycle (1-3) is fraught with considerable scientific uncertainty. There are large holes in knowledge concerning the cycling of carbon between the atmosphere, the oceans, and terrestrial biota (especially the overall biomass in forests). These equations do not solve the problem of the "missing carbon," so they do not provide a

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3 A complete discussion of these equations and the calibrations of the parameters are in Nordhaus (1998) and Nordhaus (1994).

4 A complete listing of the countries in each group is in Nordhaus (1998), or is available from the authors.

fully reliable way of translating from new emissions to long-term changes in carbon concentrations. Similar uncertainties plague the links from carbon concentrations to temperature (4-6), and from temperature to damages (7). Nonetheless, we applaud Nordhaus for constructing a workable system to analyze these issues, even as we warn ourselves against misplaced concreteness in our interpretation of the results.

*Historical contributions to rising atmospheric carbon from fossil fuels*

The Carbon Dioxide Information Analysis Center (Marland et al 1999) has estimated the global $CO_2$ emissions from fossil fuel use on a country basis beginning in 1751.[5] This data is summarized from 1860 in figure 1 and table 2. The associated stock accumulation is summarized in figure 2 and table 3. We calculated the annual stock using equations 1-3.

Non-OPEC high-income countries contributed forty-six percent of combustion emissions in 1996. Thirteen percent of total emissions came from Russia and Eastern Europe, and 15 percent came from China. Countries included in the Kyoto Protocol, the so-called Annex 1 countries of the Organization for Economic Cooperation and Development (OECD) Russia and Eastern Europe, accounted together for 59 percent of emissions. However, currently these shares are changing rapidly since emissions from Annex 1 countries are constant or falling, while emissions from developing countries (non-Annex 1) are growing at 6 to 7 percent per annum. Figure 1 shows that non-Annex 1 countries, accounting for 77 percent of the world population and only 37 percent of the world income in 1994, have been relatively insignificant contributors of $CO_2$ emissions until 1960. Although $CO_2$ emissions from countries like China began rising rapidly, it was not until 1980 that the share of non-Annex 1 in world emissions began to account for a one quarter of global emissions from fossil fuels (see figure 1).

As the emissions path suggests, more than 85 percent of the atmospheric concentrations of $CO_2$ from anthropogenic sources were contributed by the Annex 1 countries over the past 100 years. Contributions from the developed world were negligible until the 1930s. While China has contributed about a third of the balance, it has done so mostly during the past 30 years.

These historical data suggest that the main drivers of $CO_2$ emissions are income growth and population growth. Tables 4 and 5 show that with GDP growing at 6.22 percent per annum and population at 1.87 percent per annum during 1990-94, combustion emissions grew at 6.85 percent per year in developing countries. In contrast, developed (Annex 1) countries had a population growth of only 0.58 percent and GDP growth of 1.21 (or 0.86 in PPP terms) during the same period and their emissions fell by 0.64 percent (see tables 4 and 5). Indeed, developed country emissions leveled off in the early 1970s and began declining in the early 1980s, although the US and Japan (in contrast to Western Europe) had a relapse in the early 1990s (see figure 3). In per capita terms, Annex 1 countries

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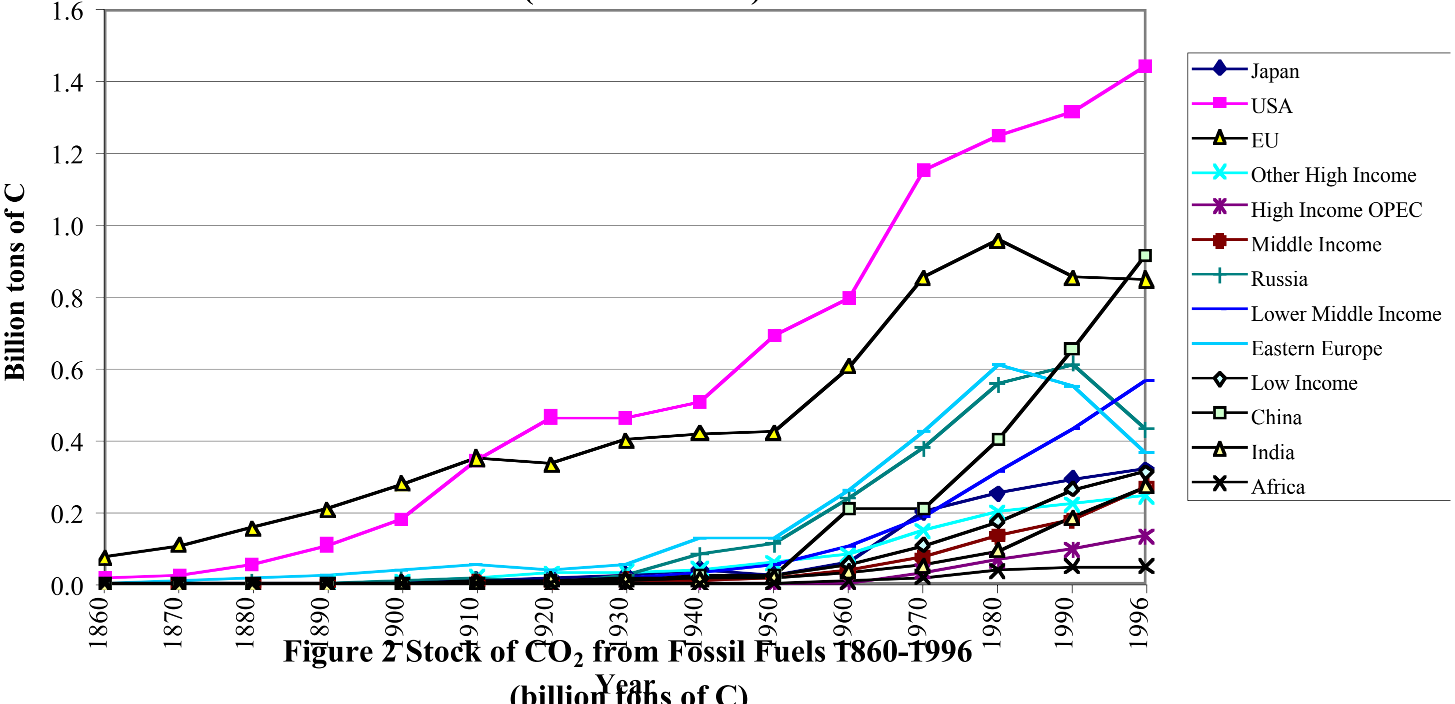
[5] As national boundaries change so do the sources of $CO_2$ for the purposes of this calculation, so the USSR is a single country and Germany is two countries until 1992. The following adjustments are also made: for 1960-72 the Ryukyu Islands are added to Japan, for 1960-69 Tanganyika and Zanzibar are combined, for 1960-79 the Panama Canal Zone is added to Panama, for 1960-69, Sabah and Sarawak are added to Malaysia, and for 1960-69 North and South Vietnam are combined.

emit more than five times as much $CO_2$ as non-Annex 1 countries (2.6 tons compared to under 0.5 tons). The disparity is even larger between low income countries, which emit 0.2 tons per person, and high income countries that emit 15 times as much per capita (see tables 6 and 7).

## Figure 1 $CO_2$ Emission Flows from Fossil Fuels 1860-1996 (billion tons of C)



## Figure 2 Stock of $CO_2$ from Fossil Fuels 1860-1996 (billion tons of C)

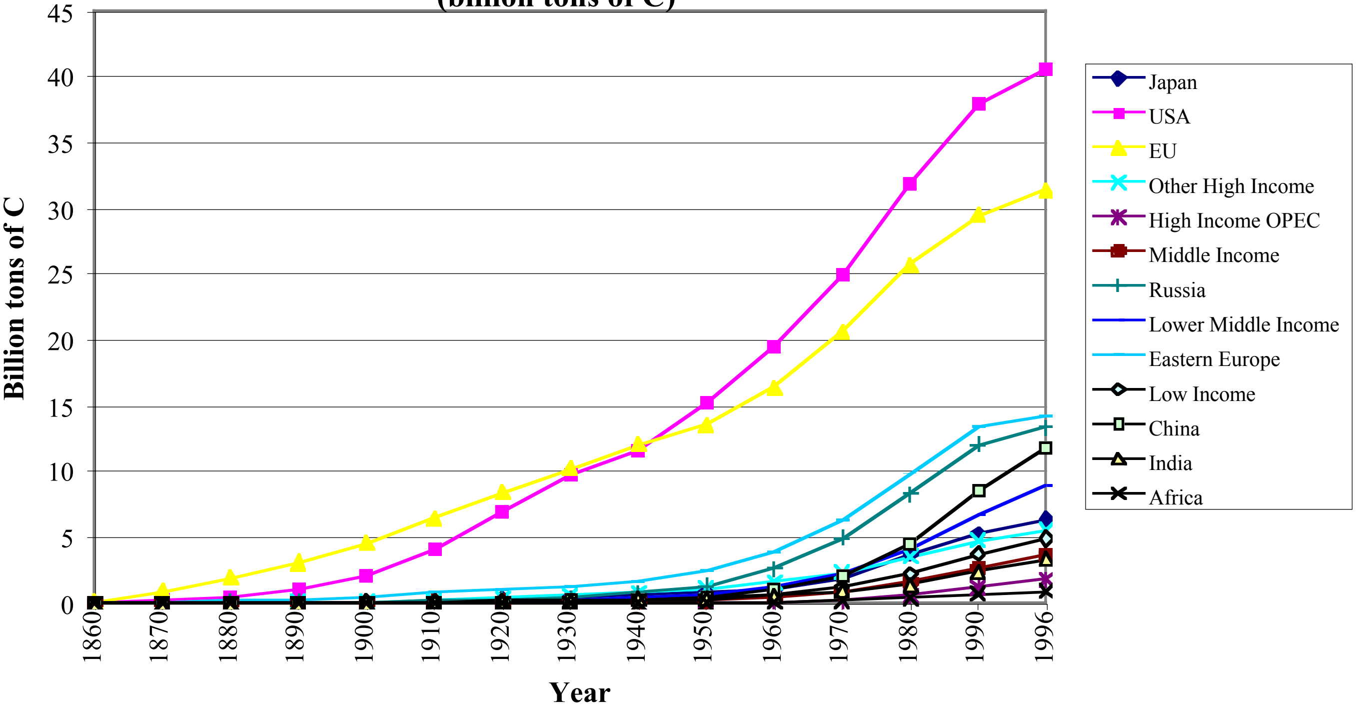


**Table 2. CO$_2$ emissions flows from fossil fuels 1860-1996 (billion tons of C).**

| Country Group | 1860 | 1870 | 1880 | 1890 | 1900 | 1910 | 1920 | 1930 | 1940 | 1950 | 1960 | 1970 | 1980 | 1990 | 1996 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Japan | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.03 | 0.04 | 0.03 | 0.06 | 0.20 | 0.25 | 0.29 | 0.32 |
| USA | 0.01 | 0.03 | 0.05 | 0.11 | 0.18 | 0.35 | 0.47 | 0.47 | 0.51 | 0.69 | 0.80 | 1.15 | 1.25 | 1.32 | 1.45 |
| EU | 0.07 | 0.11 | 0.16 | 0.21 | 0.28 | 0.35 | 0.33 | 0.40 | 0.42 | 0.42 | 0.61 | 0.86 | 0.96 | 0.85 | 0.85 |
| Other High Income | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.03 | 0.03 | 0.04 | 0.06 | 0.08 | 0.15 | 0.20 | 0.22 | 0.25 |
| High Income OPEC | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.07 | 0.10 | 0.13 |
| Middle Income | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.04 | 0.08 | 0.14 | 0.18 | 0.27 |
| Russia | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.01 | 0.02 | 0.08 | 0.11 | 0.24 | 0.38 | 0.56 | 0.61 | 0.43 |
| Lower Middle Income | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.03 | 0.05 | 0.11 | 0.19 | 0.31 | 0.44 | 0.57 |
| Eastern Europe | 0.00 | 0.01 | 0.01 | 0.02 | 0.04 | 0.05 | 0.04 | 0.05 | 0.13 | 0.13 | 0.26 | 0.42 | 0.61 | 0.55 | 0.36 |
| Low Income | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.02 | 0.05 | 0.11 | 0.18 | 0.26 | 0.31 |
| China | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.21 | 0.21 | 0.40 | 0.66 | 0.92 |
| India | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.05 | 0.09 | 0.18 | 0.27 |
| Africa | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.04 | 0.05 | 0.05 |
| TOTAL | 0.09 | 0.15 | 0.23 | 0.35 | 0.53 | 0.83 | 0.93 | 1.06 | 1.32 | 1.58 | 2.50 | 3.85 | 5.05 | 5.71 | 6.18 |

**Table 3. Stock of CO$_2$ emissions from fossil fuels 1860-1996 (billion tons of C).**

| Country Group | 1860 | 1870 | 1880 | 1890 | 1900 | 1910 | 1920 | 1930 | 1940 | 1950 | 1960 | 1970 | 1980 | 1990 | 1996 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Japan | 0.00 | 0.00 | 0.00 | 0.01 | 0.04 | 0.11 | 0.23 | 0.39 | 0.60 | 0.74 | 1.02 | 1.96 | 3.72 | 5.26 | 6.35 |
| USA | 0.01 | 0.17 | 0.48 | 1.09 | 2.09 | 4.09 | 6.86 | 9.68 | 11.67 | 15.33 | 19.41 | 25.03 | 31.96 | 37.98 | 40.55 |
| EU | 0.07 | 0.90 | 1.87 | 3.07 | 4.54 | 6.47 | 8.37 | 10.23 | 12.09 | 13.57 | 16.43 | 20.72 | 25.77 | 29.51 | 31.43 |
| Other High Income | 0.00 | 0.00 | 0.01 | 0.04 | 0.09 | 0.20 | 0.41 | 0.61 | 0.78 | 1.11 | 1.56 | 2.31 | 3.49 | 4.69 | 5.50 |
| High Income OPEC | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.04 | 0.05 | 0.20 | 0.60 | 1.17 | 1.80 |
| Middle Income | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.03 | 0.06 | 0.10 | 0.20 | 0.22 | 0.45 | 0.84 | 1.64 | 2.67 | 3.63 |
| Russia | 0.00 | 0.00 | 0.01 | 0.04 | 0.10 | 0.20 | 0.28 | 0.35 | 0.77 | 1.29 | 2.64 | 4.94 | 8.27 | 12.09 | 13.40 |
| Lower Middle Income | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.06 | 0.13 | 0.23 | 0.37 | 0.63 | 1.26 | 2.29 | 4.15 | 6.66 | 8.86 |
| Eastern Europe | 0.00 | 0.05 | 0.14 | 0.28 | 0.50 | 0.82 | 1.12 | 1.33 | 1.74 | 2.46 | 3.84 | 6.28 | 9.87 | 13.42 | 14.20 |
| Low Income | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.03 | 0.05 | 0.08 | 0.17 | 0.26 | 0.55 | 1.18 | 2.23 | 3.74 | 4.89 |
| China | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.07 | 0.13 | 0.24 | 0.35 | 1.10 | 2.10 | 4.57 | 8.44 | 11.80 |
| India | 0.00 | 0.00 | 0.00 | 0.01 | 0.03 | 0.07 | 0.15 | 0.23 | 0.31 | 0.40 | 0.56 | 0.87 | 1.37 | 2.38 | 3.37 |
| Africa | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.03 | 0.08 | 0.18 | 0.42 | 0.69 | 0.89 |
| TOTAL | 0.09 | 1.13 | 2.52 | 4.55 | 7.43 | 12.12 | 17.74 | 23.37 | 28.94 | 36.46 | 48.96 | 68.88 | 98.06 | 128.70 | 146.68 |

**Table 4. Annex 1 and Non-Annex 1 countries summary information.**

| **Per unit GDP 1994** | **Annex 1 (36 countries)** | **Non-Annex 1 (130 countries)** | **Total World Sample (166 countries)** |
|---|---|---|---|
| Combustion emissions (metric tons C per millions of 1987 PPP $) | 228 | 229 | 228 |
| Land use change emissions (metric tons C per millions of 1987 PPP $) | -9 | 180 | 100 |
| Total Antropogenic emissions (metric tons C per millions of 1987 PPP $) | 162 | 405 | 303 |
| | | | |
| **World Shares 1994 (%)** | **Annex 1 (42 countries)** | **Non-Annex 1 (113 countries)** | **Total World Sample (155 countries)** |
| Population | 23.36 | 76.64 | 100.00 |
| PPP GDP | 62.95 | 37.05 | 100.00 |
| Real GDP | 81.60 | 18.40 | 100.00 |
| Combustion emissions | 62.76 | 37.24 | 100.00 |
| Land-use change emissions | -3.59 | 103.59 | 100.00 |
| Total anthropogenic CO2 emissions | 49.22 | 50.78 | 100.00 |
| | | | |
| **Annual Growth Rates 1990-1994 (%)** | **Annex 1 (42 countries)** | **Non-Annex 1 (113 countries)** | **Total World Sample (155 countries)** |
| Population | 0.58 | 1.87 | 1.55 |
| PPP GDP | 0.86 | 6.22 | 2.62 |
| Real GDP | 1.21 | 5.02 | 1.84 |
| Combustion emissions | -0.64 | 6.85 | 1.70 |

**Table 5. Annex 1 and Non-Annex 1 countries summary information.**

| **World Totals 1994** | **Annex 1 (42 countries)** | **Non-Annex 1 (113 countries)** | **Total World Sample (155 countries)** |
|---|---|---|---|
| Population (billion) | 1.27 | 4.17 | 5.43 |
| PPP GDP (trillion 87 int'l $) | 14.64 | 8.62 | 23.26 |
| Real GDP (trillion 87 us$) | 14.47 | 3.26 | 17.74 |
| Combustion emissions (billion metric tons C) | 3.33 | 1.97 | 5.30 |
| Land-use change emissions (billion metric tons C) | -0.05 | 1.41 | 1.36 |
| Total anthropogenic $CO_2$ emissions (billion metric tons C) | 3.28 | 3.38 | 6.66 |
| Share of total emissions due to land use change (%) | -1.49 | 41.64 | 20.41 |
| | | | |
| **Per Capita 1994** | **Annex 1 (42 countries)** | **Non-Annex 1 (113 countries)** | **Total World Sample (155 countries)** |
| PPP GDP (87 int'l$/capita) | 11531 | 2069 | 4279 |
| Real GDP (87 $us/capita) | 11399 | 784 | 3263 |
| Combustion emissions (metric tons C/capita) | 2.62 | 0.47 | 0.98 |
| Land use change emissions (metric tons C/capita) | -0.04 | 0.34 | 0.25 |
| Total Anthropogenic emissions (metric tons C/capita) | 2.58 | 0.81 | 1.23 |

**Table 6. Low, middle, and high income countries summary information.**

| **Per unit GDP 1994** | **Low income** | **Middle Income** | **High Income** | **World** |
|---|---|---|---|---|
| Combustion emissions (metric tons C per millions of 1987 PPP $) | 206 | 234 | 141 | 228 |
| Land use change emissions (metric tons C per millions of 1987 PPP $) | 255 | 131 | -20 | 100 |
| Total Antropogenic emissions (metric tons C per millions of 1987 PPP $) | 454 | 389 | 196 | 303 |
| | | | | |
| **World Shares 1994 (%)** | **Low income** | **Middle Income** | **High Income** | **World** |
| Population | 33.33 | 51.07 | 15.59 | 100.00 |
| PPP GDP | 7.38 | 37.07 | 55.54 | 100.00 |
| Real GDP | 4.11 | 18.39 | 77.50 | 100.00 |
| Combustion emissions | 6.78 | 44.03 | 49.18 | 100.00 |
| Land-use change emissions | 30.91 | 75.14 | -6.05 | 100.00 |
| Total anthropogenic CO2 emissions | 11.71 | 50.38 | 37.91 | 100.00 |
| | | | | |
| **Annual Growth Rates 1990-1994 (%)** | **Low income** | **Middle Income** | **High Income** | **World** |
| Population | 2.20 | 1.46 | 0.76 | 1.55 |
| PPP GDP | 3.95 | 5.38 | 1.74 | 2.62 |
| Real GDP | 3.87 | 3.79 | 1.76 | 1.84 |
| Combustion emissions | 5.94 | 5.01 | 1.51 | 1.70 |

**Table 7. Low, middle, and high income countries summary information.**

| **World Totals 1994** | **Low income** | **Middle Income** | **High Income** | **World** |
|---|---|---|---|---|
| Population (billion) | 1.81 | 2.78 | 0.85 | 5.43 |
| PPP GDP (trillion 87 int'l $) | 1.72 | 8.62 | 12.91 | 23.25 |
| Real GDP (trillion 87 us$) | 0.73 | 3.26 | 13.75 | 17.74 |
| Combustion emissions (billion metric tons C) | 0.36 | 2.33 | 2.61 | 5.30 |
| Land-use change emissions (billion metric tons C) | 0.42 | 1.02 | -0.08 | 1.36 |
| Total anthropogenic $CO_2$ emissions (billion metric tons C) | 0.78 | 3.36 | 2.52 | 6.66 |
| Share of total emissions due to land use change (%) | 53.89 | 30.44 | -3.26 | 20.41 |
| | | | | |
| **Per Capita 1994** | **Low income** | **Middle Income** | **High Income** | **World** |
| PPP GDP (87 int'l$/capita) | 948 | 3105 | 15239 | 4278 |
| Real GDP (87 $us/capita) | 402 | 1175 | 16221 | 3263 |
| Combustion emissions (metric tons C/capita) | 0.20 | 0.84 | 3.08 | 0.98 |
| Land use change emissions (metric tons C/capita) | 0.23 | 0.37 | -0.10 | 0.25 |
| Total Anthropogenic emissions (metric tons C/capita) | 0.43 | 1.21 | 2.98 | 1.23 |

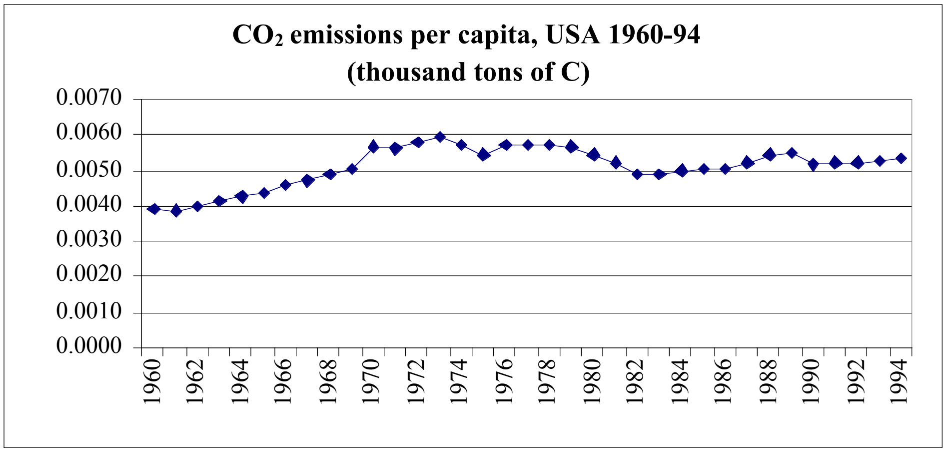
Among low income countries, particular “offenders” are often singled out as critical to the path of global emissions (see, for example Sathaye et al 1996). These include China, India, Brazil, Indonesia, Mexico, and South Africa. These are countries that have experienced high economic growth or that are regional leaders. Tables 8 and 9 report the emissions data for these countries as well as their basic summary statistics. It is not surprising that these relatively dynamic economies have high emissions but, as will be discussed below, this is a comparatively recent phenomenon.

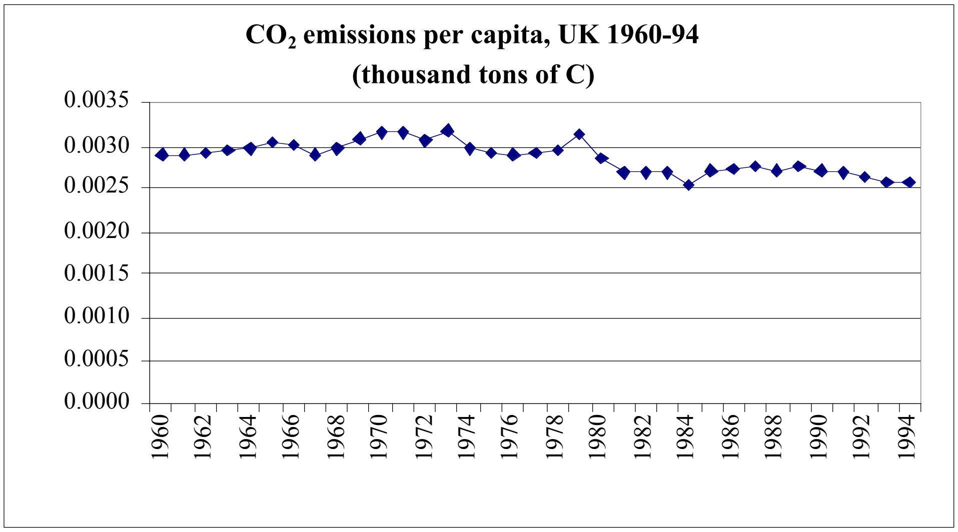
If the main determinants of $CO_2$ emissions are income and population growth, another relevant consideration is the emissions intensity of the economy. When expressed in terms of $CO_2$ emissions per unit of GDP, emissions intensity is almost three times as high in non-Annex 1 countries than in Annex 1 countries (see tables 4 and 5). However, when adjustments are made for differences in purchasing power parity (PPP, e.g. one dollar buys 2-3 times as much in China than in the US), energy intensity is strikingly identical—230 metric tons of $CO_2$ per million dollars of PPP GDP. This should surprise anyone who is familiar with the obsolete and patently inefficient power stations and vehicles in China, India, and Africa. At least three factors may help explain this paradox. First, the Annex 1 emissions are inflated by the inclusion of Eastern Europe and Russia. Second, the non-Annex 1 income is inflated by the inclusion of relatively wealthy oil producers (Saudi Arabia, Kuwait, and other Gulf states). When we group countries in low income, middle income and high income economies as defined by the World Bank, we observe an inverted U-shape relationship between income and emissions. In 1994, emissions were 206 tons per million dollars of PPP GDP for low income countries, 234 tons for middle income countries and 14 tons for high income countries (see table 6).

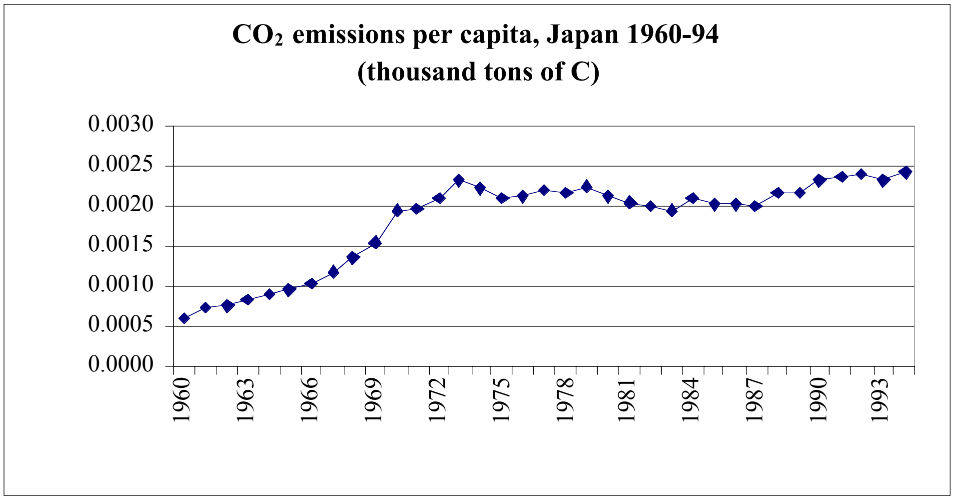
Another factor that may play a role in determining a country’s annual emissions is the different heating needs between temperate and snow-ice climates on the one hand and tropical and subtropical climates on the other. Since almost all Annex 1 countries are temperate and most developing countries are in the tropics or subtropics, the latter ought to have lower heating needs and therefore lower energy use per unit of GDP than countries in temperate and snow-ice environments. For example, when we classify countries by climate, we find that temperate countries emit 238 tons per million dollars of PPP GDP and non-temperate countries emit 196 (see tables 10 and 11). Therefore, equality of emissions intensity of Annex 1 does not necessarily imply equal energy efficiency in the production of GDP. Rather, much of this energy is being used for heating.

In summary, a review of the historical data regarding $CO_2$ emissions from fossil fuel usage suggests that while the developed world is disproportionately responsible for the current stock, the role of the developing world is increasing. The particular prominence of China is also notable. Sorting the current emissions by income and geographic distinctions suggests that income, population, and climatic zone may be the main determinants of a country’s emissions over time. We test this proposition below. We find that this hypothesis is largely confirmed, and use the econometric equation developed as the basis for projecting emissions from fossil fuels from 1996-2050 in the next section.

**Figure 3 $CO_2$ emissions per capita in selected countries.**







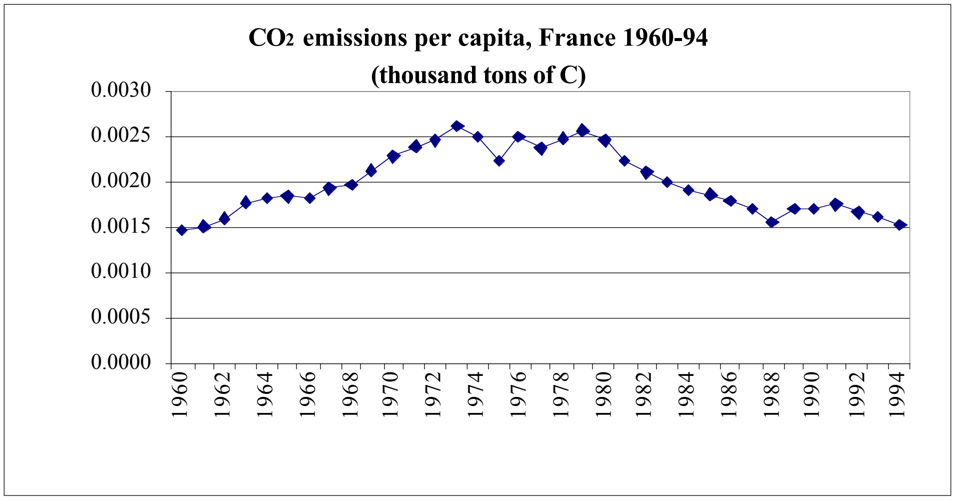
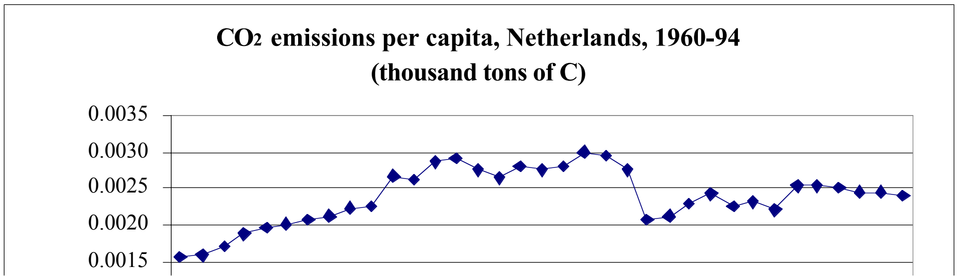
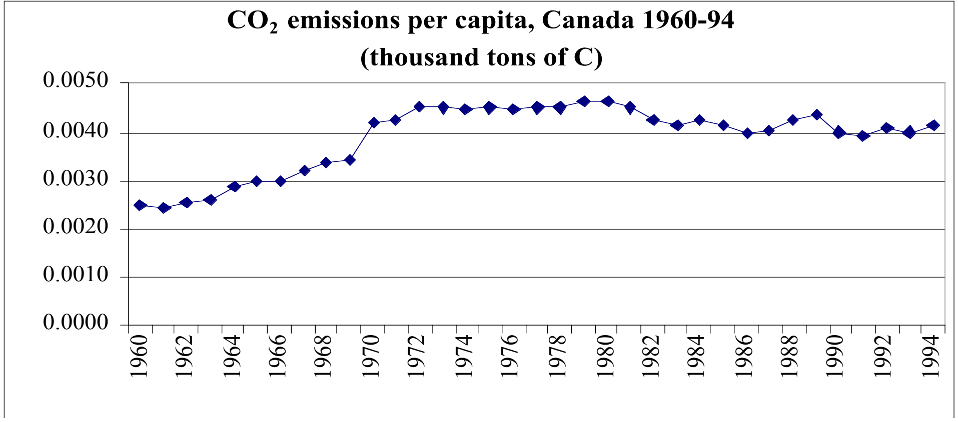


**Figure 3 $CO_2$ emissions per capita in selected countries (continued).**

**Table 8. Key countries summary information.**

| **Per unit GDP 1994** | **Brazil** | **China** | **India** | **Indonesia** | **Mexico** | **South Africa** |
|---|---|---|---|---|---|---|
| Combustion emissions (metric tons C per millions of 1987 PPP $) | 91 | 327 | 236 | 151 | 172 | 419 |
| Land use change emissions (metric tons C per millions of 1987 PPP $) | 452 | -5 | -7 | 305 | 116 | -6 |
| Total Antropogenic emissions (metric tons C per millions of 1987 PPP $) | 543 | 322 | 228 | 456 | 288 | 413 |





| **World Shares 1994 (%)** | **Brazil** | **China** | **India** | **Indonesia** | **Mexico** | **South Africa** |
|---|---|---|---|---|---|---|
| Population | 2.89 | 21.91 | 16.81 | 3.50 | 1.66 | 0.75 |
| PPP GDP | 3.05 | 10.88 | 4.32 | 1.91 | 2.44 | 0.88 |
| Real GDP | 1.79 | 2.94 | 2.10 | 0.73 | 0.96 | 0.49 |
| Combustion emissions | 1.22 | 15.63 | 4.46 | 1.26 | 1.84 | 1.61 |
| Land-use change emissions | 23.62 | -0.96 | -0.52 | 9.96 | 4.83 | -0.09 |
| Total anthropogenic CO2 emissions | 5.79 | 12.24 | 3.44 | 3.04 | 2.45 | 1.26 |
| | | | | | | |
| **Annual Growth Rates 1990-1994 (%)** | **Brazil** | **China** | **India** | **Indonesia** | **Mexico** | **South Africa** |
| Population | 1.54 | 1.23 | 1.89 | 1.71 | 2.01 | 2.34 |
| PPP GDP | 0.21 | 15.48 | 5.09 | 8.61 | 3.64 | 0.20 |
| Real GDP | 2.45 | 15.36 | 4.23 | 8.63 | 2.77 | 0.00 |
| Combustion emissions | 4.84 | 7.44 | 6.82 | 3.76 | 3.54 | 1.64 |

### Table 9. Key countries summary information.

| Country Totals 1994 | Brazil | China | India | Indonesia | Mexico | South Africa |
|---|---|---|---|---|---|---|
| Population (billion) | 0.16 | 1.19 | 0.91 | 0.19 | 0.09 | 0.04 |
| PPP GDP (trillion 87 int'l $) | 0.71 | 2.53 | 1.00 | 0.44 | 0.57 | 0.20 |
| Real GDP (trillion 87 us$) | 0.32 | 0.52 | 0.37 | 0.13 | 0.17 | 0.09 |
| Combustion emissions (billion metric tons C) | 0.06 | 0.83 | 0.24 | 0.07 | 0.10 | 0.09 |
| Land-use change emissions (billion metric tons C) | 0.32 | -0.01 | -0.01 | 0.14 | 0.07 | 0.00 |
| Total anthropogenic $CO_2$ emissions (billion metric tons C) | 0.39 | 0.82 | 0.23 | 0.20 | 0.16 | 0.08 |
| Share of total emissions due to land use change (%) | 83.29 | -1.60 | -3.08 | 66.91 | 40.19 | -1.49 |
| | | | | | | |
| **Per Capita 1994** | **Brazil** | **China** | **India** | **Indonesia** | **Mexico** | **South Africa** |
| PPP GDP (87 int'l$/capita) | 4520 | 2124 | 1099 | 2332 | 6293 | 5030 |
| Real GDP (87 $us/capita) | 2019 | 438 | 407 | 676 | 1891 | 2141 |
| Combustion emissions (metric tons C/capita) | 0.41 | 0.70 | 0.26 | 0.35 | 1.08 | 2.11 |
| Land use change emissions (metric tons C/capita) | 2.04 | -0.01 | -0.01 | 0.71 | 0.73 | -0.03 |
| Total Anthropogenic emissions (metric tons C/capita) | 2.45 | 0.68 | 0.25 | 1.06 | 1.81 | 2.08 |

**Table 10. Temperate and tropical countries summary information.**

| **Per unit GDP 1994** | **Temperate (65 countries)** | **Non Temperate (90 countries)** | **Total World Sample (155 countries)** |
|---|---|---|---|
| Combustion emissions (metric tons C per millions of 1987 PPP $) | 238 | 196 | 228 |
| Land use change emissions (metric tons C per millions of 1987 PPP $) | 6 | 276 | 100 |
| Total Antropogenic emissions (metric tons C per millions of 1987 PPP $) | 218 | 462 | 303 |
| | | | |
| **World Shares 1994 (%)** | **Temperate (65 countries)** | **Non Temperate (90 countries)** | **Total World Sample (155 countries)** |
| Population | 48.82 | 51.18 | 100.00 |
| PPP GDP | 76.38 | 23.62 | 100.00 |
| Real GDP | 86.00 | 14.00 | 100.00 |
| Combustion emissions | 79.69 | 20.31 | 100.00 |
| Land-use change emissions | 3.76 | 96.24 | 100.00 |
| Total anthropogenic CO2 emissions | 64.19 | 35.81 | 100.00 |
| | | | |
| **Annual Growth Rates 1990-1994 (%)** | **Temperate (65 countries)** | **Non Temperate (90 countries)** | **Total World Sample (155 countries)** |
| Population | 0.94 | 2.17 | 1.55 |
| PPP GDP | 2.32 | 3.63 | 2.62 |
| Real GDP | 1.57 | 3.61 | 1.84 |
| Combustion emissions | 0.68 | 6.62 | 1.70 |

**Table 11. Temperate and tropical countries summary information.**

| **World Totals 1994** | **Temperate (65 countries)** | **Non Temperate (90 countries)** | **Total World Sample (155 countries)** |
|---|---|---|---|
| Population (billion) | 2.65 | 2.78 | 5.43 |
| PPP GDP (trillion 87 int'l $) | 17.76 | 5.49 | 23.25 |
| Real GDP (trillion 87 us$) | 15.25 | 2.48 | 17.74 |
| Combustion emissions (billion metric tons C) | 4.22 | 1.08 | 5.30 |
| Land-use change emissions (billion metric tons C) | 0.05 | 1.31 | 1.36 |
| Total anthropogenic $CO_2$ emissions (billion metric tons C) | 4.28 | 2.38 | 6.66 |
| Share of total emissions due to land use change (%) | 1.20 | 54.86 | 20.41 |
| | | | |
| **Per Capita 1994** | **Temperate (65 countries)** | **Non Temperate (90 countries)** | **Total World Sample (155 countries)** |
| PPP GDP (87 int'l$/capita) | 6693 | 1974 | 4278 |
| Real GDP (87 $us/capita) | 5749 | 893 | 3263 |
| Combustion emissions (metric tons C/capita) | 1.59 | 0.39 | 0.98 |
| Land use change emissions (metric tons C/capita) | 0.02 | 0.47 | 0.25 |
| Total Anthropogenic emissions (metric tons C/capita) | 1.61 | 0.86 | 1.23 |

*Fossil fuel emissions model*

Here we attempt to estimate a simple relationship between per capita $CO_2$ emissions (c), expressed as thousands of metric tons of carbon, and per capita income (y), expressed as 1985 PPP dollars. Both variables are expressed in logarithms:

(8) $\ln(c_{it}) = a_i + \beta_t + F[\ln(y_{it})] + \varepsilon_{it}$.

The index *i* refers to countries and *t* refers to time in years. The set of parameters $a_i$ reflects country-fixed effects, that is, persistent differences across countries in climatic conditions, fossil fuels, and renewable energy endowments, in preferences, in economic structure, in regulations, and the like. The set of parameters $\beta_t$ reflect changes over time such as changes in world oil prices, in technologies, and in environmental policies as well as in preferences unrelated to income levels. The *F(•)* is a flexible functional form in *y*. Following Schmalensee, Stoker, and Judson (1998), we employ a piecewise linear spline function, which allows for distinct elasticities of emissions with respect to output in each segment of the spline function. A log-linear specification was chosen because country and time-fixed effects are more likely to be multiplicative than additive and also because tests performed in previous studies (Holtz-Eakin and Selden 1995) found no significant differences between linear and log-linear specifications. The last term in equation 8 is a stochastic error term that must be uncorrelated with the independent variables for ordinary least squares or “random effects” panel data estimation to produce consistent parameter estimates.

We test the hypothesis that income, population, and climate zone are the primary determinants of country’s emissions in the following manner: In step 1 we estimate equation 8 econometrically. To do this we use dummy variables for (T-1) of the years for which data is available. This so-called “least-squares dummy variable” (LSDV) estimation has the effect of controlling for year-specific effects that are unmeasured or unobservable. We then estimate the equation assuming that the error term is independent of the independent variables and assuming that it is correlated with them. A Hausman test confirms that the fixed effects model, which allows $E(x_{it}\varepsilon_{it})$ to differ from zero, is in fact correct (Hausman 1978, Hausman and Taylor 1981). These regressions and the specification test are reported in tables 12-14.

A brief discussion of the use of the fixed effects regression is needed to explain the possibilities for testing our hypothesis. The LSDV technique can be followed for the country-specific effects. “Within” regression, which is equivalent to using (N-1) country indicator variables, would control for time-invariant country effects, which are not included as independent variables. This would ensure that the coefficients on time variant variables such as income are consistent, provided the model is correctly specified. However, the shortcoming of this specification is that no coefficients on time-invariant variables can be determined. This is problematic if the variables of interest are unchanging over time, as climate zone is. To estimate the coefficients on variables such as climate zone two options are available. These are (1) a random effects model, appropriate only if $E(x_{it}\varepsilon_{it}) = 0$, meaning that the unobserved variables are not correlated with income, and (2) the use of instrumental variables to control for such correlation. A necessary condition for this second possibility is that the equation must have at least as many exogenous time-varying variables as there are endogenous time-invariant variables (Hausman and Taylor, 1981).

Unfortunately, the use of instrumental variables is not feasible in our case. We require a simple, reduced-form equation for forecasting purposes, and any time-varying variables that are included in the forecast equation must be forecast themselves. This would add additional uncertainty for potentially little value. The random effects model would be ideal; as shown in table 12, it provides coefficient estimates for both the income spline and the time-invariant structural variables. However, these coefficient estimates are not consistent or efficient estimates of the true parameters if important unobserved time-invariant effects that are correlated with the independent income variables remain after those in table 11 are accounted for. These other effects are included in the error term and, as such, the assumption $E(x_{it}\varepsilon_{it}) = 0$ does not hold. The Hausman specification test in table 13 confirms that this is the case. The fixed effects model must be used for forecasting. We present the random effects equation here to make a limited, primarily qualitative discussion of time-invariant determinants of fossil fuel emissions possible.

*Fossil fuel emissions data*

For the econometric estimation, we combined time series and cross-section national level data to construct a panel with 3,869 observations for the period 1960-92, of which 985 are for Annex 1 and 2,884 for non-Annex 1 countries. Our data set for income, population, and emissions is quite similar to that of Holtz-Eakin and Selden (1995) and Schmalensee, Stoker, and Judson (1998). Our sample includes 127 countries accounting for approximately 95 percent of the world population and 90 percent of the global $CO_2$ emissions from fossil fuels.[6] These countries are those with population over 1 million for which emissions and income data are available.[7] The population and hydroelectric production data (measured in megawatts) are from the World Bank Development Indicators (1998) and World Bank (1992). GDP in ($1985) PPP terms is taken from the Penn World Tables (Summers and Heston 1991), updated for 1992, and the $CO_2$ emissions data are from Marland and others (1999). Energy prices and renewable energy consumption data for developed countries are obtained from OECD (1994).[8] Population by climatic zone data is based on the Koppen-Geiger-Pohl (Geiger and Pohl 1953, Geiger 1954) system of classification, using population data from Tobler and others (1995).

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[6] Please see the earlier note discussing the treatment of changing national boundaries for this analysis.

[7] The following countries have population over 1 million and are excluded from our analysis because of a lack of readily available data: Afghanistan, Albania, Cambodia, Lebanon, Libya, Cuba, Vietnam, Namibia, Lesotho, Taiwan, and North Korea. Unlike Schmalensee, Stoker, and Judson (1998) we have not supplemented the Penn World Tables income data from other sources. We also exclude United Arab Emirates, Saudi Arabia, and Kuwait as outliers, similar to Holtz-Eakin and Selden (1995).

[8] Energy price data for Asia as calculated by the ADB (1992) was also reviewed but is not used here because weighted end-user price includes bundled distribution and transmission costs.

**Table 12. Fossil fuel emissions elasticities; Random country effects.**

| Explanatory Variables | World |
|---|---|
| 1985 $ PPP GDP per capita spline 1 * | 1.953<br>(4.08) |
| 1985 $ PPP GDP per capita spline 2 * | 0.066<br>(0.33) |
| 1985 $ PPP GDP per capita spline 3 * | 1.174<br>(10.09) |
| 1985 $ PPP GDP per capita spline 4 * | 1.252<br>(12.88) |
| 1985 $ PPP GDP per capita spline 5 * | 0.946<br>(10.83) |
| 1985 $ PPP GDP per capita spline 6 * | 1.427<br>(16.37) |
| 1985 $ PPP GDP per capita spline 7 * | 0.651<br>(6.64 ) |
| 1985 $ PPP GDP per capita spline 8 * | 0.613<br>(5.70 ) |
| 1985 $ PPP GDP per capita spline 9 * | -0.189<br>(1.97) |
| 1985 $ PPP GDP per capita spline 10 * | -0.120<br>(0.69) |
| % of people in temperate climate | 1.074<br>(6.38) |
| % of people in wet-dry climate | -0.523<br>(3.12) |
| % of people in snow-ice climate | 1.522<br>(5.61) |
| % of energy production from hydro | -0.862<br>(3.94) |
| Oil exporters | 0.240<br>(2.25) |
| Socialist Countries | 0.136<br>(2.94) |
| Constant | -21.518<br>(7.58) |
| R-sq within = 0.6798<br>between = 0.8735<br>overall = 0.8581 | |
| Numer of Observations | 2592 |

| | |
|---|---|
| Number of Countries | 85 |

* Actual variables in regression expressed as natural logs.

## Table 13. Hausman Specification Test.
## Ho: Random country effects is the correct specification

| LHS Time-variant variable | Fixed Effects | Random Effects | Difference |
|---|---|---|---|
| 1985 $ PPP GDP per capita spline 1 * | 1.519 | 1.953 | -0.434 |
| 1985 $ PPP GDP per capita spline 2 * | -0.003 | 0.066 | -0.069 |
| 1985 $ PPP GDP per capita spline 3 * | 1.131 | 1.175 | -0.044 |
| 1985 $ PPP GDP per capita spline 4 * | 1.224 | 1.252 | -0.028 |
| 1985 $ PPP GDP per capita spline 5 * | 0.896 | 0.946 | -0.051 |
| 1985 $ PPP GDP per capita spline 6 * | 1.379 | 1.427 | -0.048 |
| 1985 $ PPP GDP per capita spline 7 * | 0.623 | 0.651 | -0.028 |
| 1985 $ PPP GDP per capita spline 8 * | 0.539 | 0.613 | -0.074 |
| 1985 $ PPP GDP per capita spline 9 * | -0.238 | -0.189 | -0.049 |
| 1985 $ PPP GDP per capita spline 10 * | -0.187 | -0.120 | -0.067 |
| year 1962 | 0.022 | 0.022 | 0.000 |
| year 1963 | 0.025 | 0.022 | 0.003 |
| year 1964 | 0.048 | 0.043 | 0.005 |
| year 1965 | 0.112 | 0.105 | 0.007 |
| year 1966 | 0.148 | 0.139 | 0.009 |
| year 1967 | 0.191 | 0.181 | 0.010 |
| year 1968 | 0.189 | 0.178 | 0.011 |
| year 1969 | 0.255 | 0.242 | 0.013 |
| year 1970 | 0.284 | 0.268 | 0.015 |
| year 1971 | 0.508 | 0.491 | 0.017 |
| year 1972 | 0.523 | 0.504 | 0.019 |
| year 1973 | 0.539 | 0.517 | 0.021 |
| year 1974 | 0.608 | 0.585 | 0.023 |
| year 1975 | 0.577 | 0.552 | 0.024 |
| year 1976 | 0.549 | 0.524 | 0.025 |
| year 1977 | 0.568 | 0.541 | 0.026 |
| year 1978 | 0.544 | 0.517 | 0.028 |
| year 1979 | 0.571 | 0.542 | 0.029 |
| year 1980 | 0.575 | 0.545 | 0.030 |
| year 1981 | 0.576 | 0.546 | 0.030 |
| year 1982 | 0.543 | 0.513 | 0.030 |
| year 1983 | 0.525 | 0.495 | 0.030 |
| year 1984 | 0.553 | 0.523 | 0.030 |
| year 1985 | 0.541 | 0.511 | 0.030 |

| | | | |
|---|---|---|---|
| year 1986 | 0.528 | 0.498 | 0.030 |
| year 1987 | 0.529 | 0.498 | 0.031 |
| year 1988 | 0.540 | 0.509 | 0.031 |
| year 1989 | 0.535 | 0.503 | 0.032 |
| year 1990 | 0.507 | 0.475 | 0.032 |
| year 1991 | 0.589 | 0.555 | 0.033 |
| year 1992 | 0.590 | 0.556 | 0.034 |
| year 1993 | 0.707 | 0.671 | 0.036 |

*Fossil fuel emissions findings*

As explained above, we first estimated equation 5 using a random effects specification. Using a random effects specification also allows us to estimate the coefficients on such structural variables as percentage of population in temperate, wet-dry and snow-ice climate zones. We also estimated the coefficients on a dummy variable for whether the country is an energy-exporter,[9] and whether it has had a socialist government.[10] These results are shown in table 11.

This equation suggests that climate may have significant predictive power. Temperate climate may result in higher $CO_2$ emissions per capita and snow-ice climates may have a similar effect, presumably because of heating requirements. Energy exporters may have higher $CO_2$ emissions per capita, because of refining activity, while countries that produce relatively higher levels of hydropower emit relatively less $CO_2$. Our hypothesis is that socialist countries should have relatively high levels of emissions for their income level because of their energy-intensive development path. This regression suggests that this may be the case.

While the coefficient estimates in this regression do agree with theory, as discussed above, a Hausman test (table 13) confirms that they are not consistent estimates, since there is evidence that other fixed country effects should be included as independent variables, and that these excluded fixed effects are correlated with the included variables. In the regressions that follow, we drop the fixed effects that we have explicitly included in the regression, and simply include a vector of country-fixed effects dummy variables. This allows us to estimate the coefficients on the income spline function consistently, even though we can no longer determine separate coefficients on the climate variables.

Having confirmed that a fixed effects specification is correct, we re-estimated equation 8 with three alternative spline functions: 5 segments, 10 segments, and 12 segments. Based on significance levels we chose the 10-segment specification. Estimations of the 10-segment spline with 3,869 observations

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[9] The following countries are energy exporters at the end of the period: Angola, Argentina, Australia, Azerbaijan, Benin, Bolivia, Canada, China, Cameroon, Congo, Rep., Columbia, Algeria, Ecuador, Egypt, Gabon, U.K., Iran, Iraq, Khazakstan, Laos, Mexico, Malaysia, Nigeria, Norway, Poland, Paraguay, Russia, South Africa, Syria, Turkmenistan, Trinidad and Tobago, Turkey, Venezuela, Vietnam, and Yemen. (World Bank 1997)

[10] The following countries are considered to be socialist for all or part of the period under consideration: Soviet Union, Mongolia, Albania, Yugoslavia, Bulgaria, Czechoslovakia, Hungary, Poland, Romania, North Korea, China, East Germany, Vietnam, Cuba, Congo, Rep., Algeria, Iraq, and Syria ( Kornai 1992). If the period of socialism as defined by Kornai (1992) is longer than ten years, we consider the country socialist for the entire period of analysis under the assumption that the effects of the regime on the economy will be sufficiently profound as to persist beyond the nominal change in government.

from 127 countries explained 61 percent of within country variation and 81 percent of the between country variation. Overall, 75 percent of the variation was explained. The results of this estimation of the $CO_2$-income relationship are reported in table 14 and graphed in figure 4. For all segments except the first, the estimated income elasticity was statistically significantly different from zero at the 95 percent level.[11] The income elasticities of emissions were positive for income levels below $7,700. The elasticities become negative as incomes rise above that level. The largest elasticity is 1.05,

**Table 14. Fossil fuel emissions elasticities; Controlling for country and time fixed effects.**

| Explanatory Variables | Obs. In Spline | Max. Income in Spline | World |
|---|---|---|---|
| 1985 $ PPP GDP per capita spline 1 * | 4086 | $393 | 0.269 |
| | | | (0.58) |
| 1985 $ PPP GDP per capita spline 2 * | 4018 | $601 | 0.786 |
| | | | (5.70) |
| 1985 $ PPP GDP per capita spline 3 * | 3680 | $921 | 0.628 |
| | | | (6.35) |
| 1985 $ PPP GDP per capita spline 4 * | 3114 | $1,410 | 1.047 |
| | | | (10.69) |
| 1985 $ PPP GDP per capita spline 5 * | 2508 | $2,156 | 0.908 |
| | | | (10.13) |
| 1985 $ PPP GDP per capita spline 6 * | 1972 | $3,301 | 1.021 |
| | | | (11.80) |
| 1985 $ PPP GDP per capita spline 7 * | 1482 | $5,049 | 0.451 |
| | | | (4.61) |
| 1985 $ PPP GDP per capita spline 8 * | 1023 | $7,731 | 0.503 |
| | | | (4.82) |
| 1985 $ PPP GDP per capita spline 9 * | 640 | $11,825 | -0.390 |
| | | | (4.03) |
| 1985 $ PPP GDP per capita spline 10 * | 252 | $18,088 | -0.498 |
| | | | (2.68) |
| Constant | | | -11.818 |
| | | | (4.28) |

---

[11] Tests for heteroskedasticity suggest that there is some tendency for countries with higher incomes to have smaller squared residual estimates. The use of robust standard errors and LSDV estimation does not change the coefficient estimates and does not alter the significance of any of the coefficients either. We present the OLS results here.

| | |
|---|---|
| R-sq within | 0.607 |
| Between | 0.807 |
| Overall | 0.744 |
| | |
| Numer of Observations | 3869 |
| Number of Countries | 127 |

* Actual variables in regression expressed as natural logs.

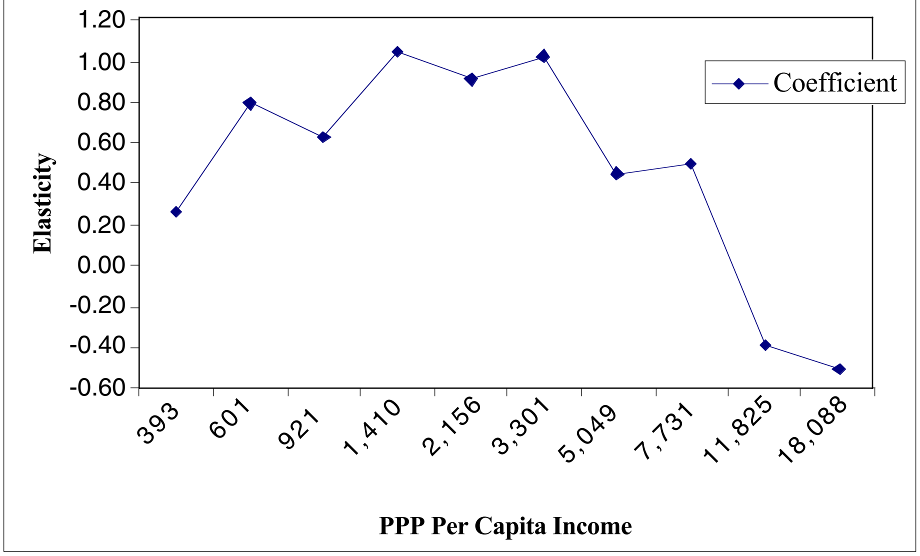

Figure 4 Income Elasticities of Emissions
10 Segment Spline, Country, and Time Fixed Effects

and occurs for per capita incomes in the range of \$921-\$1410. An income elasticity of emissions greater (smaller) than one means that a one percent increase in income increases emissions by more (less) than one percent. A negative elasticity means that further increases in income levels per capita result in reductions of emissions per capita.

Our findings suggest an inverted U-relationship between income per capita and $CO_2$ emissions per capita. As income increases from very low levels, emissions increase at an increasing rate; they reach a plateau at an intermediate level of income beyond which additional increases in incomes result in smaller additions to $CO_2$ emissions until they turn negative. This inverted U-relationship has been found by several other authors in relation to local and regional pollutants (Grossman and Krueger 1995, Selden and Song 1994, and Panayotou 1993 and 1997), and was termed the environmental Kuznets curve because it resembles the relationship between income and inequality hypothesized by Kuznets (1955). The implication of such a non-monotonic relationship between pollution and income level is that income growth is both a cause and a cure of environmental problems, a property that is not unreasonable for local pollutants.

Finding an inverted U-shaped relationship for an invisible global pollutant with much delayed effects and ample scope for free riding is a bit puzzling, but fully explainable, by the structural changes accompanying economic growth: from agriculture to industry to services. Previous studies including Holtz-Eakin and Selden (1995), Schmalensee, Stoker, and Judson (1998), and Galeotti and Lanza (1999) found a similar inverted U-relationship. The latter two studies found a turning point (where emissions per capita stop increasing and begin to fall with income growth) in the range of \$10,000 to \$17,000 compared to around \$35,000 in the former study. This is a significant finding since it suggests that $CO_2$ emissions will not continue to grow linearly with income but will slow down, level off, and even decline once a certain level of economic development is attained.

Besides income, another variable that is likely to be a significant determinant of $CO_2$ emissions is the price of energy. Unfortunately, there are no complete time series and cross section data on energy prices for our country sample. Conspicuously absent are energy price data for Africa, and the limited data available for Asia and Latin America are not comparable by construction to the available OECD information[12]. Thus, we have been unable to estimate a global emissions model with energy prices. Of course, changes in the world prices are reflected in time fixed effects, and persistent domestic price differences among countries are reflected in the country fixed effects, but the lack of comparable data prevents us from estimating what part of fixed effects is accounted by energy price differences between countries.

In an attempt to make the best of the limited energy price data available to us, we re-estimated 10-segment spline functions separately for the OECD. The results are reported in table 15. Naturally, the first six income segments were dropped from OECD since no OECD country has incomes under \$10,000 per capita. Given the small sample of countries, the absolute magnitude of the coefficients

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[12] The Asian figures are not comparable with the OECD and Latin American figures because the weighted average energy price calculated by ADB for Asia includes the bundled electricity costs to the end users (including transmission and distribution costs) rather than the costs of fuel to power producers.

(elasticities) should not be taken seriously despite the good fit. However, the signs of the energy price estimated coefficients are negative, as one would expect. The coefficient estimate for renewable energy consumption per capita is positive, which is certainly counter-intuitive, but it is not significantly different from zero.

**Table 15. OECD fossil fuel emissions elasticities; Controlling for country fixed effects, including prices.**

| **Explanatory Variables** | **OECD** |
|---|---|
| 1985 $ PPP GDP per capita spline 1 * | (dropped) |
| 1985 $ PPP GDP per capita spline 2 * | (dropped) |
| 1985 $ PPP GDP per capita spline 3 * | (dropped) |
| 1985 $ PPP GDP per capita spline 4 * | (dropped) |
| 1985 $ PPP GDP per capita spline 5 * | (dropped) |
| 1985 $ PPP GDP per capita spline 6 * | (dropped) |
| 1985 $ PPP GDP per capita spline 7 * | 0.888 |
| | (2.50) |
| 1985 $ PPP GDP per capita spline 8 * | 1.076 |
| | (5.17) |
| 1985 $ PPP GDP per capita spline 9 * | 0.628 |
| | (2.62) |
| 1985 $ PPP GDP per capita spline 10 * | 0.919 |
| | (5.06) |
| Energy price (1985 PPP$/ toe) * | -0.026 |
| | (0.68) |
| Annual renewable energy consumption per capita (mtoe/cap) * | 0.0097 |
| | 0.5 |
| R-sq within = 0.5564<br>Between = 0.5688<br>overall = 0.5601 | |
| Number of Observations | 102 |
| Number of Countries | 21 |

* Actual variables in regression expressed as natural log

To sum up, income growth drives $CO_2$ emissions, but the relationship is not a linear or monotonic one. The income-emissions relationship varies along a country's development path both quantitatively and qualitatively. At the earlier stages of development, where all non-Annex 1 countries, except the oil producers, find themselves today, emissions rise with income growth; and for the poorest among them, they rise at an increasing rate. At a later stage of development, where most Annex 1 countries find themselves, $CO_2$ emissions level off and decline with further economic growth. The implications of this result are profound for both emissions projections and formulations of policies to control climate change, as shown below.

While further research is needed to fully explain the country fixed effects, the fixed effect estimates themselves are indicative of the countries that are significant outliers in the sense that they have unduly high (or low) emissions given their level of development (as reflected by income per capita), their geographic location, and the structural characteristics of their economy. Major countries among positive outliers (excessive emissions) are United States, Canada and Eastern European countries such as Romania. Countries with small fixed effects include Laos and Nepal. Schmalensee, Stoker, and Judson (1998) suggest that this result may be attributable to the fact that income is poorly measured in these countries (see table 16 for a complete list of the country fixed effects). It should be kept in mind that this ranking is based only on $CO_2$ emissions from fossil fuels. Inclusion of emissions for land use changes is not expected to significantly change these results since land use emissions are largely limited to a group of tropical countries.

**Table 16. Country fixed effects.**

| Countries in income-only regression | Country-specific fixed effects in income-only regression |
|---|---|
| Nepal | -0.19 |
| Laos | 0.00 |
| Burundi | 0.03 |
| Burkina Faso | 0.64 |
| Bangladesh | 0.69 |
| Ethiopia | 0.73 |
| Mali | 0.81 |
| Niger | 0.88 |
| Central African Republic | 0.91 |
| Benin | 0.94 |
| Haiti | 1.22 |
| Comoros | 1.27 |
| Malawi | 1.37 |
| Cameroon | 1.47 |
| The Gambia | 1.53 |
| Sri Lanka | 1.54 |
| Mozambique | 1.56 |
| Mauritius | 1.60 |
| Guinea-Bissau | 1.64 |
| Swaziland | 1.76 |
| Guatemala | 1.84 |

| | |
|---|---:|
| Slovenia | 1.85 |

## Table 16. Country fixed effects (continued).

| Countries in income-only regression | Country-specific fixed effects in income-only regression |
|---|---:|
| Myanmar (Burma) | 1.90 |
| Congo | 1.93 |
| Cape Verde | 1.94 |
| Ghana | 1.98 |
| Costa Rica | 2.00 |
| Ivory Coast | 2.01 |
| Guinea | 2.02 |
| Fiji | 2.16 |
| Nicaragua | 2.17 |
| Kenya | 2.20 |
| Pakistan | 2.22 |
| Botswana | 2.23 |
| Honduras | 2.27 |
| Brazil | 2.33 |
| Morocco | 2.35 |
| Mauritania | 2.35 |
| Philippines | 2.38 |
| Bolivia | 2.39 |
| Ecuador | 2.46 |
| Indonesia | 2.46 |
| Peru | 2.49 |
| Uruguay | 2.52 |
| Dominican Republic | 2.56 |
| Panama | 2.63 |
| Nigeria | 2.65 |
| India | 2.66 |
| Angola | 2.68 |
| Djibouti | 2.68 |
| Colombia | 2.74 |
| Malaysia | 2.75 |
| Turkey | 2.77 |
| Iraq | 2.79 |
| Liberia | 2.84 |
| Portugal | 2.86 |
| Hong Kong | 2.87 |
| Mexico | 2.90 |
| Chile | 2.90 |
| Jordan | 2.95 |
| Egypt | 2.99 |
| Algeria | 3.02 |
| Argentina | 3.03 |
| Iran | 3.09 |
| Spain | 3.13 |
| Gabon | 3.25 |

| | |
|---|---|
| Korea | 3.27 |
| Greece | 3.28 |

**Table 16. Country fixed effects (continued).**

| Countries in income-only regression | Country-specific fixed effects in income-only regression |
|---|---|
| Cyprus | 3.32 |
| Israel | 3.42 |
| Jamaica | 3.43 |
| Italy | 3.46 |
| Guyana | 3.46 |
| New Zealand | 3.53 |
| China | 3.66 |
| Switzerland | 3.67 |
| Austria | 3.69 |
| Japan | 3.69 |
| Ireland | 3.73 |
| Hungary | 3.75 |
| Iceland | 3.80 |
| France | 3.83 |
| Bulgaria | 3.89 |
| Finland | 3.92 |
| Sweden | 3.95 |
| Netherlands | 3.98 |
| Norway | 4.01 |
| Mongolia | 4.11 |
| United Kingdom | 4.15 |
| Denmark | 4.18 |
| Former Yugoslavia | 4.19 |
| Belgium | 4.24 |
| Poland | 4.27 |
| West Germany | 4.27 |
| Australia | 4.31 |
| East Germany | 4.51 |
| Canada | 4.53 |
| United States | 4.89 |
| Romania | 5.13 |
| Luxembourg | 5.26 |

### *Historical contributions of rising atmospheric carbon from land use changes*

The burning of fossil fuels for energy is the main but not the only source of $CO_2$ emissions. Land use changes, mainly in the form of deforestation and forest land conversion to other uses contribute currently about 20 percent of the global $CO_2$ emissions from anthropogenic sources. Tables 17 and 18 report, respectively, the $CO_2$ emissions (flows) and concentrations (stocks) from land use change during the period 1860-1990. The same information is shown graphically in figures 5 and 6 from which is clear

**Table 17 Estimated flows of $CO_2$ emissions from land use change 1860-1990 (billion tons of C)**

| Country Group | 1860 | 1870 | 1880 | 1890 | 1900 | 1910 | 1920 | 1930 | 1940 | 1950 | 1960 | 1970 | 1980 | 1990 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Japan | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.05 | 0.03 | -0.02 | -0.04 |
| USA | 0.15 | 0.17 | 0.20 | 0.19 | 0.18 | 0.16 | 0.15 | 0.13 | 0.05 | 0.00 | -0.03 | -0.05 | -0.06 | -0.07 |
| EU | -0.02 | -0.02 | -0.02 | -0.02 | -0.02 | -0.02 | -0.03 | 0.09 | 0.06 | 0.03 | 0.01 | -0.03 | -0.09 | -0.09 |
| Other High Income | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.01 | 0.02 | 0.02 | 0.04 | 0.03 | 0.01 | 0.03 |
| High Income OPEC | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 |
| Middle Income | -0.01 | -0.01 | -0.02 | -0.01 | -0.02 | -0.01 | -0.02 | 0.08 | 0.09 | 0.10 | 0.17 | 0.32 | 0.46 | 0.54 |
| Russia | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.05 | 0.05 | 0.03 | 0.10 | 0.09 | 0.05 | 0.00 |
| Lower Middle Income | 0.10 | 0.11 | 0.09 | 0.15 | 0.13 | 0.25 | 0.16 | 0.15 | 0.18 | 0.25 | 0.27 | 0.32 | 0.33 | 0.27 |
| Eastern Europe | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | 0.01 | 0.01 | 0.01 | 0.05 | 0.04 | 0.02 | 0.00 |
| Low Income | 0.11 | 0.12 | 0.14 | 0.14 | 0.17 | 0.19 | 0.15 | 0.09 | 0.10 | 0.17 | 0.19 | 0.28 | 0.36 | 0.41 |
| China | 0.06 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.06 | 0.07 | 0.07 | 0.08 | 0.12 | 0.15 | 0.08 | 0.04 |
| India | 0.02 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.03 | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.02 | 0.02 |
| Africa | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.04 | 0.06 | 0.10 | 0.15 | 0.24 | 0.34 |
| TOTAL | 0.45 | 0.49 | 0.53 | 0.59 | 0.60 | 0.74 | 0.62 | 0.73 | 0.71 | 0.77 | 1.08 | 1.36 | 1.42 | 1.46 |

**Table 18 Stock of $CO_2$ emissions from land use change 1860-1990 (billion tons of C)**

| Country Group | 1860 | 1870 | 1880 | 1890 | 1900 | 1910 | 1920 | 1930 | 1940 | 1950 | 1960 | 1970 | 1980 | 1990 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Japan | 0.00 | 0.01 | 0.09 | 0.17 | 0.26 | 0.35 | 0.46 | 0.56 | 0.67 | 0.77 | 1.13 | 1.34 | 1.18 | 0.79 |
| USA | 0.15 | 1.53 | 2.82 | 3.94 | 4.84 | 5.55 | 6.09 | 6.70 | 6.58 | 6.00 | 5.27 | 4.51 | 3.82 | 3.12 |
| EU | -0.02 | -0.22 | -0.34 | -0.43 | -0.53 | -0.64 | -0.77 | 0.10 | 0.64 | 0.81 | 0.77 | 0.54 | -0.04 | -0.77 |
| Other High Income | 0.02 | 0.20 | 0.42 | 0.62 | 0.80 | 0.95 | 1.09 | 1.01 | 1.02 | 1.06 | 1.27 | 1.44 | 1.42 | 1.45 |
| High Income OPEC | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.06 | 0.07 | 0.06 | 0.05 | 0.05 | 0.05 | 0.07 | 0.15 | 0.24 |
| Middle Income | -0.01 | -0.14 | -0.25 | -0.29 | -0.38 | -0.37 | -0.45 | 0.22 | 0.88 | 1.46 | 2.53 | 4.38 | 6.79 | 9.98 |
| Russia | 0.02 | 0.18 | 0.30 | 0.41 | 0.50 | 0.58 | 0.73 | 0.99 | 1.27 | 1.37 | 2.16 | 2.73 | 2.85 | 2.68 |
| Lower Middle Income | 0.10 | 1.02 | 1.60 | 2.48 | 3.14 | 4.61 | 5.31 | 5.76 | 6.43 | 7.44 | 8.89 | 10.51 | 11.75 | 12.80 |
| Eastern Europe | -0.01 | -0.09 | -0.14 | -0.16 | -0.20 | -0.26 | -0.29 | -0.20 | -0.08 | 0.00 | 0.44 | 0.74 | 0.81 | 0.71 |
| Low Income | 0.11 | 1.14 | 2.05 | 2.84 | 3.77 | 4.71 | 5.44 | 5.44 | 5.60 | 6.12 | 7.12 | 8.48 | 10.05 | 12.12 |
| China | 0.06 | 0.54 | 0.88 | 1.12 | 1.34 | 1.54 | 1.82 | 2.14 | 2.46 | 2.78 | 3.29 | 4.07 | 4.39 | 4.34 |
| India | 0.02 | 0.24 | 0.42 | 0.59 | 0.78 | 0.98 | 1.13 | 1.02 | 0.97 | 0.97 | 1.00 | 1.06 | 1.13 | 1.20 |
| Africa | 0.01 | 0.08 | 0.14 | 0.21 | 0.28 | 0.38 | 0.52 | 0.70 | 0.91 | 1.28 | 1.88 | 2.82 | 4.15 | 6.07 |
| TOTAL | 0.45 | 4.51 | 8.03 | 11.53 | 14.65 | 18.45 | 21.14 | 24.49 | 27.41 | 30.12 | 35.79 | 42.71 | 48.44 | 54.73 |

Figure 5 Estimated $CO_2$ Emissions from Land Use Change 1860-1990 (billion tons of C)

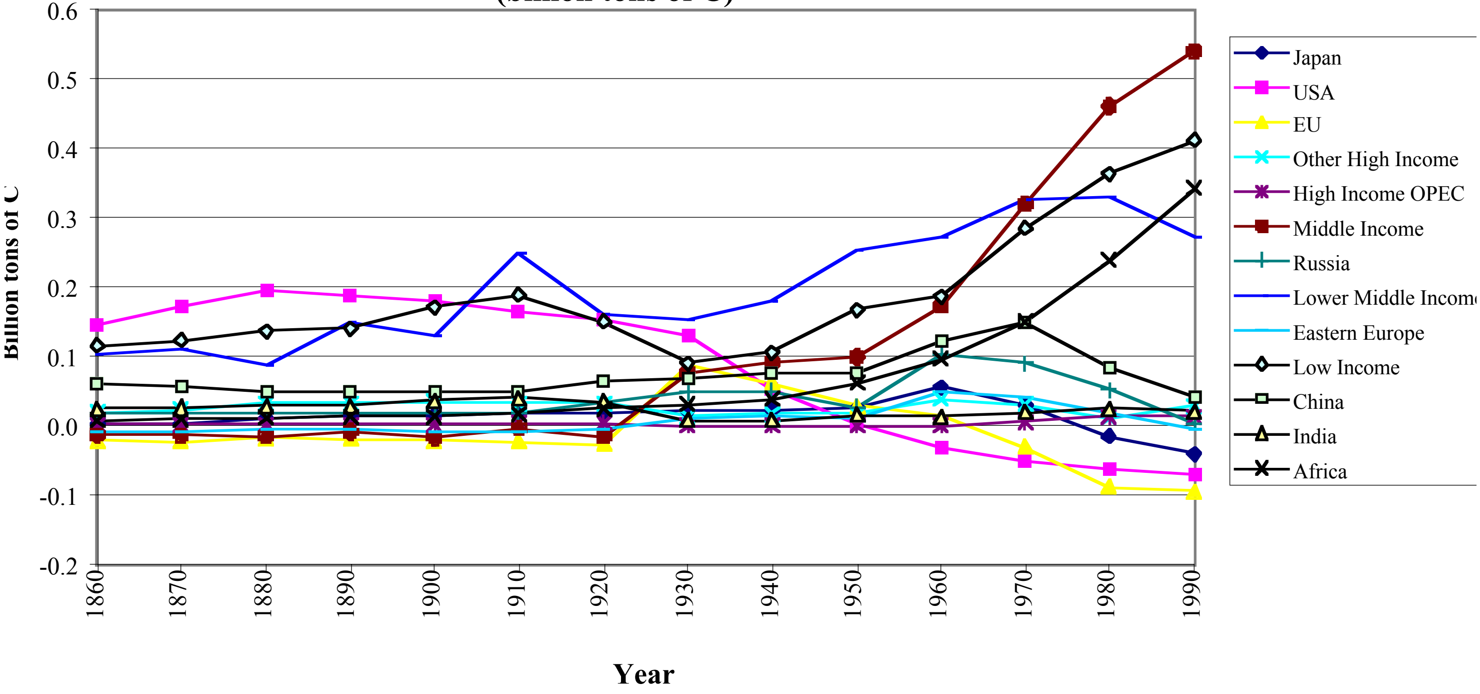
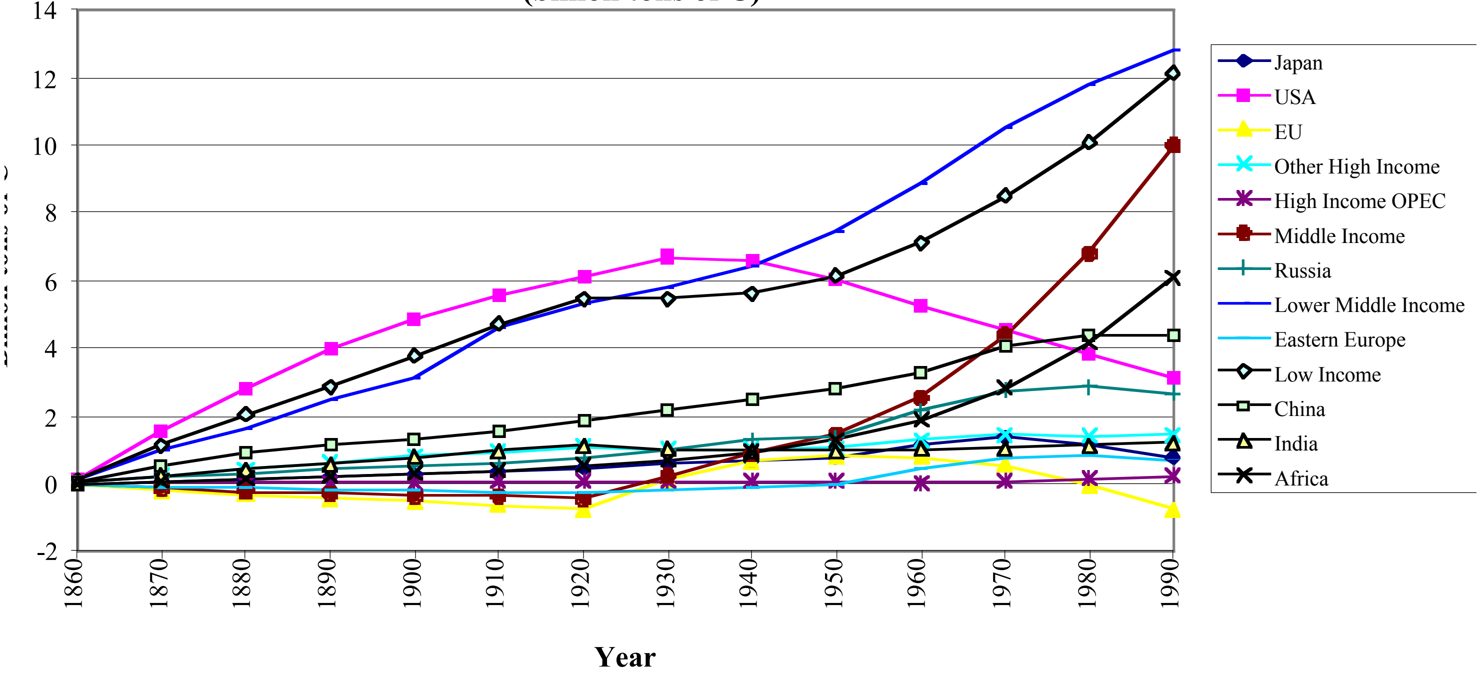


Figure 6 Stock of $CO_2$ from Land Use Change 1860-1990 (billion tons of C)



that land use change has become a significant source of $CO_2$ emissions only in the last four decades and tropical developing countries have been the main source. Developed countries have been net sequesters of carbon (negative emissions) at least since 1980.

The historical path of these emissions, on the other hand, is much different than the current picture. In the nineteenth century, deforestation, and subsequently $CO_2$ emissions from land use change, was nearly twice as high in the temperate countries of Annex 1 as in the rest of the world. During the first three decades of the twentieth century, roughly the same amount of $CO_2$ (about 300 million tons total) was released from Annex 1 and non-Annex 1 countries. Since 1930, temperate deforestation, which remained constant for almost a century, began to slow down rather rapidly, while tropical deforestation began to accelerate and rose steeply between 1940 and 1970; it leveled off in the 1980s and 1990s. Regionally, Europe was the first to deforest in earlier centuries and by 1850 deforestation was already slowing down, which North America continued to experience increased deforestation until the turn of the century. Since 1940, all tropical regions have experienced rapid deforestation, though this has leveled off in Asia.

Tables 19a-19c contain data on deforestation in 1990 and 1995. These tables are intended to highlight important forest use phenomena and the major deforesters. Since land use change is relatively poorly understood, identifying the major sources of land use change emissions is important. If the problem is concentrated in a few countries, abatement and research efforts can be more effectively directed. A comparison of tables 19a and 19c show that today, land use change is almost entirely a tropical world phenomenon. Even wood product exports are higher in the temperate world than in the tropics. Moreover, table 19b shows that that almost 75% of all emissions from land use come from 9 countries, all in Latin America and tropical Asia. The problem, while of uncertain magnitude, is undoubtedly localized.

**Table 19a Tropical World Summary Forestry Statistics**

| **Tropical World** | 1991 WRI Emissions from Land Use (bill tons of C) | 1990 Houghton Emissions from Land Use (bill tons of C) | Total Biomass (tons/ha) | Total Forest 1990 (000 ha) | Total Forest 1995 (000 ha) | Change 1990-1995 (000 ha) | Rate of Change |
|---|---|---|---|---|---|---|---|
| Central America | 0.052 | 0.070 | 157 | 84,628 | 79,443 | -5,185 | -6.1% |
| South America | 0.459 | 0.503 | 189 | 851,223 | 827,946 | -23,277 | -2.7% |
| Africa | 0.195 | 0.342 | 133 | 523,376 | 504,901 | -18,475 | -3.5% |
| Asia | 0.272 | 0.679 | 188 | 295,041 | 279,766 | -15,275 | -5.2% |
| Oceania | 0.010 | 0.020 | 191 | 42,659 | 41,903 | -756 | -1.8% |
| Total | 0.988 | 1.614 | | 1,796,927 | 1,733,959 | -62,968 | -3.5% |

**Table 19a. Tropical world summary forestry statistics (continued).**

| Tropical World | 1994 Fuelwood Production (000 m3) | 1994 Fuelwood Imports (000 m3) | 1994 Fuelwood Exports (000 m3) | Consumption (000 ha)** |
|---|---|---|---|---|
| Central America | 62,028 | 33 | 79 | 395 |
| South America | 239,354 | 4 | 92 | 1,266 |
| Africa | 483,933 | 4 | 162 | 3,637 |
| Asia | 648,448 | 295 | 2,003 | 3,440 |
| Oceania | 5,802 | 0 | 0 | 30 |
| Total | 1,439,565 | 336 | 2,336 | 8,769 |
| | | | | |
| | 1994 Roundwood Production (000 m3) | 1994 Roundwood Imports (000 m3) | 1994 Roundwood Exports (000 m3) | Consumption (000 ha)** |
| Central America | 10,108 | 159 | 235 | 64 |
| South America | 90,512 | 38 | 1,754 | 470 |
| Africa | 45,425 | 86 | 4,853 | 306 |
| Asia | 117,845 | 2,880 | 11,038 | 583 |
| Oceania | 3,345 | 2 | 4,019 | (4) |
| Total | 267,235 | 3,165 | 21,899 | 1,419 |
| | | | | |
| | 1994 Sawnwood Production (000 m3) | 1994 Sawnwood Imports (000 m3) | 1994 Sawnwood Exports (000 m3) | Consumption (000 ha)** |
| Central America | 4,680 | 2,091 | 909 | 37 |
| South America | 21,396 | 180 | 1,709 | 105 |
| Africa | 6,222 | 185 | 1,387 | 38 |
| Asia | 38,963 | 3,573 | 6,278 | 193 |
| Oceania | 276 | 75 | 45 | 2 |
| Total | 71,537 | 6,104 | 10,328 | 375 |

* Source:Emissions data WRI (1997), Houghton et al (1994); Forestry data FAO (1993), FAO (1997)

** Assumes biomass as listed above.

## Table 19b. Characteristics of major source countries for land use change emissions.

| Country | 1991 WRI emissions from land use (bill tons of carbon) | Natural forest biomass (tons/ha) | Closed broadleaf forest ave. logging intensity 1981-90 (m3/ha) | Total forest 1990 (000 ha) | Total forest 1995 (000 ha) | Change 1990-1995 (000 ha) | Percentage change 1990-1995 |
|---|---|---|---|---|---|---|---|
| Bolivia | 0.04 | 150 | 13 | 51,217 | 48,310 | -2,907 | -5.7% |
| Indonesia | 0.11 | 203 | 20 | 115,213 | 109,791 | -5,422 | -4.7% |
| Brazil | 0.30 | 189 | 6 | 563,911 | 551,139 | -12,772 | -2.3% |
| Columbia | 0.03 | 195 | 16 | 54,299 | 52,988 | -1,311 | -2.4% |
| Venezuela | 0.05 | 189 | 11 | 46,512 | 43,995 | -2,517 | -5.4% |
| Democratic Rep. Congo | 0.08 | 252 | 15 | 112,946 | 109,245 | -3,701 | -3.3% |
| Myanmar (Burma) | 0.04 | 217 | 14 | 29,088 | 27,151 | -1,937 | -6.7% |
| Malaysia | 0.06 | 261 | 75 | 17,472 | 15,471 | -2,001 | -11.5% |
| Phillippines | 0.03 | 236 | 83 | 8,078 | 6,766 | -1,312 | -16.2% |

* Source: Emissions data WRI (1997), Houghton et al (1994); Forestry data FAO (1993), FAO (1997).

## Table 19c. Temperate world summary forest statistics.

| Non-Tropical World | 1991 WRI Emissions from Land Use (bill tons of carbon) | 1990 Houghton Emissions from Land Use (bill tons of carbon) | Total Forest 1990 (000 ha) | Total Forest 1995 (000 ha) | Change 1990-1995 (000 ha) | Rate of Change |
|---|---|---|---|---|---|---|
| Temperate Africa | 0.004 | – | 15,602 | 15,336 | -266 | -1.7% |
| Temperate Asia | 0.042 | – | 195,771 | 194,406 | -1,365 | -0.7% |
| Temperate Oceania | – | – | 48,490 | 48,792 | 302 | 0.6% |
| W. Europe | 0.003 | – | 57,688 | 59,479 | 1,791 | 3.1% |
| E. Europe | – | – | 83,739 | 86,638 | 2,899 | 3.5% |
| Russia | – | – | 763,500 | 763,500 | 0 | 0.0% |
| North America | – | – | 453,270 | 457,086 | 3,816 | 0.8% |
| Temperate South America | 0.033 | – | 43,243 | 42,648 | -595 | -1.4% |
| Total | 0.036 |  | 1,401,440 | 1,409,351 | 7,911 | 0.6% |

| Non-Tropical World | 1994 Fuelwood Production (000 m3) | 1994 Fuelwood Imports (000 m3) | 1994 Fuelwood Exports (000 m3) | Consumption (000 ha)** |
|---|---|---|---|---|
| Temperate Africa | 18,320 | 303 | 177 | 132 |
| Temperate Asia | 230,533 | 1,121 | 169 | 1,653 |
| Temperate Oceania | 2,948 | 3 | 7 | 21 |
| W. Europe | 39,019 | 2,447 | 840 | 290 |
| E. Europe | 12,074 | 12 | 920 | 80 |
| Former Soviet Union | 30,800 | 3 | 236 | 408 |
| North America | 98,920 | 712 | 732 | 706 |
| Temperate South America | 18,838 | 4 | 107 | 134 |
| Total | 199,651 | 3,178 | 2,835 | 1,618 |

## Table 19c. Temperate world summary forest statistics (continued).

| | 1994 Roundwood Production (000 m3) | 1994 Roundwood Imports (000 m3) | 1994 Roundwood Exports (000 m3) | Consumption (000 ha) ** |
|---|---|---|---|---|
| Temperate Africa | 20,054 | 639 | 2,092 | 133 |
| Temperate Asia | 143,854 | 62,999 | 2,631 | 1,459 |
| Temperate Oceania | 35,445 | 14 | 12,848 | 162 |
| W. Europe | 228,958 | 47,151 | 20,953 | 1,823 |
| E. Europe | 50,396 | 797 | 4,171 | 336 |
| Former Soviet Union | 112,413 | 144 | 19,680 | 1,238 |
| North America | 580,779 | 7,698 | 21,946 | 4,047 |
| Temperate South America | 28,291 | 10 | 7,198 | 151 |
| Total | 1,000,837 | 55,800 | 73,948 | 7,594 |
| | | | | |

| | 1994 Sawnwood Production (000 m3) | 1994 Sawnwood Imports (000 m3) | 1994 Sawnwood Exports (000 m3) | Consumption (000 ha)** |
|---|---|---|---|---|
| Temperate Africa | 1,787 | 2,298 | 45 | 29 |
| Temperate Asia | 59,630 | 16,869 | 1,043 | 539 |
| Temperate Oceania | 6,348 | 1,116 | 1,090 | 46 |
| W. Europe | 70,144 | 36,404 | 28,462 | 558 |
| E. Europe | 12,022 | 1,126 | 4,496 | 62 |
| Former Soviet Union | 31,465 | 159 | 8,087 | 314 |
| North America | 155,753 | 40,555 | 52,956 | 1,024 |
| Temperate South America | 4,631 | 117 | 2,713 | 15 |
| Total | 274,015 | 78,361 | 96,714 | 1,972 |

* Source: Emissions data WRI (1997), Houghton et al (1994); Forestry data FAO (1993), FAO (1997)
** Assumes biomass of 140 tons/ha for all but Russia/ Soviet Union. There assume 75 tons/ha.

### *Land use emissions data*

Houghton and Hackler (1995) provide an estimate of regional land use change emissions from 1860-1980 for North America, Europe, the Soviet Union, and Japan; and from 1860-1990 for China, India, Tropical South and Southeast Asia, Latin America and Africa. We supplement this data with OECD emissions estimates from the United Nations Framework Convention on Climate Change (1997) and developing country estimates from World Resources Institute (1997). This data is presented in table 20.[13]

To use the Nordhaus damage equation, we must estimate emissions for the regions for which the equation has been calibrated. As such, the Houghton (1994) data must be placed into the Nordhaus categories. This was done on the basis of annual deforestation data. This data is from FAOSTAT for 1961-1990, and Zon and Sparhawk (1923) for earlier in the century. Like Houghton and Hackler (forthcoming) we assume that deforestation began in 1750 and increases linearly until 1900.

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[13] Houghton and Hackler (forthcoming) state that the 1994 figures used here are approximately 30% too low based on revisions to his methodology. Unfortunately, revisions have been made public only for South and Southeast Asia, to our knowledge.

*Land use emissions model*

In order to project $CO_2$ emissions in the future we must understand the factors behind the dramatic shift in rates of deforestation and hence forest cover between regions and over time. Unfortunately, reliable time series on deforestation and forest area are not available. FAO (various years) report data on forest area for 1960, 1980, 1990 and 1995 but they are not strictly comparable except for the last two years. Emissions at the country level are not available on an annual basis either, though emissions of developing countries are estimated by WRI for 1991. We have, therefore, limited ourselves to cross-section analysis of the 1991 emissions.

The main sources of deforestation are forest land conversion to shifting cultivation and sedentary agriculture, and unsustainable fuelwood collection and wood harvesting. Since both of these sources of land use change depend on population density, we specify the following regression equation for explaining variation of forest cover across countries:

$$\begin{aligned}(9)\ \ln(\text{emissions/ha})_i = a_o + a_1 \ln(\text{population density})_i \\ + a_2(\ln(\text{population density}))^2_i + a_3(\%\text{ change in population density})_I \\ + a_4 \ln(\text{forest cover/ha})_i + a_3(\text{dummies for climate and regions}) + \varepsilon_i\end{aligned}$$

Equation 9 was estimated using least squares regression techniques allowing for heteroskedasticity. The results are reported in table 21. As expected, higher population density results in loss of forest cover, though at a decreasing rate. Perhaps because this sample is for developing countries only, income per capita does not have a coefficient estimate that is significantly different from zero. This is not consistent with historical evidence, which has shown developing countries to be aforesting as their incomes increased. Among the climatic variables, only the percent of land in temperate zones had a significantly negative effect on forest cover, reflecting the fact that these regions are less well endowed with forest cover to begin with. The percentage of people in rainforest zones is estimated to increase emissions from land use change, possibly reflecting firewood use and slash and burn agriculture in these regions. We will employ the results of this estimation in our projections of future $CO_2$ emissions from land use change.

Since equation 9 estimates emissions, for prediction purposes this must be translated into lost in forest cover. Methodologies for making this transformation are complicated and have arrived at very different results. See Houghton and Hackler (forthcoming) for a concise summary of the varying estimates of emissions from tropical Asia. Calculating emissions from land use change requires assumptions regarding the use and type of the wood deforested, and the treatment of the land in question after deforestation occurs. We have used a simple transformation method, suggested by WRI (1997). Change in forest cover in hectares is transformed to metric tons of biomass per hectare by multiplying lost forest cover by the 140, 120, or 53 tons of biomass per hectare depending on whether the majority of a country's forests are tropical, temperate or boreal. The carbon content of this mass is then assumed to be 45%, 5% of which is sequestered in soil. Of the remaining carbon, 25% is assumed to be used for long-term construction, based on sawn wood and roundwood production in tropical countries in 1994 as calculated by the FAO (1997). The remaining carbon is emitted.

**Table 20. Historic stocks of $CO_2$ emissions from fossil fuels and land use change 1860-1990. (billions of tons of C)**

| Country Group | 1860 | 1870 | 1880 | 1890 | 1900 | 1910 | 1920 | 1930 | 1940 | 1950 | 1960 | 1970 | 1980 | 1990 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Japan | 0.00 | 0.02 | 0.09 | 0.18 | 0.30 | 0.46 | 0.69 | 0.95 | 1.26 | 1.51 | 2.15 | 3.30 | 4.89 | 6.05 |
| USA | 0.16 | 1.70 | 3.30 | 5.04 | 6.93 | 9.64 | 12.95 | 16.37 | 18.25 | 21.33 | 24.68 | 29.54 | 35.78 | 41.10 |
| EU | 0.05 | 0.68 | 1.53 | 2.64 | 4.01 | 5.83 | 7.60 | 10.33 | 12.72 | 14.38 | 17.20 | 21.25 | 25.73 | 28.74 |
| Other High Income | 0.02 | 0.21 | 0.43 | 0.66 | 0.88 | 1.15 | 1.49 | 1.62 | 1.80 | 2.17 | 2.83 | 3.75 | 4.91 | 6.14 |
| High Income OPEC | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.06 | 0.07 | 0.06 | 0.06 | 0.09 | 0.09 | 0.27 | 0.75 | 1.41 |
| Middle Income | -0.01 | -0.14 | -0.25 | -0.29 | -0.37 | -0.34 | -0.39 | 0.32 | 1.08 | 1.69 | 2.98 | 5.22 | 8.43 | 12.64 |
| Russia | 0.02 | 0.18 | 0.32 | 0.45 | 0.60 | 0.79 | 1.01 | 1.34 | 2.03 | 2.66 | 4.80 | 7.67 | 11.13 | 14.77 |
| Lower Middle Income | 0.10 | 1.02 | 1.61 | 2.48 | 3.16 | 4.67 | 5.44 | 5.99 | 6.80 | 8.08 | 10.14 | 12.80 | 15.89 | 19.47 |
| Eastern Europe | -0.01 | -0.05 | 0.00 | 0.12 | 0.30 | 0.56 | 0.83 | 1.13 | 1.66 | 2.45 | 4.27 | 7.03 | 10.68 | 14.13 |
| Low Income | 0.11 | 1.14 | 2.05 | 2.85 | 3.78 | 4.74 | 5.49 | 5.52 | 5.77 | 6.38 | 7.68 | 9.66 | 12.28 | 15.85 |
| China | 0.06 | 0.54 | 0.88 | 1.12 | 1.34 | 1.57 | 1.88 | 2.27 | 2.70 | 3.14 | 4.39 | 6.17 | 8.96 | 12.79 |
| India | 0.02 | 0.24 | 0.43 | 0.60 | 0.81 | 1.05 | 1.28 | 1.25 | 1.27 | 1.37 | 1.56 | 1.92 | 2.50 | 3.58 |
| Africa | 0.01 | 0.08 | 0.14 | 0.21 | 0.28 | 0.38 | 0.52 | 0.71 | 0.93 | 1.31 | 1.96 | 3.00 | 4.57 | 6.76 |
| TOTAL | 0.54 | 5.64 | 10.55 | 16.09 | 22.08 | 30.57 | 38.88 | 47.85 | 56.35 | 66.58 | 84.74 | 111.59 | 146.50 | 183.44 |

**Table 21. Explanation of developing countries' land use emissions 1991.**

| Explanatory Variables | World |
|---|---|
| Population density* | 1.100 |
| | (3.37) |
| Population density squared* | -0.130 |
| | (2.79) |
| Annual percentage change in population density | 7.800 |
| | (2.20) |
| 1990 forest cover per hectare* | 0.740 |
| | (9.42) |
| Asia dummy | 1.004 |
| | (3.45) |
| Latin America dummy | 1.504 |
| | (7.51) |
| % of land in temperate climate zone | -1.089 |
| | (2.69) |
| % of people in rainforest climate zone | 1.066 |
| | (2.90) |
| constant | -6.225 |
| | (10.94) |
| Number of Observations | 63 |
| R-squared | 0.819 |

* Actual variables in regression expressed as natural logs.

It is clear from the proceeding discussion that the prediction of emissions from land use change used here is extremely imprecise. The data used for prediction are cross-sectional, so that there is potential for that residual error term to be correlated with the independent variables. The data are also for developing countries only, so that the effect of income growth on deforestation cannot be modeled accurately. Nonetheless, there is a limit to the amount of error we are introducing into the forecasts of long-term carbon concentrations, because there is an upper limit to the amount of emissions that may occur as a result of land use change, i.e. the emissions that would result from total deforestation. While it is certainly not a policy prescription, table 22 shows the effect of cutting down the *entire* tropical forest at a linear annual rate by 2050. We estimate the additional stock *above the 1990 level* to be approximately 85 GtC. While the loss of the forest would be disastrous for many reasons, it would not hugely affect the stock of atmospheric $CO_2$ as of the middle of the next century, *ceteris paribus*. We proceed with projections using equation 9 and the data we have discussed, with the caveat that the land use emissions estimates are subject to a higher proportionate range of uncertainty than those for fossil fuels are.

## IV. Projections of $CO_2$ Emissions to 2050

*Fossil fuel emissions*

Having explained historical emissions, we use the econometric estimates to project emissions and concentrations to 2050. In projecting $CO_2$ emissions from fossil fuels, we use our parameter estimates from the income spline function assuming that the income elasticity of emissions estimated for the last spline within our sample applies to all higher income levels. For population, we use the average of the low and medium UN projections (1996).

To forecast income we make the following simple assumption. We assume that the U.S. economy grows at a rate of 1.5% annually each year. For other countries, we construct our own growth projections based on the following partial convergence equation:

(10) $\text{gap}_t = 0.98\text{gap}_{t-1}$; where $\text{gap}_{t-1} = \ln( y_{i\ t-1}/A_i\ y_{USt-1})$.

The parameter A is defined in the following manner:

(11) $\ln (A_i) = -0.5\ (Tr_i) - 0.5\ (L_i) - \ln (0.7)$,

Where Tr is the percentage of a county's land in tropical ecozones and L is a dummy variable for non-European landlocked countries.

The logarithmic income gap between country i and the United States closes at a rate of 2 percent per year, so that the logarithmic gap at year t equals 0.98 of the logarithmic gap at year t-1. According to this specification, developing countries attain at most 70 percent of the U.S. income level, with non-European landlocked and tropical countries falling further below that level. Countries that currently have incomes greater than 70% of the U.S. per capita income (i.e., the OECD and other high income countries) experience full convergence with the logarithmic income gap shrinking by 2 percent each year. The coefficient $A_i$ is introduced to take into account those fundamental considerations (e.g., physical geography) that may limit full convergence between country i and the United States.[14] We assume that the GDP per capita of country i converges to a long-run level equal to $(A_i * y_{US})$, where $y_{US}$ is the income level of the United States. In particular, we assume that being tropical or landlocked reduces the long-run income level by another 40 percent (0.40 = 1 – exp (-0.5)), and being both landlocked and tropical by 64 percent (0.64 = 1 – exp(-0.5)*exp (-0.5)).

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[14] For a discussion of these considerations, see Gallup, Sachs, and Mellinger (1998).

For forecasting purposes, we require a time trend that will capture energy productivity gains that lower emissions per unit of GDP at a given level of income. The time-fixed effects in our basic equation contain both changes in productivity and real price energy changes since the real price of energy is not

**Table 22. Tropical deforestation scenarios.**

| Data | Central America | South America | Africa | Asia | Oceania | Total |
|---|---|---|---|---|---|---|
| Tropical Forest 1995 000 ha | 79,443 | 870,594 | 504,901 | 279,766 | 41,903 | 1,776,607 |
| Estimated Biomass (tons/ha) | 200 | 189 | 133 | 181 | 191 | |
| Tropical Forest metric tons | 15,888,600,000 | 164,542,266,000 | 67,151,833,000 | 50,637,646,000 | 8,003,473,000 | 306,223,818,000 |
| Carbon content (.45* metric tons) | 7,149,870,000 | 74,044,019,700 | 30,218,324,850 | 22,786,940,700 | 3,601,562,850 | 137,800,718,100 |
| | | | | | | |
| Annual cut if 25% deforested in 2045 (tons of carbon) | 35,048,382 | 370,220,099 | 151,091,624 | 113,934,704 | 18,007,814 | 689,003,591 |
| Annual cut if 50% deforested in 2045 (tons of carbon) | 71,498,700 | 740,440,197 | 302,183,249 | 227,869,407 | 36,015,629 | 1,378,007,181 |
| Annual cut if 75% deforested in 2045 (tons of carbon) | 107,248,050 | 1,110,660,296 | 453,274,873 | 341,804,111 | 54,023,443 | 2,067,010,772 |
| Annual cut if 100% deforested in 2045 (tons of carbon) | 142,997,400 | 1,480,880,394 | 604,366,497 | 455,738,814 | 72,031,257 | 2,756,014,362 |
| Est. Annual emissions if 25% deforested in 2045 (bill. of carbon) | 0.03 | 0.28 | 0.11 | 0.09 | 0.01 | 0.52 |
| Est. Annual emissions if 50% deforested in 2045 (bill. of carbon) | 0.05 | 0.56 | 0.23 | 0.17 | 0.03 | 1.03 |
| Est. Annual emissions if 75% deforested in 2045 (bill. of carbon) | 0.08 | 0.83 | 0.34 | 0.26 | 0.04 | 1.55 |
| Est. Annual emissions if 100% deforested in 2045 (bill. of carbon) | 0.11 | 1.11 | 0.45 | 0.34 | 0.05 | 2.07 |
| Stock in 2045 from deforestation of 25% of tropical forest | | | | | | 21.71 |
| Stock in 2045 from deforestation of 50% of tropical forest | | | | | | 43.42 |

| | | | | |
|---|---|---|---|---|
| Stock in 2045 from deforestation of 75% of tropical forest | | | | 65.13 |
| Stock in 2045 from deforestation of 100% of tropical forest | | | | 86.84 |

included as an independent variable in the equation. Evidence for the inclusion of price effects in the time fixed effects is provided by the fact that the time-fixed effects exhibit an upward trend, with a leveling off in the early 1970s.[15] This change in slope coincides with the large change in world oil prices as a result of the oil crisis. We need to separate the price and productivity trends in the fixed effects, but are unable to do so for the entire sample because of a lack of energy price data. We do have energy price data for the OECD, and so can obtain a pure productivity effect for this sub-sample as the coefficient on a time variable. When the equation is run for the OECD alone*, including prices*, the coefficient on time is negative (-0.01) and significant. This represents productivity changes. We use this coefficient from the OECD-only regression to supplement the income spline coefficients to forecast emissions for the entire sample. (See table 23.) Since prices are excluded from the forecast, we make the implicit assumption that the real price of energy is constant for the period under consideration.

**Table 23. Fossil fuel emissions elasticities; Forecast equation.**

| Explanatory Variables | World |
|---|---|
| 1985 $ PPP GDP per capita spline 1 * | 0.269 |
| | (0.58) |
| 1985 $ PPP GDP per capita spline 2 * | 0.787 |
| | (5.70) |
| 1985 $ PPP GDP per capita spline 3 * | 0.628 |
| | (6.34) |
| 1985 $ PPP GDP per capita spline 4 * | 1.048 |
| | (10.69) |
| 1985 $ PPP GDP per capita spline 5 * | 0.908 |
| | (10.13) |
| 1985 $ PPP GDP per capita spline 6 * | 1.022 |
| | (11.80) |
| 1985 $ PPP GDP per capita spline 7 * | 0.452 |
| | (4.61) |
| 1985 $ PPP GDP per capita spline 8 * | 0.503 |
| | (4.82) |
| 1985 $ PPP GDP per capita spline 9 * | -0.390 |
| | (4.03) |
| 1985 $ PPP GDP per capita spline 10 * | -0.498 |
| | (2.68) |
| Time** | -0.010 |
| | (3.84) |

* Actual variables in regression expressed as natural logs.

** Source: within regession (country fixed effects) for OECD, including a real energy price variable. The coefficient on energy price in this regression is -.023 and the t-statistic is 1.37.

Using the income projections calculated from equations 10 and 11, and the earlier spline estimates, table 24 reports the projected flows of $CO_2$ from fossil fuel emissions between 1990 and 2050 for the major regions under consideration, as well as total world emissions. Historic and projected flows

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[15] This is shown graphically in Schmalensee, Stoker, and Judson (1998).

from 1860-2050 are shown in figure 7. As seen from the table, U.S. emissions decline steadily from 1.4 billion tons of C in 1990 to 0.85 by 2050. Chinese emissions increase from 0.92 billion tons to 1.79 in the same period. Globally, emissions increase from 6.18 to 7.01 billion tons of carbon equivalents. The stocks of $CO_2$ emissions continue to grow for all regions: by 2050, developed countries will have increased by one-half, while emissions of China, India, and the rest of the world will have increased by almost ten times (see figure 8). India experiences the greatest increase, but its emissions are still only a fraction (a third) of Chinese emissions. The projected flows and stocks are shown graphically in figures 9 and 10. The total stock of anthropogenic $CO_2$ emissions in the atmosphere is projected to reach 415 billion tons of carbon equivalents, almost three times the 1990 levels (see table 25 and figure 9).

*Land use emissions*

$CO_2$ emissions from land use sources are projected to the year 2050. We use the population and income projections described previously. We use the population projections used for forecasting $CO_2$ emissions from fossil fuels. The projected emission flows from land use changes are reported in table 26 and figure 11 for the so-called “Nordhaus regions.” Total flows from 1860-2050 are shown in figure 12. Developed countries continue to act as a net sequester of carbon through reforestation at the rate of about 200 million tons a year while the rest of the world reduces its emissions from about 1.5 billion tons in 1990 to less than 1 billion tons annually by 2050.

**Table 24. Projected flow of $CO_2$ emissions from fossil fuels 1996-2050.**

| **Country Group** | **1996** | **2000** | **2010** | **2020** | **2030** | **2040** | **2050** |
|---|---|---|---|---|---|---|---|
| Japan | 0.32 | 0.30 | 0.26 | 0.22 | 0.18 | 0.15 | 0.12 |
| USA | 1.45 | 1.42 | 1.33 | 1.24 | 1.12 | 0.98 | 0.85 |
| EU | 0.85 | 0.81 | 0.70 | 0.60 | 0.51 | 0.42 | 0.34 |
| Other High Income | 0.26 | 0.26 | 0.24 | 0.23 | 0.21 | 0.18 | 0.15 |
| High Income OPEC | 0.12 | 0.13 | 0.13 | 0.11 | 0.10 | 0.08 | 0.07 |
| Middle Income | 0.27 | 0.29 | 0.34 | 0.33 | 0.31 | 0.27 | 0.23 |
| Russia | 0.43 | 0.45 | 0.48 | 0.40 | 0.32 | 0.25 | 0.19 |
| Lower Middle Income | 0.57 | 0.63 | 0.80 | 0.90 | 0.84 | 0.76 | 0.66 |
| Eastern Europe | 0.36 | 0.38 | 0.41 | 0.38 | 0.31 | 0.25 | 0.20 |
| Low Income | 0.31 | 0.38 | 0.63 | 0.84 | 1.02 | 1.21 | 1.09 |
| China | 0.92 | 1.14 | 1.92 | 2.34 | 2.75 | 2.26 | 1.79 |
| India | 0.27 | 0.34 | 0.58 | 0.78 | 0.94 | 0.97 | 0.83 |
| Africa | 0.05 | 0.07 | 0.12 | 0.21 | 0.31 | 0.39 | 0.47 |
| TOTAL | 6.18 | 6.59 | 7.96 | 8.59 | 8.92 | 8.16 | 7.01 |

**Table 25. Projected stock of $CO_2$ from fossil fuels 1996-2050.**

| Country Group | 1996 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---:|---:|---:|---:|---:|---:|---:|
| Japan | 6.35 | 7.02 | 8.30 | 9.12 | 9.60 | 9.82 | 9.88 |
| USA | 40.55 | 43.32 | 49.11 | 53.66 | 57.10 | 59.34 | 60.56 |
| EU | 31.43 | 32.66 | 34.93 | 36.28 | 36.92 | 36.98 | 36.58 |
| Other High Income | 5.50 | 6.07 | 7.28 | 8.24 | 8.99 | 9.49 | 9.79 |
| High Income OPEC | 1.80 | 2.12 | 2.85 | 3.39 | 3.78 | 4.02 | 4.15 |
| Middle Income | 3.63 | 4.40 | 6.41 | 8.29 | 9.71 | 10.75 | 11.45 |
| Russia | 13.40 | 14.05 | 15.93 | 17.48 | 18.22 | 18.39 | 18.22 |
| Lower Middle Income | 8.86 | 10.42 | 14.89 | 20.06 | 24.33 | 27.53 | 29.76 |
| Eastern Europe | 14.20 | 14.61 | 15.93 | 17.30 | 18.04 | 18.28 | 18.19 |
| Low Income | 4.89 | 5.84 | 9.29 | 14.27 | 20.01 | 26.51 | 32.15 |
| China | 11.80 | 14.79 | 25.69 | 39.79 | 55.20 | 67.28 | 74.06 |
| India | 3.37 | 4.29 | 7.62 | 12.38 | 17.71 | 23.30 | 27.26 |
| Africa | 0.89 | 1.04 | 1.69 | 2.86 | 4.74 | 7.00 | 9.60 |
| TOTAL | 146.68 | 160.63 | 199.93 | 243.11 | 284.32 | 318.70 | 341.65 |

**Table 26. Projected flow of $CO_2$ emissions from land use change 1990-2050.**

| Country Group | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---:|---:|---:|---:|---:|---:|---:|
| Japan | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.03 | -0.03 |
| USA | -0.07 | -0.07 | -0.08 | -0.08 | -0.08 | -0.08 | -0.08 |
| EU | -0.09 | -0.09 | -0.09 | -0.09 | -0.08 | -0.08 | -0.07 |
| Other High Income | 0.03 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 |
| High Income OPEC | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Middle Income | 0.54 | 0.54 | 0.53 | 0.50 | 0.46 | 0.42 | 0.38 |
| Russia | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lower Middle Income | 0.27 | 0.27 | 0.25 | 0.23 | 0.20 | 0.17 | 0.15 |
| Eastern Europe | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Low Income | 0.41 | 0.39 | 0.35 | 0.30 | 0.25 | 0.20 | 0.15 |
| China | 0.04 | 0.04 | 0.04 | 0.03 | 0.03 | 0.03 | 0.03 |
| India | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Africa | 0.34 | 0.36 | 0.40 | 0.40 | 0.38 | 0.34 | 0.30 |
| TOTAL | 1.46 | 1.41 | 1.37 | 1.28 | 1.15 | 0.99 | 0.84 |

**Figure 7 Historic and Projected Stocks of $CO_2$ from Fossil Fuels 1860-2050 (billion tons of C)**

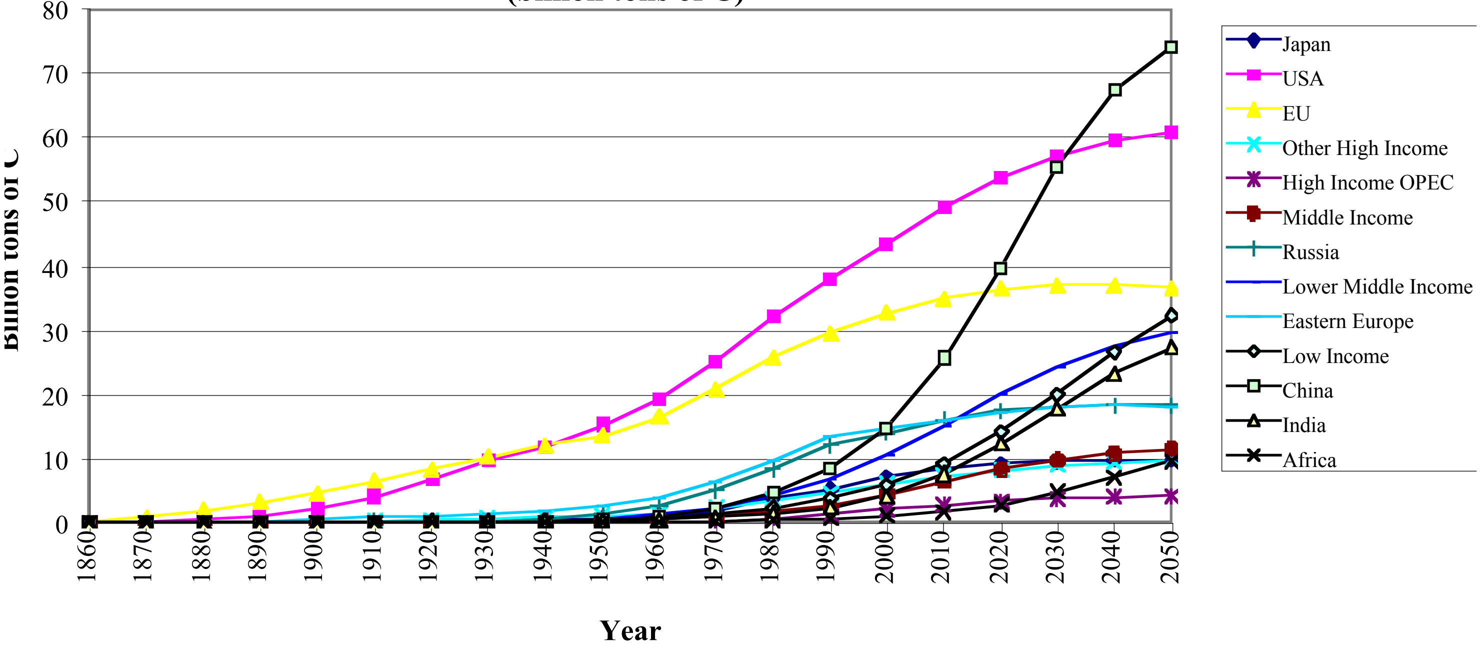


**Figure 8 Historic and Projected Flows of $CO_2$ from Fossil Fuels 1860-2050 (billion tons of C)**

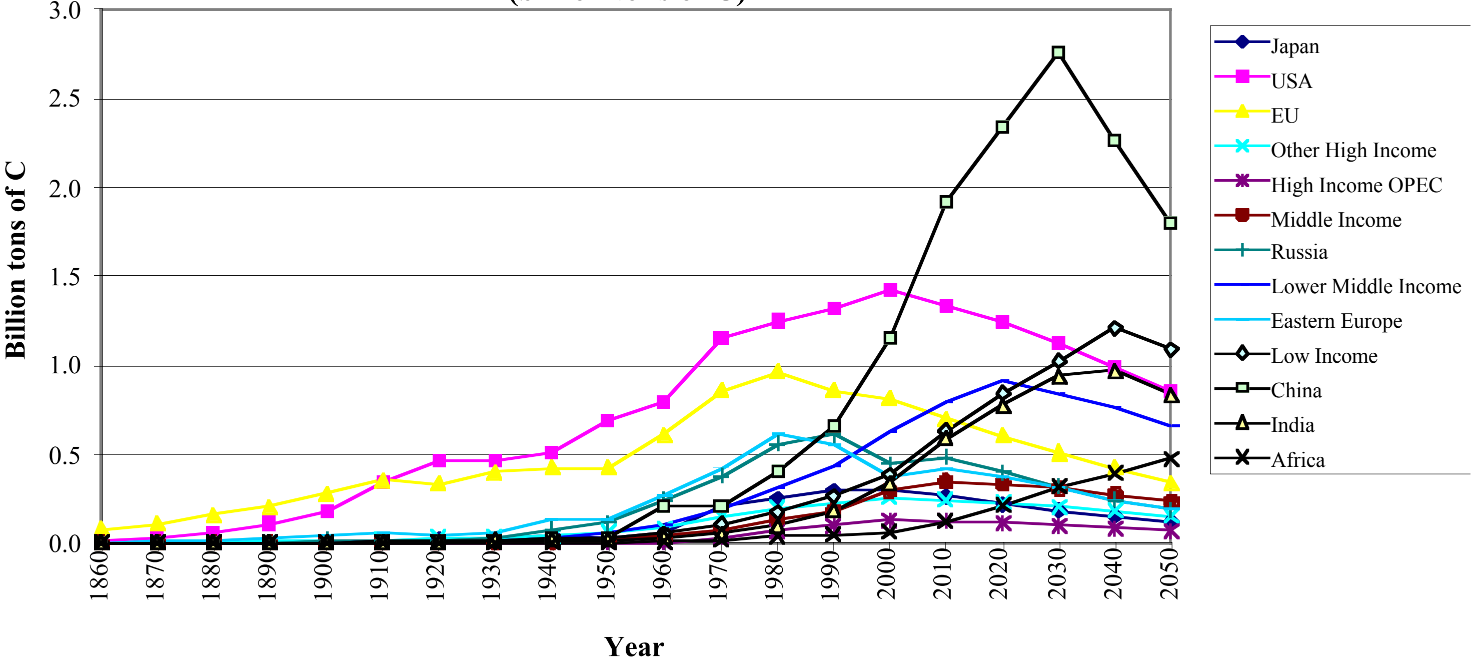


**Figure 9 Projected Flows of $CO_2$ Emissions from Fossil Fuels 1996-2050 (billion tons of C)**

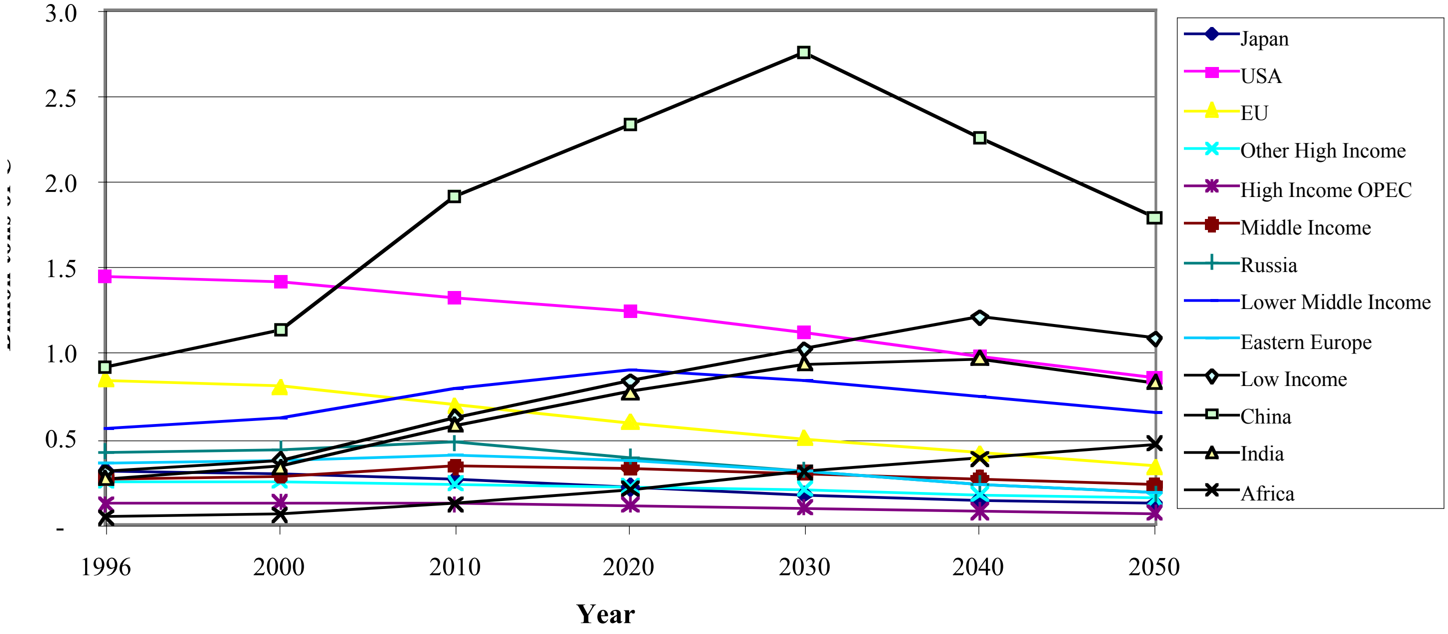


**Figure 10 Projected Stock of $CO_2$ from Fossil Fuels 1996-2050 (billion tons of C)**

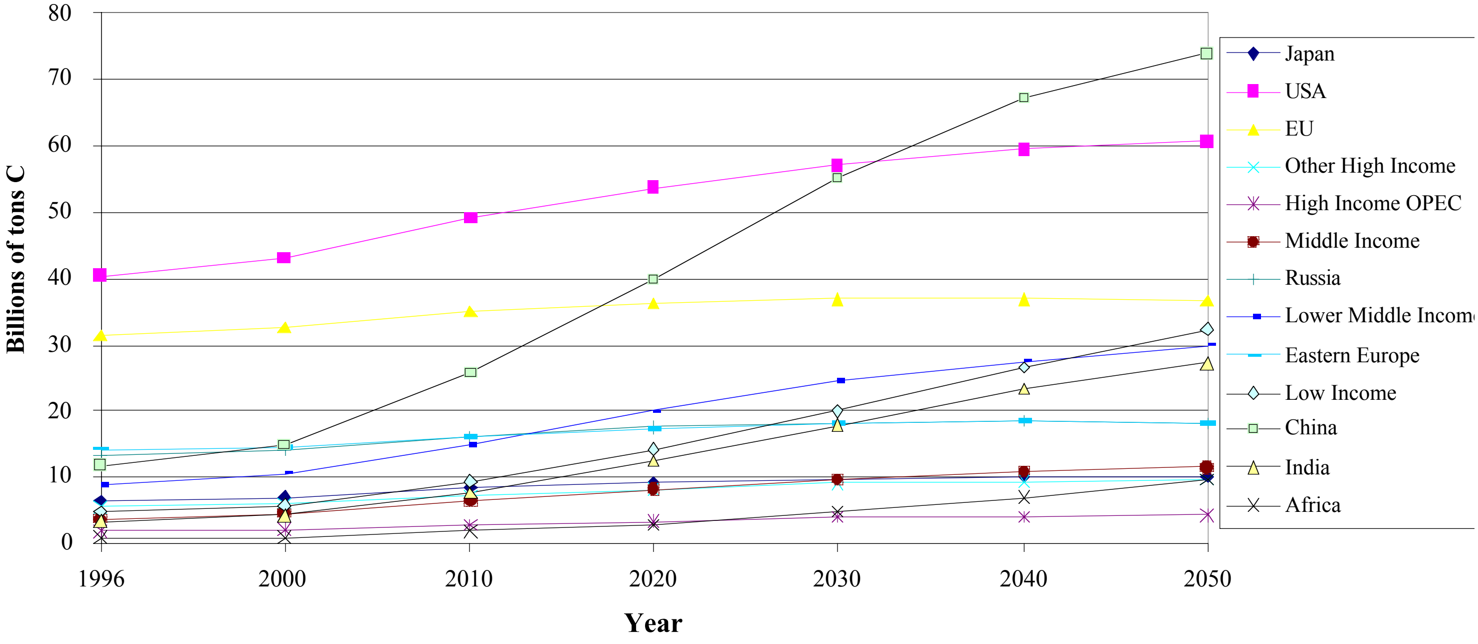


Figure 11 Projected Flow of $CO_2$ from Land Use Change 1990-2050 (billion tons of C)

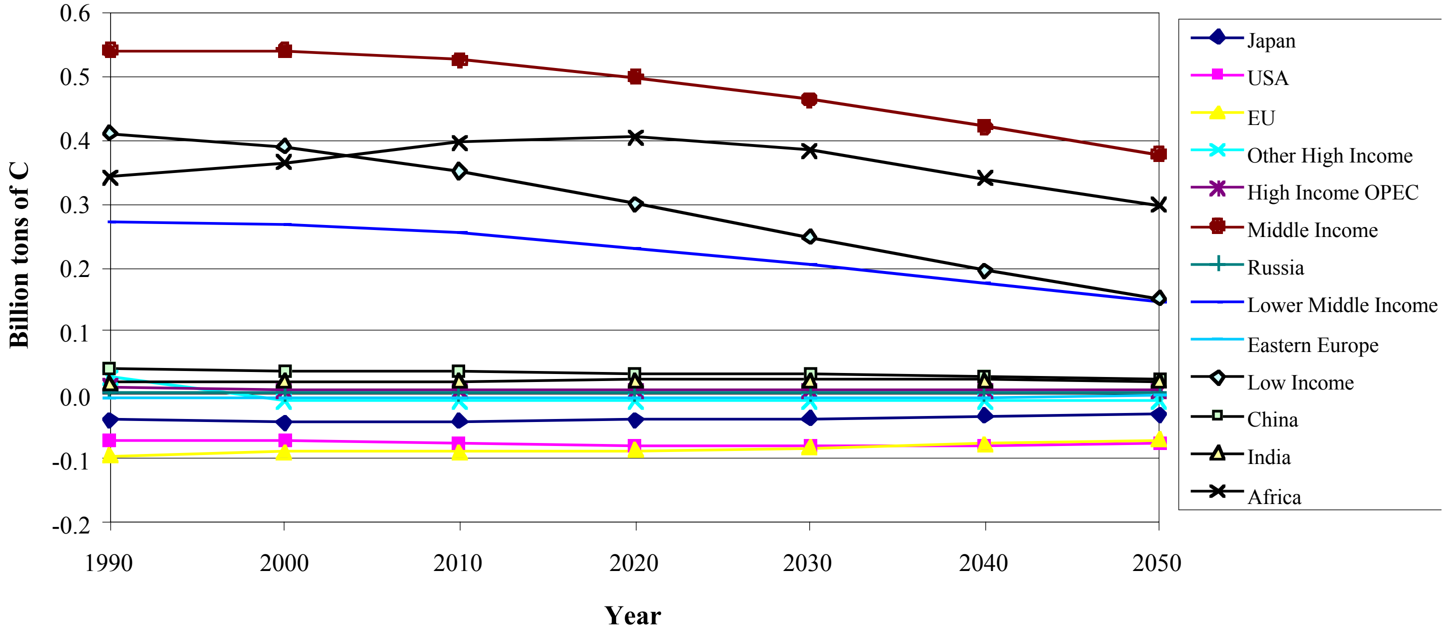
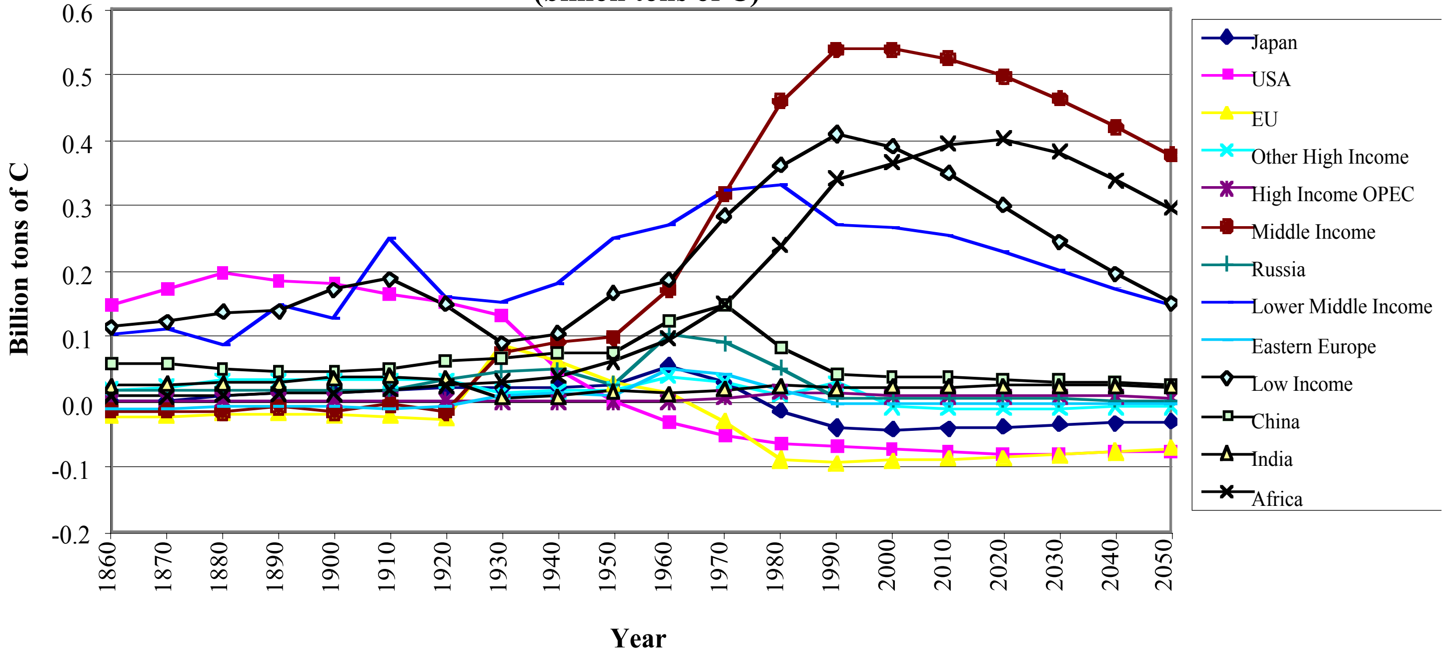


Figure 12 Historic and Projected Flows of $CO_2$ from Land Use Change 1860-2050 (billion tons of C)



The stock of emissions from land use in the atmosphere all but disappears for Annex 1 countries; for the rest of the world the stock increases very slowly (see table 27 and figures 13 and 14). As discussed previously, this suggests that land use changes as a source of emissions all but disappears by 2050 under a “business as usual” scenario, provided that developing countries continue growth at historical levels. Therefore, efforts to control climate change should focus on the consumption of fossil fuels rather than on land use change. This does not mean that the control of reforestation is not a worthwhile investment for other reasons such as biodiversity conservation and watershed protection. Recognizing and internalizing the carbon value of forests may play a critical role in efforts to conserve forests under threat or to reforest deforested areas. Controlling deforestation may not save the climate but efforts to control climate change may save forests from unsustainable uses.[16]

**Table 27. Projected stock of $CO_2$ from land use change 1990-2050.**

| Country Group | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---:|---:|---:|---:|---:|---:|---:|
| Japan | 0.79 | 0.38 | 0.05 | -0.20 | -0.40 | -0.57 | -0.71 |
| USA | 3.12 | 2.49 | 1.89 | 1.31 | 0.76 | 0.27 | -0.18 |
| EU | -0.77 | -1.34 | -1.81 | -2.23 | -2.59 | -2.88 | -3.12 |
| Other High Income | 1.45 | 1.22 | 1.05 | 0.91 | 0.79 | 0.69 | 0.60 |
| High Income OPEC | 0.24 | 0.29 | 0.31 | 0.34 | 0.36 | 0.38 | 0.39 |
| Middle Income | 9.98 | 12.97 | 15.48 | 17.58 | 19.27 | 20.56 | 21.48 |
| Russia | 2.68 | 2.42 | 2.23 | 2.09 | 1.98 | 1.87 | 1.78 |
| Lower Middle Income | 12.80 | 13.56 | 14.24 | 14.74 | 15.03 | 15.13 | 15.06 |
| Eastern Europe | 0.71 | 0.58 | 0.50 | 0.43 | 0.38 | 0.34 | 0.31 |
| Low Income | 12.12 | 13.97 | 15.33 | 16.20 | 16.63 | 16.69 | 16.47 |
| China | 4.34 | 4.20 | 4.11 | 4.05 | 3.98 | 3.91 | 3.83 |
| India | 1.20 | 1.26 | 1.32 | 1.39 | 1.45 | 1.51 | 1.56 |
| Africa | 6.07 | 8.12 | 10.15 | 12.08 | 13.74 | 14.96 | 15.76 |
| TOTAL | 54.73 | 60.12 | 64.85 | 68.69 | 71.38 | 72.86 | 73.23 |

### *Total $CO_2$ emissions projections*

Given the projected decline of deforestation and associated land use emissions over the next 50 years, the projections of total $CO_2$ emissions and their accumulated stocks in the atmosphere are not very different from the projected flows and stocks of emissions from fuel combustion. As seen in table 28 and figures 15a and 15b, total stock of $CO_2$ emissions for the world (including the natural stock of 590 GtC)

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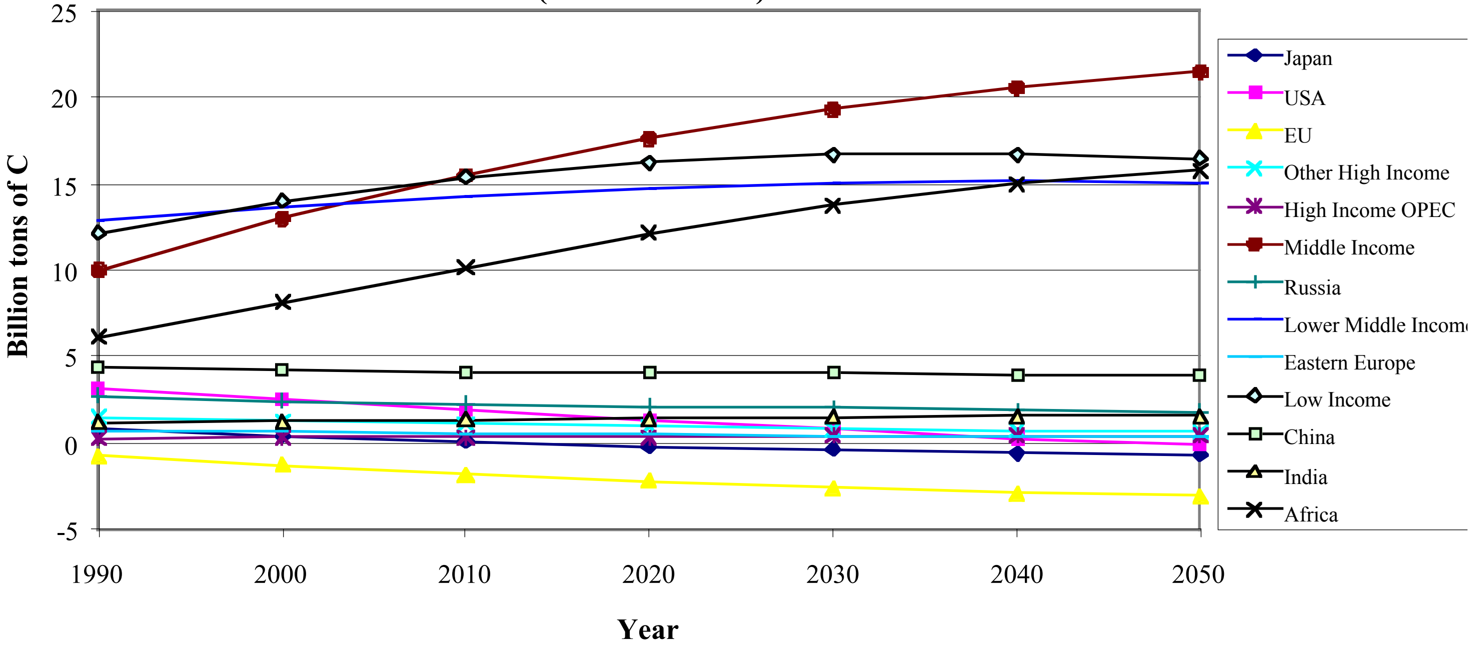
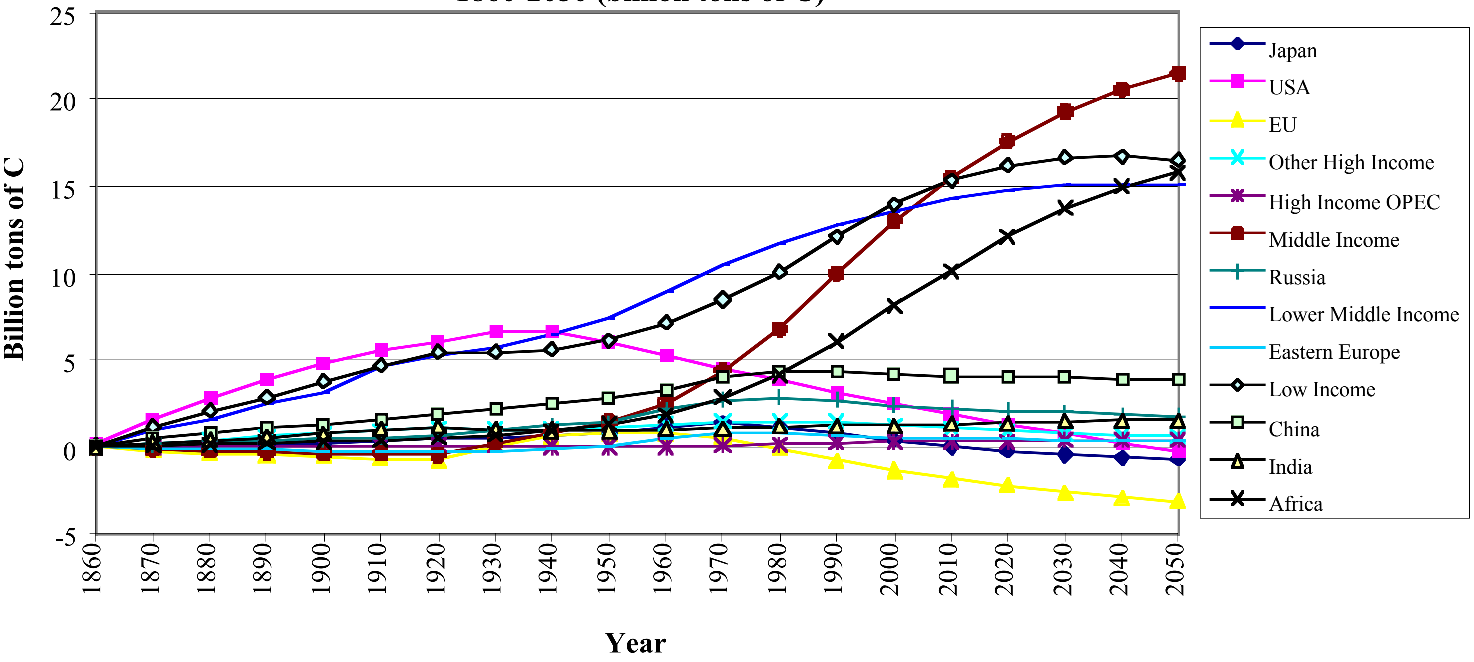
16 The caveat to this conclusion has been noted; there is a high degree of uncertainty regarding emissions from land use change and deforestation.

## Figure 13 Projected Stock of $CO_2$ from Land Use Change 1990-2050 (billion tons of C)



## Figure 14 Historic and Projected Stock of $CO_2$ from Land Use Change 1860-2050 (billion tons of C)



at 2050 is projected to reach almost one trillion tons of carbon equivalent. The land use contribution is only about 73 billion tons. Two notable observations are the constancy and slight decline of the $CO_2$ emissions from Annex 1 and the very rapid growth of Chinese emissions (see figure 16). In terms of stocks, figure 15a shows that Annex 1 continues the leveling off that began in the 1990s while China and the rest of the world begin to dominate even in stock terms past 2030, accounting for about 60 percent of global stocks in 2050.

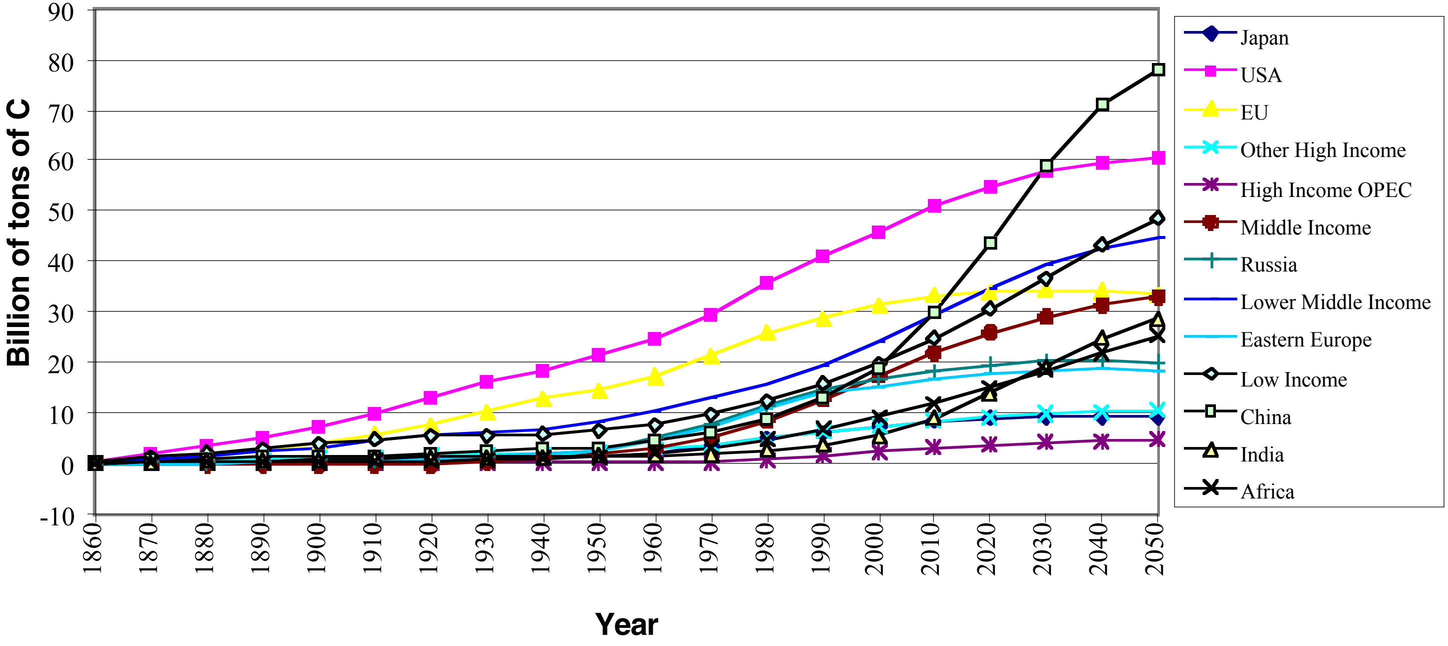
**Table 28. Projected stock of $CO_2$ emissions from fossil fuels and land use change 1990-2050.**

| Country Group | | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Japan | | 6.05 | 7.40 | 8.36 | 8.92 | 9.19 | 9.25 | 9.17 |
| USA | | 41.10 | 45.81 | 51.00 | 54.96 | 57.86 | 59.61 | 60.38 |
| EU | | 28.74 | 31.33 | 33.12 | 34.05 | 34.33 | 34.09 | 33.46 |
| Other High Income | | 6.14 | 7.29 | 8.33 | 9.15 | 9.78 | 10.18 | 10.39 |
| High Income OPEC | | 1.41 | 2.41 | 3.16 | 3.73 | 4.14 | 4.40 | 4.55 |
| Middle Income | | 12.64 | 17.37 | 21.90 | 25.87 | 28.98 | 31.31 | 32.93 |
| Russia | | 14.77 | 16.47 | 18.16 | 19.57 | 20.19 | 20.27 | 20.00 |
| Lower Middle Income | | 19.47 | 23.98 | 29.13 | 34.79 | 39.36 | 42.66 | 44.82 |
| Eastern Europe | | 14.13 | 15.19 | 16.43 | 17.73 | 18.42 | 18.62 | 18.50 |
| Low Income | | 15.85 | 19.81 | 24.62 | 30.47 | 36.64 | 43.20 | 48.63 |
| China | | 12.79 | 18.99 | 29.80 | 43.83 | 59.19 | 71.20 | 77.89 |
| India | | 3.58 | 5.54 | 8.95 | 13.77 | 19.16 | 24.81 | 28.82 |
| Africa | | 6.76 | 9.17 | 11.84 | 14.95 | 18.47 | 21.96 | 25.36 |
| TOTAL | | 183.44 | 220.75 | 264.78 | 311.80 | 355.70 | 391.56 | 414.88 |

Table 28 must be placed in the context of the econometric equation used to estimate emissions from fossil fuels. As a result, we estimate flows of $CO_2$ that level off by 2045, relative to Nordhaus' forecast (see figure 17). As the figure shows, the flows we forecast are higher than those predicted by Nordhaus (1998) until around 2035. This is because our treatment of flows from land use change is different than his and also because we employ environmental Kuznets curve emissions path.

Our forecast emissions path results in a higher predicted stock of $CO_2$ by 2045 relative to Nordhaus, and thus a higher temperature increase. Relative to 1990, we predict a 1.3-degree increase in temperature, while Nordhaus predicts a 0.83-degree increase relative to 1990 levels as a base case. Our forecasts both suggest that by 1990 the global mean temperature had increased by approximately 0.43 degrees relative to 1900. Not only is our prediction of the stock of $CO_2$ in 2045 higher than that of Nordhaus, it is higher than the main scenario of the IPCC, IPCC-92a (IPCC 1996). This is consistent with the forecasts of Schmalensee, Stoker, and Judson (1998) that also predict higher emissions than

## Figure 15a Historic and Projected Stock of CO₂ from Fossil Fuels and Land Use 1860-2050 (billion tons of C)



## Figure 15b Historic and Projected Stock of $CO_2$ from Fossil Fuels and Land Use 1860-2050 (billion tons of C)

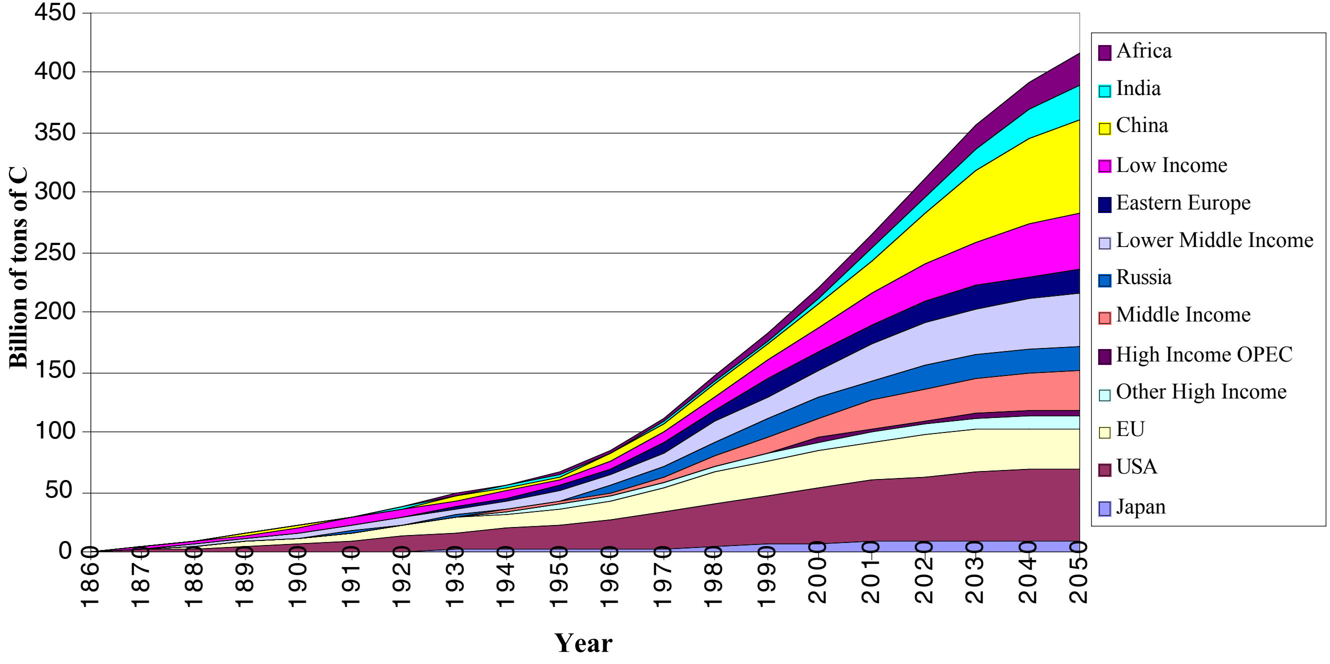


**Figure 16 Historic and Projected Flow of $CO_2$ from Fossil Fuels and Land Use Change 1860-2050 (billion tons of C)**

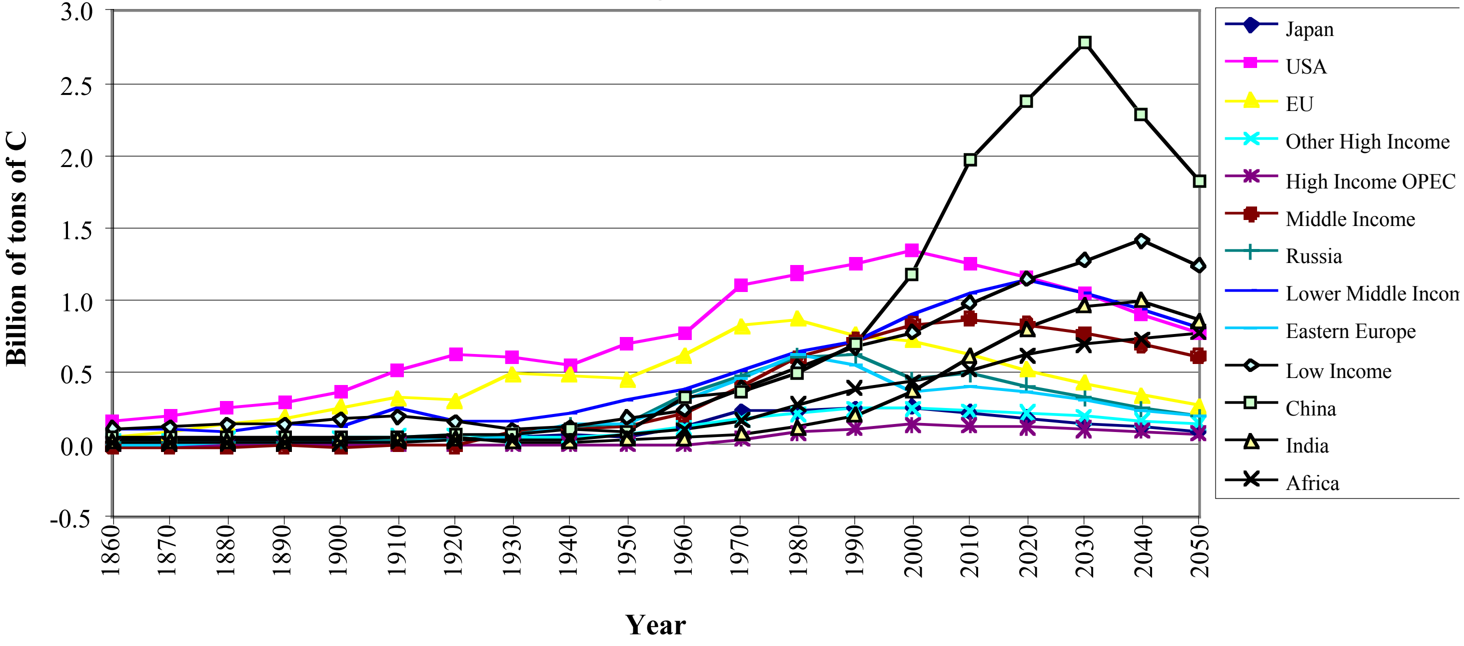
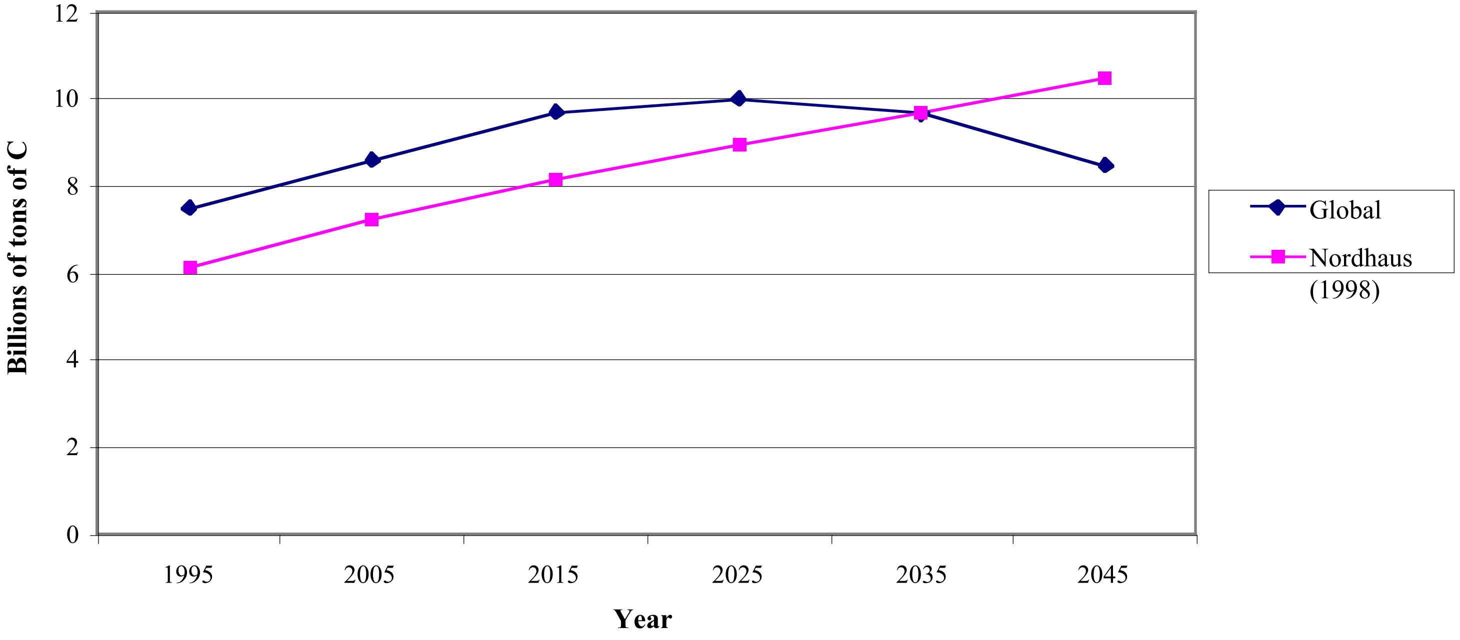


**Figure 17 $CO_2$ Emissions Comparison to the Nordhaus Regional Integrated model of Climate and the Economy (1995-2045)**



IPCC-92a through 2050 when using an environmental Kuznets curve specification. If our forecast were extended through to 2100, our emissions and stock calculations would be lower than those in Nordhaus (1998). Clearly, if $CO_2$ emissions do have an inverted U-shaped relationship to economic growth, the implications for climate change are profound.

## V. Some empirical evidence on damages from climate change

We did not carry out any original research in this paper regarding the damages from rising GHG concentrations. Our findings, therefore, rely on the literature, specifically Nordhaus (1998) as previously explained. The main points that we stress are the following. First, very little is known about likely damages, especially in the developing world. Second, even less is known about the likelihood of several hypothesized catastrophic events (such as runaway warming due to feedbacks from the release of methane from frozen soils, a collapse of ocean current systems, a major melting of arctic icecaps, or a collapse of major ecosystems and the destruction of biodiversity). Third, the risks to the tropics exceed the risks to the temperate zones, most clearly in the effects on agriculture and on disease burdens. Unfortunately, serious policy making will require a much firmer grasp of the likely damages from climate change than are yet available.

As previously explained, Nordhaus posits, then calibrates a damage function that is quadratic in temperature, making separate calibrations for major sub-regions of the world economy. He also distinguishes between non-catastrophic and catastrophic impacts, where the latter are measured as "insurance premiums" on the avoidance of catastrophic outcomes. Among the non-catastrophic damages, Nordhaus includes estimates of the costs of climate change on health, amenities (e.g. recreation), coastal flooding, and agricultural productivity.

The result of applying our projections of a 1.3-degree global temperature increase over 1990 levels by 2045 to the Nordhaus damage functions is shown in table 29.[17] We find that the U.S. economy is essentially unaffected by global warming, with a loss of just 0.05% of its own GDP. China is actually a beneficiary, because of presumed *improvements* in crop productivity. Europe is moderately affected, losing 1.54% of own GDP, mainly because of the presumed cost of sea level rising to coastal environments in Western Europe. The big losers, clearly, are the poorer countries, which generally experience major losses from agriculture, health, and rising sea levels. Africa, already the world's poorest region, is estimated to lose 3.75% of its own GDP, and India is estimated to lose 3.35% of its own GDP.

On the basis of the methodology developed in the companion theoretical paper, we can use the

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17 Though not shown here, all regions are losers in the event of catastrophic impacts; the EU, India, and low income countries are the hardest hit. These data on catastrophic impacts are enormously speculative and are mainly indicative of the considerations that should be examined in later work.

information in table 29 to obtain an estimate of the likely contributions of each region to the global

**Table 29. Damages associated with $CO_2$ emissions by region.**

| | 2045 Population (Thousands) | PPP Forecast GDP 2045 (Millions) | Damages as percentage of own GDP | Damages as percentage of world damage | Contribution to Stock of CO2 as percentage of total stock | Net transfer as percentage of World GDP | Net transfer as percentage of own GDP |
|---|---|---|---|---|---|---|---|
| Japan | 106,391 | 4,011,585 | -0.01% | 0.0% | 3.0% | -0.04% | -1.14% |
| USA | 312,983 | 12,815,233 | 0.05% | 0.4% | 18.1% | -0.24% | -2.09% |
| EU | 332,417 | 11,596,737 | 1.54% | 11.8% | 11.1% | 0.01% | 0.09% |
| Other High Income | 78,474 | 2,619,915 | -1.01% | -1.7% | 2.9% | -0.06% | -2.69% |
| High Income OPEC | 16,980 | 370,618 | 1.42% | 0.3% | 1.2% | -0.01% | -3.63% |
| Middle Income | 355,720 | 5,440,169 | 1.31% | 4.7% | 3.4% | 0.02% | 0.37% |
| Russia | 109,934 | 2,092,953 | -1.15% | -1.6% | 5.5% | -0.10% | -5.15% |
| Lower Middle Income | 936,978 | 14,663,390 | 1.40% | 13.6% | 8.7% | 0.07% | 0.51% |
| Eastern Europe | 161,521 | 2,832,811 | -0.44% | -0.8% | 5.5% | -0.09% | -3.39% |
| Low Income | 1,719,230 | 15,239,445 | 2.25% | 22.7% | 8.9% | 0.19% | 1.37% |
| China | 1,385,457 | 17,751,105 | -0.17% | -2.0% | 21.5% | -0.32% | -2.00% |
| India | 1,375,622 | 14,052,243 | 3.35% | 31.1% | 7.7% | 0.32% | 2.52% |
| Africa | 1,427,028 | 8,740,153 | 3.75% | 21.6% | 2.5% | 0.26% | 3.31% |
| Total | 8,318,733 | 112,226,358 | 1.35% | | | | |

damages and their share of these damages under a “business as usual” scenario. The balance between the two will provide an indication of the direction of compensation flows. Column 3 is derived from the Nordhaus damage equation and translated into column 4. Column 4 is equivalent to the parameter $\lambda_i$ described in section II. Column 5 is calculated from the historic and projected emissions and flow calculations described in sections III and IV. This column corresponds to the parameter $\sigma_i$ described in section II. Recall that we defined $NTP_i = (\sigma_i - \lambda_i)$ WD, where WD is total world damages. These transfers, expressed as percentage of GDP, are shown in the columns 6 and 7 of table 4. The U.S. and China are seen to contribute significantly to the global damages of which they suffer very little or slightly benefit (in the case of China). India and Africa suffer a much bigger share of the damages than their contributions to the problem, and thus would receive compensation. Under a “business as usual” scenario, this methodology results in flows from the temperate zone to the tropical zone and, in general, from rich countries to poor ones. While these transfers do not reflect optimized damages or mitigation and adaptation efforts (defined as $\Delta Y_i$ in section II); the “business as usual” damages are likely to be high relative to the optimum. Given the vulnerability of the tropics to climate change however, it is likely that transfers in a context of optimal emissions would still flow from temperate to tropic and rich to poor.

We want to end this section by stressing once again the profound uncertainties that surround estimates such as these. All along we have stressed several weak links in the analysis in the domains of atmospheric sciences, climatology, and economics. These are: (1) the links from economic development to carbon emissions via the use of fossil fuels and land use changes; (2) the link from emissions to atmospheric carbon is hindered by the problem of “missing carbon” (that is, unidentified carbon sinks that appear to be limiting the rise of atmospheric carbon); (3) the link from atmospheric carbon to global and regional climate patterns, including temperature, precipitation, extreme events; and (4) the link from global and regional climate change to regional damages, in view of the possibilities technical innovation and societal adjustments to long-term changes in climatic conditions.

## VI. Some policy implications

Even with the profound uncertainties, our empirical discussion suggests several general qualitative policy conclusions.

1. The non-Annex I countries are likely to increase significantly their rate of GHG emissions and the proportion of atmospheric GHG stocks for which they are responsible. This is because many developing countries are entering the range of GDP per capita at which emissions are a highly elastic function of GDP growth.
2. The Annex I countries are in the process of stabilizing or even reducing their levels of GHG emissions in the future, as part of an ongoing structural transformation from an industrial society to a service based, post-industrial society.
3. Along the global path of efficient mitigation, it is likely that the Annex I countries will have absolute declines in GHG emissions per capita, as they are already on a “business as usual” trajectory of declining emissions per capita and an estimated negative elasticity of emissions per unit of GDP.

4. Along the global path of efficient mitigation, it is likely that the non-Annex I countries, and especially the developing countries, will have rising emissions per unit of GDP (an elasticity of emissions per GDP that is greater than or equal to 1.0). It may not be prudent to bind such countries to a baseline that preserves the ratio of emissions to GDP, since economic development is associated with a rise in emissions-to-GDP ratio for countries below at least $8,000 per capita.
5. We do not have sufficient data about the elasticity of emissions per unit of GDP as economies continue to reach unprecedented levels of income per capita. Much will depend on the realization of this parameter for the levels of emissions and GHG stocks in future years.
6. The stock of GHG emissions due to land use changes (especially deforestation) is unlikely to be highly significant for climate change in the long term. Of course, deforestation should be slowed or reversed for many other reasons, including more sustainable and efficient land use patterns, the preservation of biodiversity, and the preservation of social habitats for indigenous populations.
7. It appears that Annex I countries will be disproportionately responsible for the projected increase in GHG atmospheric concentrations, while bearing few of the costs. On the other hand, Annex II countries, by and large, will bear heavier costs of climate change and have a disproportionately lower role in the increase of GHGs.
8. The implication of this finding is that compensation for climatic damages will flow from rich to poor countries. According to our crude estimates, these transfer payments may be as much as 1.35 percent of world GDP by 2045.
9. A major exception to this conclusion is China. China bears few projected costs of climate change, but is a projected large contributor to GHG emissions. This would also call for compensation from China to other developing countries on the "business as usual" path.
10. The projected non-catastrophic damages in the Nordhaus damage functions are too low to justify a major mitigation effort as a proportion of current worldwide GDP. Since these damage functions are very crude, and much depends on the real magnitudes of damages from climate change, much more work is needed, on a high-priority basis, to assess possible damages and thereby to calibrate better the appropriate levels of societal response.

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