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# Uncertainties in Estimating Greenhouse Gas Emissions

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## ABSTRACT

Country studies will help define national policy responses and project priorities for restraining the emissions of greenhouse gases. They might also become necessary inputs to international negotiations on sharing the burden of the required emission reductions among nations.

Yet there are many data uncertainties which effect emission estimates. As a result, it is necessary to attach quantitative and qualitative caveats to both country studies, which estimate aggregate national greenhouse gas emissions, and to global studies, which rank country contributions to the increase in atmospheric concentrations of greenhouse gases.

This study was commissioned by the Environment Department, within its broader framework of research on global warming and greenhouse gas reduction, to clarify the nature and estimate the scale of these data uncertainties at the activity, country and global levels, and to estimate the resultant uncertainty range for the estimated national greenhouse gas emission aggregates and country rankings. As shown in this study, numerical estimates and rank orders of country emissions are hardly definitive and need to be supplemented by a serious consideration of the effect of data uncertainties, as well as the method of aggregation chosen.

# UNCERTAINTIES IN ESTIMATING GREENHOUSE GAS EMISSIONS

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# UNCERTAINTIES IN ESTIMATING GREENHOUSE GAS EMISSIONS

## I. INTRODUCTION

Enhancement of the greenhouse effect, or greenhouse warming, has been described as the greatest crisis ever faced collectively by humankind.[1] As scientific understanding of the global carbon cycle and its complex interdependencies has increased over the past decade, the threat posed by greenhouse warming and the potential for an associated change in the global climate has rapidly become an important item on international political and environmental agendas. It is now widely accepted that changes in the natural temperature regulation of the earth's surface are being caused by increasing atmospheric concentrations of radiatively active trace gases including anthropogenic emissions of carbon dioxide, methane, nitrous oxide, and various halocarbons such as the family of chemicals known as chlorofluorocarbons (CFCs).[2] Accurate activity- and country-specific estimates of these greenhouse gas (GHG) emissions are important requisites for formulating comprehensive national and multilateral strategies to address greenhouse warming. At present, however, most countries lack national inventories of GHG emissions, thus making it difficult to develop the appropriate mitigative or adaptive responses. This paper examines ongoing attempts to measure, aggregate, and attribute GHG emissions. The primary focus of the discussion is on the uncertainties in estimating GHG emissions and how such uncertainties can affect analyses which attempt to rank emissions on a country-by-country basis.

There are many uncertainties associated with GHG emissions estimates. The overall effect of these various uncertainties is to attach both quantitative and qualitative caveats to the results of analyses which attempt either to aggregate emissions estimates by applying a GHG weighting indicator or to attribute these emissions to countries using responsibility types of indicators. Depending on the degree of scientific uncertainty, these caveats may actually provide more useful information than the supposedly final and definitive results. Accordingly, this paper can roughly be divided into two parts. The first part (Sections II to IV) deals with the uncertainties in estimating global, country-, and activity-level emissions while the second part (Section V to VII) addresses the importance of these uncertainties in schemes to rank countries by GHG emissions:

> Sections II and III discuss issues associated with GHG emission estimates and emissions inventory construction. In particular, these sections focus on the decision to include specific GHGs and the uncertainties associated with measuring and calculating different GHG emissions and the anthropogenic source activities that generate them;
>
> Section IV details the input assumptions, data sources, and key methodologies of published attempts at developing GHG emission databases;
>
> Section V places the discussion of uncertainties associated with GHG emissions databases into context by describing various purposes that such tools can ultimately be used to serve.

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[1] International Conference on "Global Warming and Climate Change: Perspectives from Developing Countries", New Delhi, India, February 21-23, 1989.

[2] See for example, the closing statements of the Second World Climate Change Conference, October, 1990; and, Arrhenius, E., and T.W. Waltz (1990), "The Greenhouse Effect: Implications for Economic Development", World Bank Discussion Paper Number 78, Washington, DC.

Section VI selects one emission database and one means of aggregating emissions from different GHGs and incorporates the discussion of uncertainties into a sensitivity analysis that illustrates how the rankings of countries' overall GHG emissions can change, depending on the baseline assumptions chosen for a particular analysis; and

Section VII summarizes the key issues raised in the paper and provides some conclusions.

Supplemental information, germane to the analysis performed in Section VI, is presented in two Appendices.

Appendix A provides a brief overview of the various competing methodologies for aggregating and attributing GHG emissions (i.e., GHG weighting indicators);

Appendix B provides data relevant to the analysis contained in Section VI.

## II. GREENHOUSE GAS EMISSIONS

One of the first decisions that analysts constructing a GHG emissions inventory have to make is which GHGs to include in their analysis. This section reviews the major GHGs and provides ranges for estimates of the global budget for these gases. Exhibit II-1 summarizes the key GHGs emitted from anthropogenic sources.

### 1. Carbon Dioxide

Anthropogenic sources of carbon dioxide emissions include combustion of solid, liquid, and gaseous fossil fuels (e.g., coal, oil, and natural gas, respectively), deforestation, and cement manufacturing. The range of estimates for the key sources and sinks of this GHG are summarized in Exhibit II-2. Some activities, such as reforestation efforts, could actually create a net sink for carbon and could therefore be viewed as an emission credit (i.e., negative emissions.)

### 2. Methane

Methane is emitted from various sources including natural wetlands, wet rice cultivation, enteric fermentation by domestic livestock, anaerobic fermentation of solid wastes, production and transportation of natural gas, the burning of biomass, termites, and coal mining. Exhibit II-3 shows the range of estimates for the global sources and sinks of methane.

### 3. Halogenated Fluorocarbons

Chlorofluorocarbons (CFCs) make up the main source of emissions from this group of chemicals. CFCs are used in a variety of sectors including refrigeration, cooling and air conditioning, aerosols, foam-blowing, and solvent cleaning applications. In addition to the family of chemicals known as CFCs, there are several other halocarbons with significant effectiveness in absorbing infrared radiation. Many of these, such as halons, carbon tetrachloride, and methyl chloroform, are expected to be phased out under the Montreal Protocol (including the 1990 London Amendments to the Protocol). Many of the chemical substitutes for substances controlled under the Protocol include partially halogenated fluorocarbons (HCFCs). While these

chemicals are not currently controlled under the Protocol, they are, however, listed as transitional substances and will eventually be phased out. While most of the HCFCs and HFCs (a family of chemicals with zero ozone depleting potential) have significantly shorter atmospheric residence times than CFCs, some scientists believe that they are, however, potent GHGs. Exhibit II-4 displays the production of CFCs by region.

### 4. Nitrous Oxide

Nitrous oxide is produced from a wide variety of biological as well as anthropogenic sources such as biomass burning. Exhibit II-5 shows the range of estimates for the key sources and sinks of this GHG.

### 5. Tropospheric Ozone and Related Trace Gases

Tropospheric ozone is a GHG whose distribution is controlled by several complex processes including the photo-oxidation of carbon monoxide and non-methane hydrocarbons (NMHC) in the presence of reactive nitrogen oxides. These gases, which are precursors of tropospheric ozone, could also be considered for inclusion in an emissions inventory. However, at present there are no reliable global emission estimates for these gases, although some regional emission estimates are available. Furthermore, the science underlying the role of tropospheric ozone in the atmosphere is poorly understood, although most scientists agree that its percentage contribution to climate change is quite small.

### 6. New Synthetic Chemicals

In constructing a GHG emissions inventory, an analyst must also consider how to address the emissions produced from the use of other new synthetic chemicals that may be found to have long atmospheric residence times and strong infrared heating effectiveness.

### 7. Gases Making Negative Contributions to Greenhouse Warming

Another complex issue is how GHG emissions inventories should address emissions from gases making negative contributions to greenhouse warming. For example, it has been suggested that sulfate aerosols in the troposphere emitted from the combustion of fossil fuels may have dampened greenhouse warming in northern latitudes.[3] In determining rankings of countries, one possibility might be to assign credits for emissions of GHGs with negative greenhouse forcing effects.[4] Other environmental impacts of the gases may also need to be taken into account.

Credits may also be assigned for activities that reduce the potential for greenhouse warming. For example, as mentioned earlier, reforestation efforts result in a net uptake of carbon that will slow the build-up of $CO_2$ in the atmosphere. Similarly, activities that capture GHGs prior to their release to the atmosphere, such as methane recovery at landfills or from coal mining activities, reduce net releases to the atmosphere and could be assigned emission credits.

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[3] Wigley, T.M.L. (1989), "Possible Climate Change due to Sulphur Dioxide-Derived Cloud Condensation Nuclei," in Nature, Volume 339, pages 365-367.

[4] Dickenson, R.E. and R.J. Cicerone (1986), "Future Global Warming from Atmospheric Trace Gases," in Nature, Volume 319, pages 109-115.

**Exhibit II-1**
**Summary of Key Greenhouse Gases Influenced by Human Activities[5]**

| PARAMETER | CARBON DIOXIDE | METHANE | CFC-11 | CFC-12 | NITROUS OXIDE |
|---|---|---|---|---|---|
| Pre-industrial atmospheric concentration (1750-1800) | 280 ppmv | 0.8 ppmv | 0 | 0 | 288 ppbv |
| Current atmospheric concentration (1990) | 353 ppmv | 1.72 ppmv | 280 pptv | 484 pptv | 310 ppbv |
| Current rate of annual atmospheric accumulation | 1.8 ppmv (0.5 percent) | 0.015 ppmv (0.9 percent) | 9.5 pptv (4 percent) | 17 pptv (4 percent) | 0.8 ppbv (0.25 percent) |
| Atmospheric lifetime (years) | 50-200 | 10 | 60 | 130 | 150 |

**Exhibit II-2**
**Sources and Sinks of Carbon Dioxide[6]**

| | Amount of Carbon (Gt C per year) |
|---|---|
| **Source**<br>Emissions from fossil fuels into the atmosphere<br>Emissions from deforestation and land use | <br>5.4 +/- 0.5<br>1.6 +/- 1.0 |
| **Sink**<br>Accumulation in the atmosphere<br>Uptake by the ocean | <br>3.4 +/- 0.2<br>2.0 +/- 0.8 |
| **Net Imbalance** | **1.6 +/- 1.4** |

[5] IPCC (1990), "Climate Change: The IPCC Scientific Assessment", Section 1.2.4.3., Cambridge University Press. page 7. Key: ppmv -- parts per million by volume, ppbv -- parts per billion by volume, pptv -- parts per trillion by volume.

[6] IPCC (1990), op. cit., Section 1.2.4.3..

**Exhibit II-3**
**Estimated Sources and Sinks of Methane[7]**

| | Annual Release (Tg Methane) | Range (Tg Methane) |
|---|---|---|
| **Source** | | |
| Natural Wetland | 115 | 100 - 200 |
| Rice paddies | 110 | 25 - 170 |
| Enteric Fermentation | 80 | 65 - 100 |
| Gas Drilling | 45 | 25 - 50 |
| Biomass Burning | 40 | 20 - 80 |
| Termites | 40 | 10 - 100 |
| Landfills | 40 | 20 - 70 |
| Coal Mining | 35 | 19 - 50 |
| Oceans | 10 | 5 - 20 |
| Freshwaters | 5 | 1 - 25 |
| Methane Hydrate Destabilization | 5 | 0 - 100 |
| **Sink** | | |
| Removal by soils | 30 | 15 - 45 |
| Reaction with OH in the atmosphere | 500 | 400 - 600 |
| **Atmospheric Increase** | 44 | 40 - 48 |

**Exhibit II-4**
**World CFC Production (Thousand Tons 1988)[8]**

| | Total | Refrig. | Foams | Aerosols | Cleaning |
|---|---|---|---|---|---|
| **WORLD** | 1139 | 342 | 319 | 216 | 262 |
| **U.S.A.** | 355 | 123 | 106 | 17 | 111 |
| **W. EUROPE** | 317 | 34 | 109 | 119 | 56 |
| **JAPAN** | 182 | 45 | 37 | 12 | 88 |
| **REST OF THE WORLD** | 285 | 140 | 67 | 68 | 9 |

[7] IPCC (1990), op. cit., Table 1.2.

[8] Chemical Economics Handbook (1990), as cited in King, K. and M. Munasinghe (1991), "Montreal Protocol: Incremental Costs of Phasing Out Ozone Depleting Substances", World Bank Environment Working Paper No.47.

**Exhibit II-5**
**Estimated Sources and Sinks of Nitrous Oxide[9]**

| Sources and Sinks of Nitrous Oxide | Range (Tg N per year) |
|---|---|
| **Source** | |
| Oceans | 1.4 - 2.6 |
| Soils (tropical forests) | 2.2 - 3.7 |
| Soils (temperate forests) | 0.7 - 1.5 |
| Combustion | 0.1 - 0.3 |
| Biomass burning | 0.02 - 0.2 |
| Fertilizer (including groundwater) | 0.01 - 2.2 |
| TOTAL | 4.4 - 10.5 |
| **Sink** | |
| Removal by soils | ? |
| Reaction with OH in the atmosphere | 7 - 13 |
| **Atmospheric Increase** | 3 - 4.5 |

## III. UNCERTAINTIES IN ESTIMATES OF GHG EMISSIONS

Scientific uncertainties contained in the GHG emissions database stem primarily from indeterminable factors affecting our understanding of the anthropogenic activities that generate GHG emissions. Such uncertainties could be associated with both the estimation of the global budget for a particular GHG as well as estimates for GHG-producing activities in specific countries. Moreover, uncertainties in the global budget for a particular GHG or activity can translate into even greater uncertainties when attributing emissions to countries. Specifically, even if the global budget for a certain GHG or activity is known with a good deal of precision, the means by which we attribute the global budget of the GHG or activity to countries may not accurately reflect specific factors determining emissions in each country.

Uncertainties concerning how the level of GHG emissions from a specific activity and from specific countries should be measured fall into two basic categories: (1) source activity data, which describe the level of human activity that is a source of GHG emissions (e.g., the amount of fossil fuel consumed, the amount of land deforested, etc.), and (2) emission factor data, which describe the rate at which GHG emissions are produced for a specified activity (e.g., $CO_2$ emissions per unit of coal consumed or hectare of land deforested). The lack of certainty may affect the overall level of confidence one has in the reliability of the GHG emissions database, or at least in certain components of a database that may be less reliable than other components. These uncertainties can affect individual country rankings, estimates of the relative importance of

[9] IPCC (1990), op. cit., Table 1.4.

each GHG, estimates of each activity's contributions to greenhouse warming, etc. This section reviews uncertainties in emission estimates for each of the key GHGs discussed in Section II.

### 1. Carbon Dioxide

Global estimates for carbon dioxide are complicated by the fact that the gas is continuously cycled between the atmosphere, the terrestrial biosphere and the oceans. Moreover, the seasonal asynchronicity of these exchanges results in periodic oscillations in atmospheric carbon dioxide concentrations.[10] The major anthropogenic contribution to carbon dioxide comes from the combustion of fossil fuels. As Exhibit II-2 indicates, emissions from fossil fuels have an uncertainty range of approximately plus or minus 10 percent. Such estimates can be considered fairly accurate as they are based upon data such as estimates of the quantity of fossil fuels consumed and the carbon contents of these fuels. Sources for these primary data items are generally quite reliable since energy consumption data are available from most countries and the carbon contents of the various fossil fuels are known with a relatively high degree of certainty. Estimates of carbon emission coefficients for fuels from different studies are summarized below in Exhibit III-1. In each case, the coefficients are expressed in units of kg C/gigajoule ("net" heating value basis). As can be seen from Exhibit III-1, even in cases where multiple studies have been performed, there is little difference in the value of the derived carbon emission coefficients.

Despite this convergence of estimates for emission coefficients, in many cases, the coefficients cited for specific fuel types do not reveal the underlying uncertainties behind the estimates. For example, the carbon emission coefficient of 21.4 kg C/GJ for crude oil suggested by Marland and Rotty is derived from an estimate of 85% +/- 1% for the carbon content of oil. Similarly, the carbon emission coefficient for coal of 25.5 kg C/GJ also suggested by Marland and Rotty is derived from an estimate of 74.6% +/- 2% for the carbon content on a per tonne coal-equivalent basis.[11] Cited estimates of the amount of carbon oxidized from energy use do not usually reveal their uncertainties. In the case of oil, for example, 1.5% +/- 1% remains unoxidized and for coal, 1% +/- 1% of carbon supplied to furnaces remains unoxidized.[12] Despite these uncertainties, in general it is fair to state that estimates for carbon dioxide emissions from fossil fuel combustion have a fairly tight band of certainty. It is interesting to note, however, that any uncertainties that may exist are most likely to affect emission estimates at more disaggregated levels. That is, while global estimates may be relatively accurate, there may be greater uncertainty in country level estimates due to differences in fuel quality or other data limitations that are not adequately captured with average global assumptions. By comparison, however, the uncertainty range for the contribution of carbon dioxide emissions to the global budget from the other major anthropogenic source, deforestation and land-use changes, is approximately plus or minus 60 percent. There are five main components in the calculation of net GHG emission from these activities: (1) burning associated with land use change; (2) decay of biomass on site (roots, stumps, slash, twigs, etc.); (3) oxidation of wood products removed from

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[10] United States Environmental Protection Agency (1990), "Policy Options for Stabilizing Global Climate," Report to Congress, Main Report, page II-10.

[11] OECD (1991), op. cit., p. 2-16.

[12] OECD (1991), op. cit., p. 2-19.

site (paper, lumber, waste, etc.); (4) oxidation of soil carbon; minus (5) regrowth of trees and redevelopment of soil organic matter following harvest.[13]

**Exhibit III-1**
**Carbon Emission Coefficients for Fuels from Different Studies[14]**
**(kg C/gigajoule; net heating value basis)**

| STUDY / FUEL TYPE | MARLAND & ROTTY (1984) | GRUBB (1989) | OECD (1991) |
|---|---|---|---|
| ANTHRACITE | | 26.8 | |
| BITUMINOUS COAL | 25.5 | 25.8 | 25.8 |
| LIGNITE | | 27.6 | |
| PEAT | | 28.9 | |
| CRUDE OIL | 21.4 | 20.0 | 20.0 |
| GASOLINE | | 18.9 | |
| KEROSENE | | 19.5 | |
| DIESEL/GAS-OIL | | 20.2 | |
| FUEL OILS | | 21.1 | |
| NATURAL GAS | 15.2 | 15.3 | 15.3 |

Part of the uncertainty in estimating net flux to the atmosphere is due to the difficulties in determining the outcome in a specific land area. As forests are cut down, most of the carbon in the cleared biomass (including carbon in the soils) is released to the atmosphere as carbon dioxide. Unless the forests are allowed to regrow, these emissions will be a net contributor to atmospheric carbon dioxide levels. On the other hand, forests also have the capability to store additional carbon if previously unforested lands are converted to forests.

Estimating emissions from land-use changes such as deforestation is an uncertain exercise primarily due to limited data on the amount of land affected by various land-use changes, the ultimate fate of these lands, and the rate at which changes in emissions rates occur.[15] These problems are most critical in the tropics because most emissions from land-use change are thought to occur in these regions and the research performed to date does not adequately characterize

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[13] IPCC (1990), op. cit., p. 12.

[14] OECD (1991), "Estimation of Greenhouse Gas Emissions and Sinks," Final Report from the OECD Experts Meeting, February 18-21, 1991, Prepared for the Intergovernmental Panel on Climate Change. Revised August 1991. p. 2-16.

[15] Moreover, there are scientific uncertainties associated with the carbon cycle, including the size of various sinks such as carbon uptake by the oceans or how much carbon can be sequestered in above-ground biomass and soils.

emission rates under all conceivable changes in land-use patterns. Substantial research is underway at this time to resolve many of these uncertainties. The most critical uncertainties in estimating emissions from savanna burning and the burning of agricultural wastes are due to primarily poor data on emission factors and secondarily to a lack of data on the extent of each practice.

Country-specific estimates for deforestation have proven to be a matter of international controversy. For example, Agarwal and Narain have severely criticized the estimates of deforestation in Brazil and India that the World Resources Institute (WRI) uses to construct its Greenhouse Index.[16] Exhibit III-2 indicates the large range of uncertainty for measuring forest loss in Brazil. While WRI chose 8 million hectares as the annual average deforestation rate in Brazil during the 1980s, Agarwal and Narain (1991) suggest that 2.3 million hectares is a more reasonable figure. Similarly, Agarwal and Narain (1991) claim that WRI's use of 1.5 million hectares per year as the annual rate of deforestation in India during the 1980s is far too high. Additionally, since there is substantial uncertainty in the net carbon flux due to deforestation, even agreements on total area affected leads to a substantial uncertainty range about total carbon emissions.

Another important anthropogenic contribution to the carbon dioxide budget is cement production, in which carbon dioxide is emitted during the calcination process that occurs in cement kilns. The amount of $CO_2$ emitted is a function of the lime (CaO) produced domestically by calcination that is used in the production of both masonry and Portland cement. Such lime enters cement production 1) as a component of domestically produced clinker used in the manufacture of Portland and Masonry cement; and 2) as a component (60%) of additional substances (5% by weight) added to masonry cement during manufacture. Most of the structural cement currently produced in the world is of the "Portland" cement type, which contains 60 to 67 percent lime by weight.[17] Applying an emissions coefficient to material balances for each input yields $CO_2$ emissions from each relevant upstream process. Summing these subtotals yields an overall estimate of carbon dioxide emissions from cement production.

International cement production data are available from the United Nations (1988) and from the U.S. Bureau of Mines (1988).[18] While the CaO content is usually assumed to be a point estimate of 63.5 percent, as discussed above, the range for the fraction of CaO is properly defined as 60 to 67 percent. This assumption represents an uncertainty range of approximately plus or minus 6 percent in the estimates for carbon dioxide emissions. Moreover, country estimates of carbon dioxide from cement production are only reliable if the clinker from which the cement is manufactured is produced domestically.[19] It is during the production of clinker

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[16] Agarwal, A and S. Narain (1991), "Global Warming in an Unequal World," Centre for Science and Environment, India, discussion paper critique of Hammond, A.L., E. Rodenburg, and W. Moomaw (1990), "Accountability in the greenhouse," Nature, Volume 347, October 25, 1990..

[17] Much of the discussion on emissions from cement production is taken from OECD (1991), op. cit.

[18] See for example: United Nation (1988), "United Nations Statistical Yearbook," United Nations, New York; U.S. Bureau of Mines (1988), "Cement Minerals Handbook," Department of Interior, Washington DC.

[19] Clinker forms in a cement kiln. It is ground into dust in order to manufacture cement.

**Exhibit III-2**
**Estimates for Forest Loss in Brazil[20]**

| YEAR | SOURCES | ESTIMATED EXTENT OF ANNUAL DEFORESTATION (in million of hectares) |
|---|---|---|
| 1981-85 | FAO, United Nations | 1.4 |
| 1987 | Alberto Setzer, National Space Research Institute (INPE), Brazil (using remote sensing) | 8.0 |
| 1988 | Alberto Setzer, INPE, Brazil (using remote sensing) | 4.8 |
| 1989 | Alberto Setzer, INPE, Brazil (using remote sensing) | 2.0 - 2.4 |
| 1988 | Philip Fearnside, INPE, Brazil (using remote sensing) | 3.5 |
| 1988 | Roberto Pereira da Cunha, INPE, Brazil (survey in 1988 based on 10 years data using Landsat Thematic Mapper) | 1.7 |
| 1988 | Recalculation using INPE data, personal communication (Centre for Science and the Environment with Jose Goldemberg, President, University of Sao Paulo, Brazil. | 2.3 |

that carbon dioxide emissions are produced; emissions from imported clinker should be attributed to the country from which the clinker was imported.

Cumulatively, the release of carbon dioxide from fossil fuel use and cement manufacturing from 1850 to 1987 is estimated at 200 Gt of carbon plus or minus 10 percent.[21] The total release of carbon to the atmosphere from changes in land use, primarily deforestation, between 1850 and 1985 was estimated at 115 Gt of carbon with an error range of plus or minus 35 Gt.[22] Due to difficulties in ascertaining reliable activity data at the country level (as discussed above) and uncertainties in emission factors for these activities (e.g., what is the net carbon flux per hectare

[20] Adapted from Agarwal and Narain (1991), op. cit., p. 5.

[21] Marland, G, T.A. Boden, R.C. Griffin, S.F. Huang, P. Kanciruk, and T.R. Nelson (1989), "Estimates of Carbon Dioxide Emissions from Fossil Fuel Burning and Cement Manufacturing, Based on the United Nations Energy Statistics and the U.S. Bureau of Mines Cement Manufacturing Data", Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center, U.S. Department of Energy, Oak Ridge, TN.

[22] IPCC (1990), op. cit., Executive Summary.

due to land-use change), country level estimates may exhibit wider variability than indicated by global emissions totals.

## 2. Methane

Cicerone and Oremland (1988) have reviewed the uncertainties contained in estimating the global sources and sinks of methane.[23] As Exhibit II-3 indicates, the sources of methane are diverse and the uncertainty ranges for specific sources are quite significant in some cases. For example, the uncertainty in the range of estimates of methane emissions from rice paddies is large (emission estimates are between 25-170 Tg of methane per annum) because of the heterogeneity of rice cultivation techniques and lack of data on methane fluxes during the rice cultivation cycle. These activity-specific uncertainties are reinforced by uncertainties in the role methane plays in atmospheric chemistry. Current scientific limitations on understanding the complex atmospheric interactions involving methane also lead to major uncertainties in the size of the global methane budget.

Methane emissions from rice cultivation occur due to anaerobic decomposition of organic material in flooded rice fields, with the methane escaping to the atmosphere primarily through the rice plant. The rate of methane emissions varies significantly during the growing season and can be influenced by several factors, including soil composition, temperature, water management practices, and fertilizer application. In recent years some research has been conducted to measure the rate of methane emissions from flooded rice fields, yet the pattern of methane emissions is not yet fully understood. Annual global emission estimates for methane emissions from rice fields vary by as much as a factor of four. Averaged over the growing season, as much as 60% to 80% of the methane produced in flooded rice fields is oxidized. Transport of the remaining, non-oxidized methane from the submerged soil to the atmosphere occurs by diffusion through the floodwater, amongst other vehicles. The range for emissions coefficients for daily emission fluxes for rice fields is 0.19 - 0.69 g methane/$m_2$/day.[24] Ranges for $CH_4$ emission rates derived from flux/temperature relationships are shown in Exhibit III-3. It should be noted, however, that these estimates are based on a study performed in Italy from which figures have been extrapolated to obtain regional estimates.

In order to obtain better estimates for emissions from paddy fields, more research needs to be conducted in the major rice-growing regions, particularly China and India where 60 percent of the world's harvested area of rice paddies are located. As Exhibit II-3 shows, present estimates suggest great uncertainty in the range of 25 to 170 Tg methane per year in the global budget for methane emissions from rice cultivation. Preliminary data collected by the Council for Scientific and Industrial Research (CSIR) in India suggests that the range of methane emissions from rice paddies in India is between 3 and 9 million tonnes rather than IPCC's estimate of 7 to 49 million tonnes.[25]

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[23] Cicerone, R.J. and R.S. Oremland (1988), "Biogeochemical Aspects of Atmospheric Methane," in Global Biogeochemical Cycles, Volume 2, Number 4, pp 299-327, December 1988.

[24] OECD (1991), op. cit., pp. 5-28 to 5-37.

[25] Agarwal and Narain (1990), op. cit., p.7.

Methane emissions from enteric fermentation in animals occur as a result of the digestive process by which microorganisms break down carbohydrates in the animal feed. Globally this accounts for between 65 and 100 Tg per year. The amount of methane is a function of the type, weight, and age of the animal, the quality and quantity of the feed, and the energy expenditure of the animal. Because there are so many variables that affect the amount of methane emitted, a significant amount of information is required in order to accurately determine these emissions. Estimates of emissions range from 94 kg methane per animal per year from German dairy cattle to approximately 35 kg methane per animal per year from Indian cattle fed on kitchen refuse, to less than 8 kg methane per animal per year for sheep. Although animal population data, such as those from the United Nations Food and Agriculture Organization (FAO), require improvements, a substantial amount of research is being conducted in this area, which will improve an analyst's ability to estimate emissions from this source category. Future emission estimates could be improved if available data on animal feeding practices, feed characteristics, and type of management system were improved.

**Exhibit III-3**
**Methane Emission Rates Derived from Flux/Temperature Relationships[26]**

| REGION | AVERAGE SOIL TEMPERATURE IN THE UPPER LAYER (1-10 cm) deg. C | METHANE EMISSION RATE (g/m.sq./day) |
|---|---|---|
| Temperate: Europe, United States, and Japan | 21 - 26 | 0.28 - 0.59 |
| Tropical: Asia, Africa, and South America (wet season) | 25 - 28 | 0.50 - 0.80 |
| Tropical: Asia, Africa, and South America (dry season) | 20 - 26 | 0.24 - 0.59 |

Methane is emitted from animal wastes when these wastes decompose in an anaerobic environment. The amount of methane produced as a result is highly uncertain. It is believed that only a minor portion of waste is disposed of in an anaerobic environment, which would imply that actual emissions from this category are much lower than the theoretical potential. Precise emission estimates are hampered by the lack of information on the type of management system used to handle animal wastes and the most likely rate of emissions from each management system.

[26] Schutz, H., A. Holzapfel-Pschorn, R.Conrad, H.Rennenberg, and W.Seiler (1989), "A 3-Year continuous record of the influence of daytime, season, and fertilizer treatment on methane emission rates from an Italian rice paddy," in Geophysical Research 94:16405-16416.

Methane is also emitted from landfills as a result of the anaerobic (in the absence of oxygen) decomposition of organic matter. Many factors can affect the rate of methane emissions from landfills, including the amount and type of waste, type of waste management system, size of the waste particles, moisture content, temperature, etc. Due to the wide variety of conditions under which waste may be disposed, more research needs to be performed to adequately characterize emissions from this source. These uncertainties account for the range in estimates of methane emissions from landfills of 20 to 70 Tg per annum shown in Exhibit II-3. A significant amount of research has been done in this area, and the reliability of emission estimates is gradually improving.

Improved estimates of emissions from biomass burning, mostly in the tropical and sub-tropical regions, will require better understanding of the amount and type of vegetation burned each year on an area basis along with information on the type of burning (i.e., smoldering versus flaming.)

At present, estimates of methane emissions from coal mining and natural gas exploration and distribution are generally poor. Emission estimates from coal mining depend on the in-situ methane content of the coal, the mining method, and the quantity of coal removed from the seam. Lack of data on a coal's methane content and the rate at which methane will desorb (emit) from the coal seam hamper the reliability of these emission estimates. Global assessments of coal-bed methane emissions can provide a first-order approximation of how important this category of emissions may be. More accurate emission estimates may, however, require region-specific data which is not readily available at this time.

Emission estimates from gas exploration and distribution have usually been based on assumptions about the rate of natural gas escape from transmission networks. Such estimates are thought to be on the order of 2 to 4 percent of total production, although data on these leakage rates are very limited. Other factors that have not been considered in previous estimates include emissions from oil exploration and recovery, and losses due to explosive events.

Globally, gas venting and flaring is thought to represent around 4% of total gas-production. Regional venting and flaring varies considerably: 0.5% of gross natural gas production in the U.S.; 16% in the Middle East. These estimates are highly uncertain. The assumed carbon content of the gas is also variable. According to estimates from Marland and Rotty (1984), the carbon content of natural gas flared is assumed to be 525 g C/m$^3$. Their earlier estimate for dry gas was 510 g C/m$^3$. Depending on the 'wetness' of the natural gas at its point of release, this number could certainly vary.[27] It is often assumed that the proportion of vented gas that is methane is 80%. This value depends on the gas resource in question; it appears that for the U.S., Mexico, and The Netherlands a range of values of 60% to 90% is more appropriate.

### 3. Halogenated Fluorocarbons

In assessing the contribution of halogenated fluorocarbons to greenhouse warming, analysts must be cautious about distinguishing among production, consumption, and emissions data. Estimates for the production and consumption of fluorocarbons contributing most to

[27] OECD (1991), op. cit., p. 2-73.

greenhouse warming (CFC-11 and CFC-12) are generally fairly accurate due to reliable chemical production data as well as data from industrial sectors in which these substances are used. Emissions data are, however, much more difficult to obtain or even derive since emissions depend on the types of end-use applications and operating and maintenance procedures in which these chemicals are used.

The U.S.-based Chemical Manufacturers Association (CMA) produces extensive data on CFC-11 and CFC-12 production. Certain data gaps still exist such as chemical usage in China and Eastern Europe. These gaps result in approximately a 15 percent uncertainty in global use of CFC-12 and smaller uncertainties for CFC-11.[28] However, because the Montreal Protocol on Substances that Deplete the Ozone Layer now controls production of these substances and those nations which have ratified this international agreement have begun to comprehensively regulate domestic consumption, there is an increasing amount of data about countries' use of controlled substances. Where data gaps once existed, they are now being filled. For example, data on China's use and emissions of halogenated fluorocarbons have recently been obtained through a case study conducted by the United Nations Development Programme.[29] Comprehensive global data on use of other halogenated fluorocarbons such as other CFCs, HCFCs, methyl chloroform, halons, and carbon tetrachloride are more uncertain.

In order to obtain emission estimates, analysts have to use a vintaging analysis framework that takes into account the differing emissions profiles of the stock of various capital equipment using halogenated fluorocarbons. This could, for example, include end uses as diverse as household appliances, automobile air conditioners, and industrial chillers. As such, country-specific emissions estimates are very difficult to obtain since the end-use profiles for each country, including vintaging data, typically do not exist. Globally, current emission fluxes for the major ozone-depleting GHGs are estimated to be 350 Gg/year for CFC-11, 450 Gg/year for CFC-12, 150 Gg/year for CFC-113, and 140 Gg/year for HCFC-22.

### 4. Nitrous Oxide

Global emissions of nitrous oxide have significant uncertain ranges. Nitrous oxide emissions occur from fertilizer use because the application of nitrogen-based fertilizers to the soil increases nitrous oxide flux rates to the atmosphere. Several variables are believed to affect the rate of emissions, including soil temperature, precipitation, type of fertilizer applied, mode of application, and soil conditions. The interrelationships among these factors are poorly understood, although some emission factor data have been developed based primarily on differences in the type of fertilizer applied. Emission estimations will improve as additional research improves our understanding of the variability of emission rates under a variety of field conditions.

Current estimates of annual $N_2O$ emissions due to applications of nitrogen fertilizer vary widely. Estimates of the percentage nitrogen content of principal fertilizer materials vary as well:

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[28] USEPA (1990), op. cit., p. II-22.

[29] People's Republic of China, National Environmental Protection Agency (1990), "Report of a United Nations Development Programme Mission to Investigate Ozone Layer Protection in China."

Ammonia, aqua 16-25%; nitrogen solutions, 21-49%; phosphoric acid, 2-4.5%; Ammoniated superphosphate, 3-6%; Ammonium phosphate-sulfate 13-16%; Di-ammonium phosphate, 16-21%; nitric phosphates, 14-22%. Even though point estimates are often given for use in calculations, the percentage of total nitrogen by fertilizer type that could evolve to $N_2O$ can vary significantly: Anhydrous ammonia, Aqua ammonia, 0.86-6.84%; Ammonium nitrates, 0.04-1.71%; Ammonium types, 0.02-105; urea, 0.07-1.5%; Nitrates, 0.001-0.5%; other nitrogen fertilizers, 0.001-6.84%; other complex fertilizers, 0.001-6.84%. These estimates do not take into account other factors believed to affect emissions, including soil characteristics, crops planted, application method, precipitation, etc.

Estimates for emissions of nitrous oxides from soils of both tropical and temperate forests have large uncertainty ranges. The impact of deforestation on nitrogenous emissions from tropical soils is unclear. In the case of temperate forests' soils and grasslands, there is limited data and results from studies performed to date are conflicting and therefore inconclusive.

Finally, biomass burning and combustion are now thought to be less of a source of nitrous oxide emissions than was previously believed.[30] Recent estimates are 1 to 2 orders of magnitude less than previous estimates. The range of estimates for combustion is 0.1 to 0.3 Tg of nitrogen and for biomass burning 0.02 to 0.2 Tg of nitrogen per year. It is important to consider, however, that the standard deviation of emission factors for stationary combustion of non-carbon dioxide emissions such as those of nitrous oxide are rarely reported with emission factor data. One study shows that when considered, variation in the final estimates by energy activity vary widely, from more than 20 to more than 50 per cent.[31]

Estimates of nitrous oxide from energy consumption are much less reliable than similar estimates for carbon dioxide because the level of emissions not only depends on the type of fuel consumed, but also on the type of technology in which the fuel is consumed, the combustion characteristics that can be affected by the operation and maintenance practices, the age of the equipment, and the extent of pollution control equipment that may be included. The detailed source activity data disaggregated to this level are often not available in most countries. Additionally, emission factor data that describe the expected emission rates for each source activity may not be available if a country has not analyzed these emission rates previously or if it cannot identify appropriate emission factors from available data. There is no inherent reason why nitrous oxide emissions cannot be estimated with fairly high reliability; to do so simply requires access to a substantial amount of data that may not exist within a country.

## IV. EXISTING GREENHOUSE GAS DATABASES

This section identifies and characterizes existing GHG emission databases. Specifically, it summarizes which GHGs and human activities are included in each GHG inventory. It also examines each databases' degree of completion, its expected future modifications, and its relationship to other databases. We will discuss three GHG emissions databases that have

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[30] See USEPA (1990), op. cit., page II-21. Measurements of nitrous oxide emissions from combustion appear to have been affected by a sampling artifact.

[31] OECD (1991), op. cit., p. 2-32.

received public attention. These are as follows: (1) The World Resources Institute (WRI), U.S.A.; (2) The United States Agency for International Development (USAID); and (3) Tellus Institute (affiliated with The Stockholm Environment Institute, Sweden). Exhibits IV-1 and IV-2 summarize the GHGs and GHG-producing human activities included in these GHG databases.

In reviewing these GHG databases, note that for several reasons direct measurements of GHG emissions are not indicative of net contributions to greenhouse warming. Overall, the effectiveness of a GHG in affecting radiative forcing depends on three factors[32]: (1) its concentration in the atmosphere; (2) its atmospheric residence time; and (3) its ability to absorb outgoing long-wave terrestrial radiation.[33] The difference in each GHG's abilities to absorb infrared radiation means that, for example, the net warming effect resulting from large emissions of a weakly absorptive gas may be similar to the small emissions of a strongly absorptive gas. Appendix A investigates three methodologies for determining the scientific relationship among emissions of different GHGs. The first focuses on GHG emissions, the second focuses on atmospheric concentrations of GHG gases, and the third is a hybrid of the first two approaches. Appendix A also provides an overview of different approaches for establishing the rankings of emissions.

**Exhibit IV-1**
**GHGs Included in Emissions Databases**

| GHGs | WRI | USAID | TELLUS |
|---|---|---|---|
| CARBON DIOXIDE | X | X | X |
| METHANE | X | X | X |
| CFC-11 | X | X | X |
| CFC-12 | X | X | X |
| OTHER HALOCARBONS | | X | X |
| NITROUS OXIDES | | X | X |
| CARBON MONOXIDE | | | X |

### 1. The World Resources Institute (WRI)

WRI first published its "Greenhouse Index" in Nature magazine in 1990.[34] This GHG emissions database was based on GHG emissions released during 1987. Comparisons based on the index were presented earlier in its biannual report, "World Resources 1990-91." WRI has since published an index based on GHG emissions released during 1988 and will shortly be

[32] Radiative forcing describes a change imposed on the climate system that modifies the radiative balance of the climate system.

[33] IPCC (1990), op. cit., Section 1.1.

[34] Hammond, A. et al. (1990), op. cit.

publishing an index based on 1989 emissions data. After publication of the 1989 Greenhouse Index in the "World Resources 1992-3" report, WRI will likely publish only emissions data rather than a formal structured annual index.[35]

### *A. Assumptions and Data*

The WRI Greenhouse Index ("Index") uses estimates of emissions from four key GHGs: carbon dioxide, methane, and CFC-11 and CFC-12. These gases are estimated to represent 85 percent of all GHGs emitted.[36] The developers of the Index believe that estimates of emissions for other gases such as nitrous oxides, carbon monoxide, and other halocarbons are not of sufficient certainty to include in the Index.

The main data sources for the emission estimates used in the WRI Index are as follows:

- Carbon dioxide emissions from fossil fuel consumption and cement manufacturing are obtained from the Carbon Dioxide Analysis Center at the Oak Ridge National Laboratories.[37] Deforestation data is obtained from the United Nations Food and Agriculture Organization (FAO) and country-specific studies contained in "World Resources 1990-91".[38] Data on forest clearing are taken from the work of Houghton and others.[39]

- Estimates of methane emissions are derived from several sources. Emission estimates from municipal solid wastes are obtained from Bingemer and Crutzen[40] while estimates of emissions from domestic livestock are obtained from Lerner, Mathews, and Fung.[41] Data from coal mining emissions are based on various

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[35] Personal communication between Abyd Karmali, ICF Incorporated and Eric Rodenburg, WRI, August 5, 1991.

[36] Hammond, A., E. Rodenburg, and W. Moomaw (1991), "Calculating National Accountability for Climate Change", in Environment Magazine, Volume 33, No. 1, pp.11-15.

[37] See for example, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, (1990), "Trends '90: A Compendium of Data on Global Change."

[38] United Nations Food and Agriculture Organization (1989), "An Interim Report on the State of Forestry Resources in the Developing countries", Rome, FAO.

[39] For example, Houghton, R.A. (1989), "Emissions of Greenhouse Gases," in N. Myers, (editor), Deforestation Rates in Tropical Forests and Their Climatic Implications, London, Friends of the Earth, 1989.

[40] Bingemer, H.G. and P.J. Crutzen (1987), "The production of Methane from Solid Wastes," in the Journal of Geophysical Research, Volume 92, no. D2 pp. 2181-87.

[41] Lerner, J, E. Mathews, and I. Fung (1987), "Methane Emissions from Animals: A Global High-Resolution DataBase," in Global Biogeochemical Cycles, Volume 2, no.2, June 1988, pp. 139-146.

**Exhibit IV-2**
**Human Activities Included in Emissions Databases**

| HUMAN ACTIVITIES | WRI | USAID | TELLUS |
|---|---|---|---|
| CARBON DIOXIDE: | | | |
| Fossil Fuel Use | X | X | X |
| Deforestation | X | X | X |
| Reforestation | X | X | X |
| Cement Production | X | X | X |
| Gas Flaring | X | X | X |
| METHANE: | | | |
| Wet Rice Cultivation | X | X | X |
| Domestic Livestock | X | X | X |
| Fossil Fuel Use | X | X | X |
| Biomass Burning | | X | X |
| Landfills | X | X | X |
| HALOCARBONS: | | | |
| CFC-11 AND CFC-12 | X | X | X |
| Other CFCs | | X | X |
| Halons | | X | X |
| Carbon Tetrachloride | | X | X |
| Methyl Chloroform | | X | X |
| NITROUS OXIDES: | | | |
| Fertilizer Use | | X | X |
| Land Clearing | | X | X |
| Biomass Burning | | X | X |
| Fossil Fuel Use | | X | X |
| CARBON MONOXIDE: | | | |
| Fossil Fuel Use | | | X |

information on coal types in each country.[42] Estimates on agricultural sources of methane emissions are derived from FAO and other sources.[43]

- CFC-11 and CFC-12 data are obtained from various government and industry data on consumption of these two halocarbons.[44]

### *B. Methodology*

WRI's Index is based on the greenhouse forcing contribution (GFC) methodology discussed in Appendix A. The calculation of each GHG's airborne fraction is an essential component of this methodology. Essentially, the airborne fraction is a measure of the atmospheric lifetime of a particular GHG. The developers of the Index use airborne fractions of 1, 1, 0.71, and 0.26 for CFC-11, CFC-12, carbon dioxide, and methane, respectively. An equivalent assumption is that these gases have atmospheric lifetimes of 100, 100, 71, and 26 years, respectively. The infrared heating efficiencies for each GHG are those listed in Exhibit IV-2.

A key assumption of this methodology is that the measurement of GFC is equivalent to attributing to each country a share of the observed atmospheric increase in proportion to its share of GHG emissions. The method used to establish rankings is to calculate the percentage share of atmospheric GHG increases for each country.[45] The Centre for Science and Environment in India (CSE) published a report in 1991 entitled, "Global Warming in an Unequal World"[46] to provide a direct response to the WRI Greenhouse Index. While the CSE study contains many criticisms of specific assumptions and data for GHG emission estimates used by WRI, its main criticism is of the methodology used to establish the comparative rankings of different countries.

### 2. The United States Agency for International Development (USAID)

In a 1990 report to the U.S. Congress, USAID included estimates of GHG emissions from various countries.[47] The quantitative data on which the report is based were developed from GHG emission scenarios presented by the Intergovernmental Panel on Climate Change (IPCC).

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[42] See for example, Burns, D.W. and J.A. Edmonds (1989), "An Evaluation of the Relationship Between the Production and Use of Energy and Atmospheric Methane Emissions", Washington, DC.

[43] See ofr example, Schutz, H. and A. Holzapfel-Pschorn, R. Conrad, H. Rennenberg, and W. Seiler (1989), "A 3-Year Continuous Record on the Influence of Daytime, Season, and Fertilizer Treatment on Methane Emission Rates from an Italian Rice Paddy," in Journal of Geophysical Research, Volume 94, No. D13, pp. 16405-16.

[44] See for example, United States Environmental Protection Agency, Stratospheric Protection Program, Office of Air and Radiation (1988), "Appendices of Regulatory Impact Analysis: Protection of Stratospheric Ozone, Vol. 2, Washington DC.

[45] Because this approach is tied to changes in atmospheric concentrations, one theoretical limitation is that it does not account for the possibility that atmospheric concentrations of a GHG may not necessarily increase but could be maintained at elevated levels by on-going emissions from human activities. These emissions would still be influencing global climate, but the WRI approach would not account for these emissions since atmospheric concentrations had not actually increased. As long as atmospheric concentrations increase (or decrease), this limitation is not an issue with the indicator.

[46] Agarwal, A. and S. Narain (1991), op. cit.

[47] USAID (1990), "Greenhouse Gas Emissions from Developing Countries and the USAID Response", Report to Congress.

USAID also used the Global Warming Potential (GWP) indices published by Working Group 1 of the IPCC to establish the interrelationships among the different GHGs on a $CO_2$-equivalent basis.[48]

### *A. Assumptions and Data*

The USAID report serves several purposes: (1) to examine the potential contributions of developing countries to future emissions of GHGs under different growth scenarios; (2) to estimate the relative contribution of those countries to global GHGs; and, (3) to identify specific key countries that stand to contribute significantly to global GHGs. The GHGs included in the USAID index are carbon dioxide, methane, nitrous oxide, CFC-11, CFC-12, CFC-113, HCFC-22, Halon 1301, carbon tetrachloride, and methyl chloroform. Sources of data used in the index include: Marland et al. (1989)[49], Houghton et al. (1987)[50], Cicerone and Oremland (1989)[51], IRRI (1986)[52], Lerner et al. (1988)[53], Crutzen et al. (1979)[54], Bingemer and Crutzen (1987)[55], United Nations (1987)[56], Bolle et al. (1986)[57], FAO (1987)[58], and U.S.EPA (1988)[59].

### *B. Methodology*

Estimates of present and projected GHG emissions are based on the work of Working Group 1 of the Intergovernmental Panel on Climate Change. GWPs assuming a time horizon of

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[48] Specifically, USAID used the GWP factors specified by the IPCC for a time horizon of 100 years. The selection of a specific time horizon is arbitrary; the GWPs for a 100-year time horizon are the factors most frequently used at this time by the working groups of the IPCC.

[49] Marland, G. et al. (1989), op. cit.

[50] Houghton, R.A., R.D. Boone, J.R. Frucci, J.E. Hobbie, J.M. Melillo, C.A. Palm, B.J. Peterson, G.R. Shaver, G.M. Woodwell, B. Moore, D.K. Skole, and N. Myers (1988), "The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land use: Geographic distribution of the global flux," in Tellus, 39B:122-139.

[51] Cicerone, R.J. and R.S. Oremland (1989), "Biogeochemical aspects of atmospheric methane, in Global Biogeochemical Cycles, 2:299-327.

[52] International Rice Research Institute (1986), "World Rice Statistics 1985", IRRI, Manila.

[53] See footnote 54.

[54] Crutzen, P.J., L.E. Heidt, J.P. Krasnec, W.H. Pollock, and W. Seiler (1979), "Biomass burning as a source of atmospheric gases," in Nature, 282:253-256.

[55] See footnote 53.

[56] United Nations (1987), "1985 Yearbook of World Energy Statistics", U.N., New York.

[57] Bolle, H.J., W.Seiler, and B.Bolin (1986), "Other greenhouse gases and aerosols: Assessing their role for atmospheric radiative transfer", in Bolin, B., B.R.Doos, J.Jager, and R.A. Warrick, (editors) The Greenhouse Effect, Climate Change, and Ecosystems, Scope 29, John Wiley and sons, Chichester, pp.157-203.

[58] United Nations Food and Agricultural Organization (1987), "1986 FAO Fertilizer Yearbook", Vol.36, FAO, Rome.

[59] See footnote 57.

100 years are used to express the comparative radiative forcing of different GHGs (see Exhibit IV-1).

### 3. Tellus Institute/Stockholm Environment Institute

The Tellus Institute is developing an analytical tool entitled the "Greenhouse Gas Scenario System (G2S2)." G2S2 is a database and policy assessment tool that estimates the anthropogenic flux of GHGs and projects future emissions based upon policy scenarios that the analyst can input. It estimates emissions from several human activities including energy consumption, cement production, halocarbon use, landfills, land use changes, livestock production, rice cultivation, and fertilizer consumption.[60]

#### *A. Assumptions and Data*

The G2S2 database includes anthropogenic emissions of carbon dioxide, methane, carbon monoxide, nitrous oxide, and CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, carbon tetrachloride, methyl chloroform, HCFC-22, Halon 1301, and Halon 1211.

#### *B. Methodology*

At this point Tellus has not published its database, although the emission estimation methodologies embedded in the G2S2 have generally been taken from methods developed by other sources.

## V. CONSIDERATIONS IN ATTRIBUTING GHG EMISSIONS TO COUNTRIES

The rest of this discussion paper addresses how analyses to determine rankings of countries' GHG emissions are affected by decisions regarding which GHGs to include (see discussion in Section II) and how to address the many uncertainties associated with GHG emission estimates from different GHG emitting activities (see discussion in Section III). In order to guide this discussion, we will use only one of the databases discussed above (i.e., an updated version of the USAID database discussed in Section V) and one of the means of weighting emissions from different GHGs (i.e., the GWP factors specified by the IPCC for a 100-year time horizon as discussed in Appendix A). First, however, it is necessary to place the discussion of uncertainties into some context.

While a GHG emissions database can be developed as a stand-alone product, it is likely that such a database will ultimately be used to fulfill many differing purposes. For example, one of the most critical ways that databases have recently been used is to aggregate GHG emissions on a country-by-country basis and provide some indicator of contribution to greenhouse warming. Existing analyses which purport to determine contributions to greenhouse warming have, however, rarely made clear their attendant reliability or inherent uncertainties, including the emission databases on which they rely. In some cases, they have been vigorously contested both on scientific grounds and for their concomitant far-reaching policy implications. It is therefore

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[60] Tellus Institute/Stockholm Environment Institute (1991), "Greenhouse Gas Scenario System: Overview", May 1991.

important to understand the possible ways that an emissions inventory can be used so as to recognize that the propagation of uncertainties in estimating and attributing GHG emissions can have far-reaching policy implications.

GHG emissions databases can be used to serve many differing but complementary purposes. Broadly speaking, these can be categorized as: scientific, policy, and diplomatic. Some GHG databases may be developed with the intention of serving only one of these purposes. However, in the debates about greenhouse warming that have transpired thus far, these purposes often appear to be closely linked to one another.

### 1. Scientific

GHG emissions databases serve an important scientific function in that they enable comparison of emissions of different GHGs and emission activities. Moreover, they can provide relevant parties with an agreed upon scientific basis for assessing the likely impacts of such emissions by application of a common metric to establish understandable relationships among these different GHGs and activities. For example, the Intergovernmental Panel on Climate Change (IPCC), whose goals are to provide assessments of the latest understanding of the science of greenhouse warming, the potential effects of greenhouse change on human society and ecosystems, and the possible response strategies for addressing greenhouse change, released its final report at the Second World Climate Conference in October, 1990. One of the main themes in the final report is the need for an intensification of research regarding the science of climate change, including better understanding of GHG emission sources and sinks. Application of a GHG weighting indicator to an emissions database is one way to assist one's understanding by providing estimates of the relative contributions from various human activities and the relative contribution to greenhouse warming by various GHGs.

### 2. Policy

GHG databases can also be used to serve several policy-related purposes. These include identifying areas for emissions reduction and fostering national accountability for GHG emissions.

They can assist countries in developing strategic plans for emissions reductions by identifying which GHGs and activities are most important. Such efforts to mitigate greenhouse warming can be both unilateral and multilateral. In either case, GHG databases can assist policy-makers in setting realistic goals for GHG emissions reductions through modification of particular activities. Furthermore, to the degree that greenhouse warming is a consequence of economic activities that directly or indirectly produce emissions of GHGs, GHG databases will provide an important means by which the World Bank and other government development assistance agencies can target financial and technical assistance more strategically such that maximum environmental protection and economic growth are achieved.

GHG databases can promote each country's accountability both internally and to the international community for its emissions. It is important to note, however, that, by themselves, GHG databases do not assist in measuring a country's vulnerability to greenhouse warming or its ability to bear subsequent burdens resulting from greenhouse warming.

### 3. Diplomatic

Diplomatic purposes include facilitating international negotiations on a global atmospheric change treaty and developing a mechanism for monitoring and enforcing compliance.

In addition to providing an agreed upon scientific basis for estimating the consequences of greenhouse warming, GHG emissions databases provide a starting point for discussions on a global atmospheric change treaty. Such a treaty might, for example, use estimates of emissions to determine permissible emission quotas, access to natural sinks for emissions, or the weight of contributions to a financial mechanism (perhaps similar to the Interim Multilateral Fund of the Montreal Protocol on Substances that Deplete the Ozone Layer). The framework that an international atmospheric treaty could adopt might be based upon one or more of the following concepts: the so-called "polluter pays" principle, the ability to pay basis, equal percentage reductions of GHG emissions by each country, or emissions rights for each country up to levels determined to be the limit of the natural absorptive capacity of the biosphere. An accepted GHG emissions database could assist in the development of each of these four types of frameworks by serving as a baseline from which to evaluate levels of GHG emissions and changes in these levels over time.

Assuming that it is possible to periodically update GHG databases based on specific measures taken by countries to reduce emissions, such databases could also serve as a useful mechanism for monitoring and enforcing compliance as well as in resolving international disputes.

## VI. GHG EMISSIONS DATA UNCERTAINTIES AND COUNTRY RANKINGS

### 1. Purpose

While the ranking of overall GHG emissions on a country-by-country basis is a useful analytical exercise, it must be viewed with caution. Any attempt to attribute global emissions to countries is subject to the uncertainties discussed above. The purpose of this section is to illustrate how such rankings can change under alternative assumptions. One emissions database and a single method of aggregating emissions from different GHGs were chosen for consistency so that sensitivity analyses could be performed. Selection of other databases or methods for aggregating emissions would not appreciably alter the analytical findings discussed below. Given a specific methodology for comparing the radiative forcing of different GHGs, there are three essential underlying sets of assumptions in ranking countries by GHG emission totals: 1) which GHG gases to include, 2) the global emissions budget for each gas, and 3) the actual emissions rate for specific countries. This analysis examines the sensitivity of country rankings to modifications in each of these sets of assumptions. First, however, it details both the assumptions and methodology used to perform the analysis.

### 2. Assumptions

This section reviews the sources for GHG emissions estimates used in the database. As discussed earlier, there are uncertainties inherent in estimating emissions from each of the emission source categories. The approaches summarized below were used to develop the USAID database discussed in Section V.

### *A. Carbon Dioxide*

$CO_2$ estimates were developed for three categories -- fossil fuel consumption, cement production, and deforestation. Whenever available, $CO_2$ estimates from energy were taken from the IPCC Working Group I Energy and Industry Subgroup (EIS) report containing information for specific countries. If estimates were not available from this source, emission estimates were derived by applying country/world emission ratios from Marland et al. (1988) to the EIS global total, i.e., countries were given a proportional share of global emissions based on their share of global fossil fuel consumption. Emission estimates in Marland et al. (1988) were based on country-specific fossil fuel consumption data from the United Nations *Energy Statistics Yearbook.* Carbon dioxide emissions from deforestation were taken from Houghton et al. (1987) and included both temperate and tropical regions. Reforestation estimates (i.e., a net absorption of carbon) were not included in this analysis; for those countries that had a net reforestation estimate (primarily temperate countries in Europe), the net flux of carbon was assumed to be zero. The amount of $CO_2$ emitted from cement production on a country-specific basis was taken from Marland et al. (1988).

### *B. CFCs*

The emission estimates for CFCs were originally developed by U.S. EPA/OAR for analysis of the Montreal Protocol and are consistent with the estimates used for U.S. EPA's Report to Congress *Policy Options for Stabilizing Global Climate.* These emission estimates (originating in 1985) were only provided for several large regions, specifically the U.S., the EEC, Japan/Australia/New Zealand, other developed countries, the USSR/Eastern Europe, China/India, and other developing countries. In order to estimate emissions for specific countries within each of these broad classifications, the regional estimates were disaggregated on a population-weighted basis (i.e., each country's share of population within the region was used to determine its share of estimated emissions). This approach does not take into account potential differences among countries within a region in the types and amount of CFCs that are consumed. It should also be noted that the original emission estimates developed by the U.S. EPA were derived from CFC production data since consumption data are not available; much of the data on this subject is considered confidential business information.

### *C. Methane*

The activities that contributed to methane emissions included enteric fermentation, animal wastes, rice cultivation, fuel production, landfills, and biomass burning.

- Methane from enteric fermentation was based on Lerner et al. (1987), which provided estimates on a country-by-country basis.

- The $CH_4$ emissions from animal wastes were taken from 1985 data in Casada and Safley, 1990, which developed estimates on a country-by-country basis.

  $CH_4$ from rice cultivation was based on the global methane estimate from Cicerone and Oremland (1989). This global estimate was apportioned by country based on each country's share of rice paddy

harvest area; we used 1985 rice paddy harvest area by country from the 1985 FAO Production Yearbook.

- Fuel production was separated into two activities: coal mining and natural gas production and transmission. The $CH_4$ emissions produced from coal mining were taken from ICF Resources, 1990, *Methane Emissions to the Atmosphere From Coal Mining* (Draft), which provided estimates on a country-by-country basis. Since these were 1987 numbers, they were proportionately reduced by the global difference in 1985 and 1987 coal production so the total amount of methane produced from coal mining matched what was used in the EIS Reference Scenario. The global amount of methane produced from natural gas production and transmission was apportioned by country using 1985 country-specific production data for natural gas found in the *1985 UN Energy Statistics Yearbook.*

- Methane from landfills was estimated based on the global estimate from Cicerone and Oremland (1989). This global estimate was apportioned among the following four regions using Bingemer and Crutzen (1987): U.S./Canada/Australia, Other OECD, USSR/E. Europe, and Developing Countries. The four regional estimates were disaggregated into country estimates based on country-specific GNP/capita data, except for the USSR and E. Europe which was based on population.

- The global biomass burning emission estimate was taken from Cicerone and Oremland (1989). This global estimate was disaggregated by country using the deforestation numbers provided by Houghton et al. (1987). We used only 96% of the methane emissions from biomass burning since ~4% originates from natural activities (i.e., wild fires).

### *D. Nitrous Oxides*

The activities that contributed to emissions of nitrous oxide included fossil fuel combustion, nitrogenous fertilizer use, biomass burning, and gain in cultivated land. The total amount of $N_2O$ for each activity was taken from the EIS Reference Scenario as well.

- The global emissions of $N_2O$ from fossil fuel combustion were based on Hao et al. (1987) and more recent research done by U.S. EPA. This global estimate was divided among coal, oil, and gas using $N_2O/CO_2$ ratio described in Bolle et al. (1986). Each fuel type subtotal was then apportioned on a country-by-country basis using each country's global share of fuel consumption as reported in the *1985 UN Energy Statistics Yearbook.*

- The global estimate from fertilizer use was derived from Seiler and Conrad (1981). We assumed that in 1985 the U.S. emitted 53% of the world $N_2O$ total due to the type and amount of fertilizer used; therefore, the remaining 47% was divided among the rest of the world (Fung, personal communication). To apportion the remaining emissions, we used each country's share of 1984/1985 nitrogenous fertilizer consumption from the *1986 FAO Fertilizer Yearbook.*

- The global amount of $N_2O$ due to biomass burning was based on Bolle et al. (1986). The deforestation estimates provided by Houghton et al. (1987) were used to determine each country's share of this total; we used 96% of total $N_2O$ emission from biomass burning because 4% accounts for natural emissions from wild fires (Seiler and Crutzen, 1980). The global amount of $N_2O$ due to the gain in cultivated land was based on Bolle et al. (1986). Deforestation numbers from Houghton et al. (1987) were again used to split the global $N_2O$ emissions from gain in cultivated land.

*E. Carbon Monoxide*

Two sources were used to derive the global CO emission total -- commercial energy consumption and wood use. For commercial energy, the mechanisms affecting the rate of CO formation are poorly understood, particularly as CO may affect the rate of tropospheric ozone formation. As a surrogate measure for each country's contribution to CO emissions, we used 1984 gasoline consumption (including motor and aviation) by country (EIA, 1986, *International Energy Annual 1985*). CO emitted from wood use by country was based on fuelwood data by country (Meyers and Leach, 1989, *Biomass Fuels in the Developing Countries: An Overview*).

To allow comparison across different types and quantities of greenhouse gases, the emission estimates were converted to a $CO_2$-equivalent basis using the Global Warming Potentials[61] developed by Working Group #1 of the IPCC. An integration time horizon of 100 years was used. The specific GWPs are summarized in Exhibit VI-1.

### 3. Methodology

The methodology used in this analysis for comparing different GHGs is consistent with IPCC recommendations for GWPs integrated over a 100-year time horizon. Country-specific emission estimates of each gas were calculated from a given global budget for major anthropogenic GHG producing activities. A ranking was then established for both countries and regions based on their individual share of total global GHG emissions. As discussed earlier, this is just one approach to attributing contributions to greenhouse warming. Other methods, such as establishing rankings on a per capita basis, per GNP basis, etc., could have been used to compare emission totals. However, such methods address the choice of an appropriate emissions indicator, which is not the primary analytical issue in this assessment. Hence, the rankings included in this

[61] see Section IV-1A

**Exhibit VI-1**
**Global Warming Potentials (GWP) of GHGs (100 Year Time Horizon)**

| Gas | (GWP) |
|---|---|
| Carbon Dioxide | 1 |
| Methane (direct) | 6 |
| Methane (indirect) | 15 |
| Nitrous Oxide | 290 |
| Carbon Monoxide | 3 |
| CFC-11 | 3500 |
| CFC-12 | 7300 |
| CFC-113 | 4200 |
| CFC-114 | 6900 |
| CFC-115 | 6900 |
| $CCl_4$ | 1300 |
| $CH_3CCl_3$ | 100 |
| HCFC-22 | 1500 |
| Halon 1301 | 5800 |

analysis are intended to be illustrative rather than definitive. For the purposes of this study, the only requirement is that a consistent method be used for each scenario. It is important to note that, because of the methodology used, only current emissions are estimated and attributed. No attempts are made in this analysis to account for historical emissions or to project future emissions.

Input assumptions were altered to incorporate the discussion of uncertainties into a sensitivity analysis. As discussed previously, these assumptions fell into three categories: the selection of specific GHGs in the analysis, the global emissions budget for each GHG, and the emissions rate for individual countries. Accordingly, three sets of analyses were undertaken. In each case, only one factor differed from the base case assumptions. After each run, rankings were calculated on a regional and country-by-country basis. The regions used throughout the analysis are as follows:

- North America
- China
- Other Asia/Pacific
- Other Latin America
- Oceania
- Eastern Europe
- Western Europe
- Brazil
- Africa
- Japan
- India
- USSR
- Middle East

In the first set of analyses, different GHGs were excluded from the analysis to ascertain the effects of varying the inclusion of GHGs on individual rankings. For example, in a country where wet rice cultivation is the primary economic activity, the exclusion of methane from emissions calculations would likely have a significant impact on its relative ranking.

In the second set of analyses, an attempt was made to discern whether varied emphasis of a specific emissions category alters relative regional or country rankings. Accordingly, in order to address the uncertainties associated with global estimates of GHG emissions from specific activities, the global emissions budget for individual activities was altered, first to the low end of the IPCC (1990, op. cit.) reported range, and then to the high one. Results were examined to determine the impact of such variations on rankings relative to the reference case. The reference case was the same as that used in the first analyses. The modified activities included fossil fuel production and use, deforestation, enteric fermentation, rice cultivation, landfills, biomass burning, and fertilizer use.

In the third set of analyses, uncertainties in the emission rates of individual countries for certain emission activities were considered. First, key countries (i.e., major emitters) were identified and their emissions rates effectively altered relative to the rest of the world. This was achieved by expressing the level of uncertainty at the country level through alterations in the global budget for specific GHG producing activities; the actual amount of uncertainty in emission rates could be higher or lower at the country level due to factors that are currently poorly understood. Second, this same analysis was also performed on countries contributing significantly less to the global budgets than the selected key countries. In either case, country emissions rates were effectively adjusted to produce emissions at the upper bound of the reported range for a specific activity, while the remaining countries emitted at the lower end. A second analysis was then conducted with the situation reversed. These analyses illustrate the possible effect that a high degree of uncertainty in a country's emissions rate could have on its ranking.

Throughout the data tables shown below, numerical values have been presented with a precision of two decimal places. This was done in order to make apparent the reasons for the order of many of the rankings. Without a precision of two decimal places, it would not have been possible to distinguish between the total emissions for several countries as their percentage contributions to global emissions would have been the same. It is important to note that this level of precision would not be justified in a statistical sense given the level of uncertainty in the region/country emission calculations. This concern should be kept in mind when evaluating the apparent precision of point estimates.

## 4. Results

### *A. Inclusion of Different GHGs*

The first set of analyses focuses on how the inclusion of different GHGs in an emissions inventory affects country rankings. The reference case included both the indirect and direct effects of $CO_2$, $CH_4$, $N_2O$, CO, and CFCs. Three additional cases were considered:

- reference case without CO;
- reference case without CO or CFCs; and
- direct effects only ($CO_2$, $CH_4$, and $N_2O$).

These cases accounted for the fact that CO does not directly contribute to greenhouse warming, and for recent uncertainties concerning the net greenhouse warming effect of CFCs. According to recent UNEP findings[62], "observed lower stratospheric ozone changes and calculated temperature changes would have caused a decrease in the radiative forcing of the surface troposphere system in the middle to high latitudes that is larger in magnitude than that predicted for the CFC increases over the last decade. In addition, the ozone depletion may indeed have offset a significant fraction of the radiative forcing due to increases of all greenhouse gases over the past decade."

The resulting rankings of current GHG emissions on a regional basis are contained in Exhibit VI-2. The top four countries - the U.S., U.S.S.R., China and Brazil - maintained their positions each time, and only when the direct effects were considered alone did India drop from the top five. The individual shares of GHG emissions from these countries and the differentials between them are sufficiently large that any reasonable change in the selection of GHG gases will not alter their rank. Collectively, these five nations account for roughly 47% of total present global GHG emissions. To confirm how the choice of a GHG emissions allocation indicator can affect rankings, emissions contributions for the reference case are also shown on a per capita basis in Exhibit VI-3.

Further down in the rankings, the emission shares for certain countries are low enough that the decision to include certain greenhouse gases will almost certainly have an impact on their country's standings. For example, Canada drops 3 places when CO is excluded. Countries that fall below the top twenty positions each have emission shares less than 0.55%. It is unlikely that they will significantly shift their relative positions with the other nations through changes in the reference assumptions.

With regard to regional rankings, North America consistently appears as the foremost contributor to current GHG emissions, while the Middle East and Oceania (Australia and New Zealand) always occupy the last two positions. Also, China, Africa, and the other Latin American Countries held steady at the fifth, sixth, and seventh positions, respectively. The remaining regions exhibit some variability in rankings with respect to changes in GHG selection. Overall, the various selections of GHGs did not result in a large-scale reordering of country or regional emission shares, although percentage contributions to global emissions did change.

### *B. Global GHG Emissions Estimates Uncertainties from Specific Activities*

The second set of analyses addresses the uncertainties associated with global estimates of GHG emissions. To account for this uncertainty, the global emissions budget for several activities was changed, first to the low end of the IPCC reported range (IPCC (1990), op. cit.), and then to the higher one. The objective was to ascertain whether more (or less) emphasis on a specific emissions category would alter regional or country rankings. The reference case was identical to the one used for the previous set. The modified activities included:

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[62] UNEP (1991), "Executive Summary: Scientific Assessment of Stratospheric Ozone".

## Exhibit VI-2
## Regional Rankings of Global GHG Emissions

| Reference Case | | Without CO | | Without CO and CFCs | | Direct Effects Only | |
|---|---|---|---|---|---|---|---|
| Region | Share of Emission | Region | Share of Emission | Region | Share of Emission | Region | Share of Emissions |
| North America | 18.88% | North America | 18.88% | North America | 17.28% | North America | 18.49 |
| Western Europe | 13.11% | Western Europe | 12.80% | Other Asia/Pacific | 13.17% | USSR | 12.95% |
| USSR | 12.21% | Other Asia/Pacific | 12.30% | USSR | 12.39% | Other Asia/Pacific | 12.19% |
| Other Asia/Pacific | 12.04% | USSR | 12.14% | Western Europe | 10.98% | Western Europe | 11.63% |
| China | 8.49% | China | 8.60% | China | 9.58% | China | 8.90% |
| Africa | 7.41% | Africa | 7.49% | Africa | 7.91% | Africa | 7.85% |
| Other Latin America | 6.70% | Other Latin America | 6.61% | Other Latin America | 7.22% | Other Latin America | 7.34% |
| Eastern Europe | 5.09% | Brazil | 5.15% | Brazil | 5.70% | Eastern Europe | 5.63% |
| Brazil | 5.08% | Eastern Europe | 5.15% | Eastern Europe | 5.14% | Brazil | 5.60% |
| India | 3.96% | India | 4.02% | India | 4.44% | Japan | 3.16% |
| Japan | 3.69% | Japan | 3.63% | Japan | 2.87% | India | 2.86% |
| Middle East | 1.68% | Middle East | 1.62% | Middle East | 1.72% | Middle East | 1.87% |
| Oceania | 1.60% | Oceania | 1.56% | Oceania | 1.53% | Oceania | 1.47% |

**Exhibit VI-3**
**Regional Rankings on a Per Capita Basis**

| Ranking/(Ranking in Reference Case) | Region | Emissions (Mg/capita) |
|---|---|---|
| 1 (1) | North America | 29.90 |
| 2 (13) | Oceania | 28.92 |
| 3 (3) | USSR | 18.49 |
| 4 (9) | Brazil | 16.04 |
| 5 (8) | Eastern Europe | 15.25 |
| 6 (2) | Western Europe | 13.56 |
| 7 (11) | Japan | 12.80 |
| 8 (7) | Other Latin America | 10.40 |
| 9 (4) | Other Asia Pacific | 6.88 |
| 10 (12) | Middle East | 6.33 |
| 11 (6) | Africa | 5.44 |
| 12 (5) | China | 3.40 |
| 13 (10) | India | 2.21 |

- fossil fuel production and use;
- deforestation;
- enteric fermentation;
- rice cultivation;
- landfills;
- biomass burning; and
- fertilizer use.

The global emissions budget used for each activity examined in this sensitivity analysis are shown in Appendix B. In almost every scenario, the U.S. ranked first, followed by the Soviet Union, China, Brazil, India, and Japan. The only exceptions occurred when the lower deforestation rate was used (Brazil fell from the fourth position to the sixth), and when the lower emissions rate for rice cultivation was used (India fell from the fifth position to the seventh). These last two results are hardly surprising when considering that Brazil has the most land area experiencing some form of land use change and that India's rice production is 29% of the global total. In every other scenario, there was very little movement in rankings for the top fifteen GHG emitting nations. Any changes that did occur primarily took place in the eighth through fifteenth positions. However, the same countries consistently appeared in the top ten, while the remaining countries had individual global emission shares ranging from only 1.3% to 2%.

In terms of individual activities, rankings changed little when alternate $CO_2$ emission rates were used for the fossil fuel sector. Although $CO_2$ from fossil fuels accounts for a major share of global GHG emissions, the majority of these emissions (72%) are from the U.S., U.S.S.R., China, Japan, and Western Europe, whose relative shares are large enough to withstand minor changes in the global budget. As mentioned before, altering the global budget for deforestation had the greatest impact on Brazil's ranking. For methane emitting activities, modifying global budgets for enteric fermentation, gas production, and landfill use produced identical country rankings. Changes in the global budgets for coal mining and biomass burning produced a slightly different ranking, while changes in the global budget for rice cultivation had a significant impact on India's position.

Together, $N_2O$ emissions account for merely 6% of the current contribution to radiative forcing.[63] Consequently, the rankings remained virtually unchanged when different emission rates for these activities were used.

As before, the regional rankings exhibited slightly more variation than the country rankings, but no regions were subject to radical displacement. For example, in all but one case (low deforestation) Brazil and Eastern Europe held either the eighth or ninth position. Also, North America and Western Europe invariably held the first two positions.

Although rankings in this analysis were not particularly sensitive to alterations in assumptions about the global budget, significant changes in country or regional contributions to GHG emissions often occurred without being reflected in a rankings change. For example, the relative contributions of Western Europe and North America rose by approximately 13% and 11% respectively versus the reference case when using the low range for deforestation. When using the high range for deforestation, the relative contribution of North America to the global budget fell by approximately 6% versus the reference case.

### *C. Individual Country Emission Rate Uncertainties*

The third set of analyses incorporates uncertainties in the emission rates of individual countries. For certain emission activities, key countries were identified and their emissions rates altered relative to the rest of the world. Initially, the key country's emissions rate was adjusted to produce emissions at the upper bound of the reported range for a specific activity, while the remaining countries were assumed to emit at the lower end. A second analysis was then conducted with the situation reversed. The purpose of this exercise was to show how country-specific emission rates that differ markedly from average global assumptions could have a direct impact on a country's ranking. The level of uncertainty in the global budget was used to specify the potential range of variability in emissions rates at the country level. The actual differences in country emission rates compared to global average emission rates could be higher or lower due to processes that are currently poorly understood. This approach captures potential changes in country rankings if emission rates from a specific activity turn out to be substantially different for one country as compared to the global average. The key activities and regions evaluated in this analysis were as follows:

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[63] IPCC (1990), op. cit.

- $CO_2$ from Deforestation
  - India
  - Brazil

- $CO_2$ From Fossil Fuels
  - U.S.A.
  - U.S.S.R.

- $CH_4$ from Rice Cultivation
  - China
  - India

- $CH_4$ From Enteric Fermentation
  - U.S.A.
  - India

- $N_2O$ From Fertilizer
  - China
  - U.S.A

The emissions levels for country activities evaluated in this analysis are shown in Appendix B. The reference case for this analysis included the direct effects only from $CO_2$, $CH_4$, and $N_2O$. For $CO_2$ emissions from fossil fuels, the U.S. and U.S.S.R. were chosen as the key countries. Both countries finished first and second, respectively, in each of the runs, as they had done throughout the entire sensitivity analysis. For $CO_2$ emissions from deforestation, the key countries were India and Brazil. Both countries' rankings changed as different emission rates were used. India went from fifth to eighth place as its emission rate changed from the higher to the lower bound, and Brazil moved from fourth to seventh.

Varying country emission rates for rice cultivation also produced changes in rankings. India again moved from fifth to eighth place as its emission changed from the higher to the lower bound (see Exhibit VI-4). China, the other key country for this activity, remained in third position. For the remaining activities, changes in the emissions rate for key countries failed to affect those rankings. These activities (and key countries) included $CH_4$ emissions from enteric fermentation (U.S. and India) and $N_2O$ emissions from fertilizer use (China and U.S.).

In many cases, the relative shares of key countries are large enough to withstand minor changes in emission rates. Indeed, it would seem more likely that the effect of minor variations in this area of consideration would have the most telling impact lower down the list where the relative positions of some of the smaller countries are far less differentiated. Accordingly, additional analyses were performed for the following representative sample of countries and activities:

- $CO_2$ from Deforestation
  --Indonesia;

- $CO_2$ from Fossil Fuels
  --Poland;

**Exhibit VI-4**
**Country Rankings Under Alternative Scenarios for Current Emissions from Rice Cultivation**

| Reference Case | | India w/ High Emissions Rate | | India w/ Low Emissions Rate | |
|---|---|---|---|---|---|
| Country | Share of Emissions | Country | Share of Emissions | Country | Share of Emissions |
| U.S. | 16.76% | U.S. | 17.04% | U.S. | 16.57% |
| U.S.S.R. | 12.95% | U.S.S.R. | 13.16% | U.S.S.R. | 12.80% |
| China | 8.90% | China | 8.67% | China | 9.06% |
| Brazil | 5.60% | Brazil | 5.64% | Brazil | 5.57% |
| Indonesia | 3.22% | India | 3.26% | Indonesia | 3.26% |
| Japan | 3.16% | Japan | 3.18% | Japan | 3.14% |
| India | 2.86% | Indonesia | 3.16% | West Germany | 2.69% |
| West Germany | 2.73% | West Germany | 2.77% | India | 2.34% |
| United Kingdom | 1.99% | United Kingdom | 2.03% | United Kingdom | 1.97% |
| Canada | 1.73% | Canada | 1.76% | Thailand | 1.73% |

- $CH_4$ from Rice Cultivation
  --Thailand.

Using the low end of Poland's range, its relative ranking remained unchanged, but when the high end of the range was used, its ranking rose from thirteenth to tenth (see Exhibit VI-5). As with Poland, Thailand's position remained unchanged with the use of the low end of its rice emissions range. With the use of the high end of the range, however, Thailand went from twelfth to tenth place. The use of the high end of Indonesia's deforestation range resulted in a rise from fifth to fourth, while use of the range's low end resulted in a drop from fifth to eleventh place (see Exhibit VI-6).

### 5. Conclusions from the Sensitivity Analysis

The sensitivity analyses demonstrate how uncertainties in baseline assumptions can modify the results of country and regional rankings of GHG emissions. To claim, for example, that Brazil is presently the fifth largest contributor to greenhouse warming based on a single ranking of GHG emissions shares can be misleading, and perhaps even erroneous. In some of the cases in our analysis, the emissions range was not sufficiently broad (i.e. the degree of uncertainty was not large enough) to affect country rankings. In other instances, alternative assumptions did prove influential in determining emission shares. The concern here is that an individual country, such as

Brazil or India, may be portrayed in an entirely different light during greenhouse warming discussions, depending on the assumptions used to evaluate GHG emissions.

Our intention was not to invalidate existing estimates of GHG emissions, but rather to place them in the proper perspective. Although minor changes to the input assumptions may subsequently result in minimal changes in rankings, attributing GHG emissions to countries can still be regarded as a worthwhile exercise. One must remember, however, to draw conclusions with care and to be cognizant of the applicable caveats.

**Exhibit VI-5**
**Country Rankings Under Alternative Scenarios for Current Emissions from Fossil Fuels**

| Reference Case | | Poland w/ High Emissions Rate | | Poland w/ Low Emissions Rate | |
|---|---|---|---|---|---|
| Country | Share of Emissions | Country | Share of Emissions | Country | Share of Emissions |
| U.S. | 16.76% | U.S. | 16.31% | U.S. | 17.19% |
| U.S.S.R. | 12.95% | U.S.S.R. | 12.63% | U.S.S.R. | 13.20% |
| China | 8.90% | China | 8.75% | China | 8.89% |
| Brazil | 5.60% | Brazil | 5.67% | Brazil | 5.15% |
| Indonesia | 3.22% | Indonesia | 3.26% | Japan | 3.24% |
| Japan | 3.16% | Japan | 3.07% | Indonesia | 2.96% |
| India | 2.86% | India | 2.85% | West Germany | 2.80% |
| West Germany | 2.73% | West Germany | 2.65% | India | 2.75% |
| United Kingdom | 1.99% | United Kingdom | 1.93% | United Kingdom | 2.06% |
| Canada | 1.73% | Poland | 1.87% | Canada | 1.75% |
| Thailand | 1.67% | Thailand | 1.69% | Thailand | 1.54% |
| Poland | 1.62% | Canada | 1.69% | Mexico | 1.43% |
| Mexico | 1.46% | Mexico | 1.44% | Poland | 1.41% |

**Exhibit VI-6**
**Country Rankings Under Alternative Scenarios for Current Emissions from Deforestation**

| Reference Case | | Indonesia w/ High Emissions Rate | | Indonesia w/ Low Emissions Rate | |
|---|---|---|---|---|---|
| Country | Share of Emissions | Country | Share of Emissions | Country | Share of Emissions |
| U.S. | 16.76% | U.S. | 18.88% | U.S. | 15.61% |
| U.S.S.R. | 12.95% | U.S.S.R. | 14.35% | U.S.S.R. | 12.19% |
| China | 8.90% | China | 9.45% | China | 8.60% |
| Brazil | 5.60% | Indonesia | 4.84% | Brazil | 6.90% |
| Indonesia | 3.22% | Japan | 3.58% | Japan | 2.93% |
| Japan | 3.16% | Brazil | 3.27% | India | 2.82% |
| India | 2.86% | West Germany | 3.09% | West Germany | 2.53% |
| West Germany | 2.73% | India | 2.94% | Thailand | 2.03% |
| United Kingdom | 1.99% | United Kingdom | 2.36% | United Kingdom | 1.79% |
| Canada | 1.73% | Poland | 1.86% | Canada | 1.67% |
| Thailand | 1.67% | Canada | 1.84% | Indonesia | 1.55% |

## VII. CONCLUSIONS

GHG emissions are not easily characterized by the requisite traits that typically underpin policy-making - namely measurability and predictability. At the crossroads between simply recognizing the problem and implementing particular mitigative and/or adaptive policies, the international community is in the process of attempting to characterize the problem and its sources. One fundamental aspect of this process involves estimating and attributing global greenhouse gas emissions. The possible impact of such data on members of the international community cannot be underestimated, because eventually, countries will be made accountable for their emissions. As a consequence, the process of consolidating knowledge and standardizing methodologies will inevitably be subject to heated political as well as scientific dispute.

This paper therefore, has attempted to highlight uncertainties in assumptions that serve as the current basis for estimating and attributing GHG emissions. As in any scientific endeavor, these uncertainties certainly do exist regardless of the seeming definitiveness with which data is sometimes presented. Accordingly, a number of possible sources of uncertainty have been highlighted, such as which GHGs to include and uncertainties regarding activity, country, and global emission estimates. Also considered were competing methodologies for aggregating GHG emissions and different approaches to attributing emissions to countries. Such uncertainties are notable when juxtaposed to discussions of the input assumptions, key methodologies, and data sources used in published attempts at developing GHG emission databases. Furthermore, the question of uncertainties becomes increasingly relevant given the purposes that such databases can ultimately be used to serve (e.g., priority setting, cost assessments, accountability, etc.)

Recognizing such a given array of uncertainties, the goal of this paper is to instill a sense of caution in GHG database users in the international community that often use "reliable data" as the basis for policy and as a guide to future scientific endeavors. Between recognizing the problem and implementing policies to retard greenhouse warming, we are still at an early stage. This discussion paper reminds us of that and warns us not to start relying too heavily on data that is far from conclusive or certain.

The importance of such caveats is demonstrated in Section VI. By altering the inclusion of certain gases and by varying numbers for the emission rates of certain countries as well as for the global estimates of GHG emissions for specific activities, the relative GHG rankings of individual countries and regions often changed. Seemingly definitive country and regional rankings display sensitivity to the incorporation of certain uncertainties, thereby demonstrating that there is room for narrowing such uncertainties through continued research. This recommendation is further strengthened by that fact that this paper's approach was scientifically conservative. By performing true sensitivity analyses in which variables are only altered one at a time, the range of possible variations in final ranking results is diminished. Greater variation could be achieved, and therefore greater doubt generated, by the simultaneous variance of multiple variables. Finally, the ranking of countries to a precision of two decimal places underscores the caution with which such country and regional GHG contribution rankings should be viewed. Given the magnitude of many of the uncertainties discussed herein, the use of such precision is certainly unwarranted. The fact, however, that such an approach may be necessary to distinguish between current emission levels of several countries demonstrates the limitations of the ranking process.

# APPENDIX A
# COMPETING METHODOLOGIES FOR AGGREGATING AND ATTRIBUTING GHG EMISSIONS

This section briefly reviews various competing methodologies for aggregating and attributing different GHG emissions. It first investigates three methodologies for determining the scientific relationship among emissions of different GHGs.

## 1. Methods Used to Establish Scientific Relationships Among GHG Emissions

### *A. Greenhouse Warming Potential*

This approach attempts to estimate the long-term contributions of GHGs by calculating the Global Warming Potential (GWP) of emissions of each greenhouse gas. Essentially, GWP is a means of weighting the relative contributions of GHG emissions over a specific time period. GWP depends on (1) the position and strength of the adsorptive bands of the GHG; (2) its atmospheric residence time; (3) its molecular weight; and (4) the time period over which the heating effects are of concern.[64] While the first three factors can be scientifically determined, the fourth is a choice that must be made by the analyst. This selection is important because the GWP of each GHG depends on the time period over which its heating effects are calculated. Various time periods have been proposed, including 20 years, 50 years, 100 years, 500 years, or an infinite time period. In general, shorter time periods dilute the long-term contributions of GHGs with long atmospheric residence times (e.g., carbon dioxide), whereas longer time periods dilute the long-term contribution of GHGs with short residence times (e.g., methane).

For convenience, GWPs are usually quoted in quantities relative to carbon dioxide (i.e., carbon dioxide equivalence). That is, the indicator is defined such that a given quantity of a GHG such as methane can be converted to the quantity of carbon dioxide that would have an impact on greenhouse warming equivalent to the original amount of methane. However, any other metric could be used. For example, some scientists have suggested using a methane-based GWP system.[65] One set of GWPs developed by the Intergovernmental Panel on Climate Change is shown in Exhibit A-1. The exhibit illustrates the effect that the choice of time-period has on GWPs. Other efforts to develop GWPs include those of Lashof and Ahuja (1990), Rodhe (1990), and Derwent (1990).

Despite uncertainties about processes governing carbon dioxide's presence in the atmosphere, GWPs can still assist in aggregating GHG emissions to a common unit. It is possible that GWPs could be recalculated as our scientific understanding increases, just as Ozone Depleting Potentials (ODPs) have been recalculated for the Montreal Protocol on Substances that Deplete the Ozone Layer. It is important to note, however, that such recalculations can sometimes have profound implications for strategies affecting individual gases. For example, the ODP of one of the substitutes for substances controlled under the Protocol, HCFC-141b, was recently modified from 0.08 to 0.15 so as to reflect the discovery of its more adverse impact on

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[64] IPCC (1990), op. cit.; Executive Summary, Section 2, "Radiative Forcing of Climate."

[65] Enting, I.G. and H. Rodhe (1990), Letter to the Editor, Nature, Volume 349, February 7, 1991.

chlorine loading in the atmosphere. Its utility as a substitute chemical has now been called into question. Current reassessments by the IPCC on appropriate GWP factors could have similar implications.

**Exhibit A-1**
**Time-Horizon Dependency of GWPs**

| GREENHOUSE GAS | LIFETIME (YEARS) | GWP 20 YEARS | GWP 100 YEARS | GWP 500 YEARS |
|---|---|---|---|---|
| Carbon Dioxide | (*[66]) | 1 | 1 | 1 |
| Methane | 10 | 63 | 21 | 9 |
| Nitrous Oxide | 150 | 270 | 290 | 190 |
| CFC-11 | 65 | 4,500 | 3,500 | 1,500 |
| CFC-12 | 130 | 7,100 | 7,300 | 4,500 |

*B. Modelling Atmospheric Concentrations of GHGs*

This methodology relies on information on the atmospheric concentration of GHGs, and often requires the use of a climate model to simulate the time-dependent effects of atmospheric concentrations of GHGs.[67] Many three-dimensional climate models have been used to determine the timing and predicted impact of a doubling of atmospheric concentrations of carbon dioxide on global climate. Atmospheric concentrations of GHGs are increasing gradually, however, and this approach enables analysts to determine the variations in climate resulting from such changes in atmospheric content. This approach differs from the GWP methodology in that it is not concerned with sources of GHGs, per se. Rather, its purpose is to predict the changes from modifications to atmospheric concentrations of GHGs.

*C. Greenhouse Forcing Contribution (GFC)*

The GFC approach is based on the concept of the "airborne fraction" of GHGs. A GHG's airborne fraction is defined by the observed increase in atmospheric concentration of the gas over a specific time period divided by the total anthropogenic source of that GHG over the same time period. If a time period of one year is used, the airborne fraction multiplied by the

[66] Unlike other GHGs which are eventually destroyed, carbon dioxide continuously cycles throughout the biosphere between various reservoirs (i.e., atmosphere, oceans, and biota). Thus, it does not possess an atmospheric lifetime.

[67] See for example, Hansen, J., I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, G. Russell, and P. Stone (1988), "Global Climate Changes as Forecast by Goddard Institute for Space Studies Three-Dimensional Model," Journal of Geophysical Research, B:Vol. 93, No. D8, pp.9341-9364, August 20, 1988.

infrared heating effectiveness could be described as being a measure of a GHG's annual greenhouse forcing. Exhibit A-2 shows proposed weighting factors for the infrared heating effectiveness of different GHGs.[68]

**Exhibit A-2**
**Weighting Factors for Infrared Heating Effectiveness of GHGs**

| GREENHOUSE GAS | WEIGHTING FACTORS FOR INFRARED HEATING EFFECTIVENESS (kg of C equiv.) |
|---|---|
| Carbon Dioxide | 1 |
| Methane | 15.8 |
| CFC-11 | 1,083 |
| CFC-12 | 1,568 |

Mathematically, the GFC of a particular GHG can be expressed as follows:

$$GFC = R * A$$

where R is the infrared heating efficiency of the gas, and A is the empirically determined airborne fraction.[69] Since it calculates the incremental contributions to greenhouse warming, the emphasis of the GFC approach is often on computing the current rate of forcing rather on historical emissions or future projections of emissions. This distinction has important implications for assigning accountability for greenhouse warming. For example, present warming is the cumulative result of past emissions which are not reflected in the present rate of greenhouse forcing. Thus, in assigning responsibility for greenhouse warming, it is necessary to look beyond current rates of forcing.

### 2. Methods Used to Establish Comparative Rankings

Just as there are competing methodologies for determining the scientific relationship between GHGs, there are different approaches for establishing the rankings of emissions. Two of the basic approaches are discussed below. The first focuses on determining the sources of emissions while the second emphasizes the allocation of emission rights. As will be discussed below these two approaches overlap to some degree.

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[68] Hammond A.L., E. Rodenburg, and W. Moomaw (1990), "Accountability in the greenhouse", Nature, Volume 347, October 25, 1990.

[69] Hammond, A. et al.(1990), op. cit.

### *A. Accounting for Emission Sources*

In ranking countries by total GHG emissions, an analyst can choose from several different approaches. For example, national emissions can be ranked in total, or emissions per capita, per available natural sink in that country, per GDP, per GNP, or by any combination of these measures. The rankings of countries will vary significantly depending upon the approach selected.

One significant concern in attributing sources of GHG emissions to specific countries is that many GHG emissions are generated by one country producing goods for consumption in another country. For example, many countries are reliant on energy produced in other countries. In such cases, one contentious issue is whether all of the emissions from energy production (e.g., fossil fuel combustion) should be attributed to the producer, to the consumer, or whether they should be divided and attributed to both countries, and if so, what type of attribution method should be used. Most emission databases assign the emissions to the country in which the emissions are produced; such an assignment of emissions to the country of origin does not necessarily imply responsibility for those emissions. Ultimately, that is a matter for international discussions concerning global climate change.

### *B. Determining Emission Rights*

Greenhouse warming has been termed the ultimate "tragedy of the commons."[70] This term, coined by Hardin, describes the situation where rational exploitation of a resource by individuals produces an irrational outcome of resource depletion. The term as applied to greenhouse warming has been described as a misnomer since unlike Hardin's common grazing pastures, the global atmosphere is an open access resource that can not be saved simply by the imposition of property rights.[71] Arguably, however, the natural absorptive capacity of the earth is a global commons.[72] The emphasis of this approach is to assign the equivalent of property rights as a solution to the overuse of a global resource. Applying the concept of property rights to the natural adsorptive capacity of the earth would result in distributing rights to emit GHGs based on some previously-agreed upon level of emissions, including an allocation based on an estimate of the global sinks for GHGs. These sinks or agreed-upon emission levels could be attributed in several ways such as per nation, per capita, per GNP, per GDP, or by any hybrid of these factors.[73] Developing a GHG indicator would thus involve determining each country's net emissions of GHGs, i.e., total emissions minus its predetermined share of global GHGs.

One issue central to the determination of emission rights is whether certain activities should be exempt from emissions reductions or subject to less restrictions than others. For example, GHG emissions resulting from subsistence activities such as wet rice cultivation could be

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[70] Flavin, C. (1988), "The Heat is On", in Worldwatch, November, 1988. The concept of global commons was first articulated by Hardin, G (1968) in "The tragedy of the commons", in Science, Volume 162, pp.1243-8.

[71] Lipschutz, R and P. Gleick (1989), "Climatic Change and Strategies for Control: Linkages to other issues."

[72] Agarwal, A, and S. Narain (1991), op. cit.

[73] See for example, Smith, K., J.N. Swisher, R. Kanter, and D. Ahuja (1991), "Indices for a Greenhouse Gas Control Regime That Incorporates Both Efficiency and Equity Goals," World Bank Environment Department Divisional Working Paper 1991-22; also Wilson, R. (1991), "A New Approach to GHG Emissions Trading: Allocation by a Carbon Reservoir Index," draft discussion paper.

weighted less than emissions resulting from the use of aerosol products on the assumption that food production is a more essential activity than aerosol applications. One method of weighting emissions from specific activities could be to ascertain the contribution of the activity to a country's GNP or GDP. Emissions from activities that contribute large shares of GNP might be weighted less than emissions resulting from more marginal economic activities.

## APPENDIX B
## DATA USED TO DERIVE THE COUNTRY RANKINGS

The following two exhibits provide the background data used to derive the country rankings in Sections VI-B and VI-C of the report. Exhibit B-1 summarizes the range of global emission estimates for specific activities for the scenarios analyzed in Section VI-B and Exhibit B-2 summarizes the range of country emission estimates used for specific activities for the scenarios analyzed in Section VI-C.

**Exhibit B-1**
**Global Emission Estimates for Scenarios in Section VI-B**

| ACTIVITY | BASE CASE | LOW | HIGH |
|---|---|---|---|
| Fossil Fuel Production and Use (Gt C) | 5.1 | 4.9 | 5.9 |
| Deforestation (Gt C) | 1.8 | 0.6 | 2.6 |
| Enteric Fermentation (Tg $CH_4$) | 76 | 65 | 100 |
| Rice Cultivation (Tg $CH_4$) | 109 | 25 | 170 |
| Landfills (Tg $CH_4$) | 30 | 20 | 70 |
| Biomass Burning (Tg $CH_4$) | 53 | 20 | 80 |
| Fertilizer Use (Tg N) | 1.6 | 0.01 | 2.2 |

**Exhibit B-2**
**Country Emission Estimates for Scenarios in Section VI-C**

| ACTIVITY | BASE CASE | LOW | HIGH |
|---|---|---|---|
| **$CO_2$ from Deforestation (Tg C)** | | | |
| India | 33.0 | 11.1 | 47.9 |
| Brazil | 336.1 | 112.5 | 487.7 |
| **$CO_2$ from Fossil Fuels (Tg C)** | | | |
| U.S.A. | 1229.2 | 1168.4 | 1406.8 |
| U.S.S.R. | 899.0 | 854.5 | 1028.9 |
| **$CH_4$ from Rice Cultivation (Tg $CH_4$)** | | | |
| China | 24.3 | 5.5 | 37.7 |
| India | 31.8 | 7.3 | 49.4 |
| **$CH_4$ from Enteric Fermentation (Tg $CH_4$)** | | | |
| U.S.A. | 7.0 | 6.0 | 9.2 |
| India | 10.3 | 8.8 | 13.6 |
| **$N_2O$ from Fertilizer (Tg N)** | | | |
| China | 0.33 | 0.0021 | 0.47 |
| U.S.A. | 0.28 | 0.0015 | 0.33 |