“Financing Global Environment Programs: Institutional Design with Equity and Efficiency”

94-04-30

Chitru Fernando, Paul Kleindorfer and Kevin Fitzgerald
Financing Global Environmental Programs: 
Institutional Design with Equity and Efficiency

Chitru S. Fernando 
The Freeman School of Business 
Tulane University

Paul R. Kleindorfer 
The Wharton School 
University of Pennsylvania

Kevin B. Fitzgerald 
The Wharton School 
University of Pennsylvania

October 15, 1993

---

We thank Mohan Munasinghe for his advice and assistance, and participants at the IIASA Workshop on Risk and Fairness (June 19-22, 1993) for constructive comments. This research has been supported by a grant from the World Bank.
Executive Summary

This paper identifies and addresses several issues related to global cooperation for reducing greenhouse gas (GHG) emissions related to global climate change. This is an area of significant policy interest because of the potential magnitude of investments associated with achieving significant reductions in GHGs and because of the growing concern by policymakers and the public about the dangers of climate change. We address the following issues:

1. The nature of the GHG problem and the associated mitigation effort and the benefits of global cooperation in addressing this problem.

2. The role of equity considerations in global cooperation.

3. The appropriate structuring of international resource transfers to achieve GHG mitigation in the most efficient and equitable manner.

While the present research builds on previous World Bank sponsored work on the implementation of the Montreal Protocol, we note the considerable differences between the Montreal Protocol and a corresponding international convention on global climate change. These differences arise from (a) the magnitude of the economic impacts that would be under consideration and the resources at stake; (b) the prevailing scientific uncertainty relating to global climate change; and (c) the heterogeneity of impacts associated with climate change.

The bulk of this paper is focussed on the development of an economic framework to evaluate alternative institutional mechanisms for global GHG abatement. This framework is built around a group of countries or country groups with heterogeneous preferences and incomes. We investigate alternative outcomes when countries carry on with "business-as-usual", (non-cooperatively) maximizing their individual welfare, allocating resources for consumption and GHG-reducing investment accordingly, and when they cooperate in global efforts to mitigate global climate change. Our focus is on seeking out opportunities for cooperation through international resource transfers used to leverage the funding of GHG mitigation projects, especially in developing countries where projects could not be undertaken without international support. Thus, for example, the OECD countries might find it more cost effective to invest in GHG abatement projects in developing countries, and fund a pool of resources such as the Global Environmental Facility (GEF) to put such a program into effect.

The focus of GEF transfers is clearly to promote efficiency through targeted project funding. But resource transfers for funding GHG abatement projects are also important for promoting perceived fairness or equity. Besides income transfers, a number of other determinants of perceived fairness are considered, including acceptability, information sharing on best practices and available technologies, grandfathering, feasibility, efficiency, and volunteerism. Designing institutions which incorporate these determinants of perceived equity may lead to efficiency losses relative to the full cooperative solution. But, as we argue, the full cooperative solution is likely not to be acceptable without a perception of equitable burden sharing. Thus, in implementing the Climate Change Convention, these determinants of perceived equity must be balanced against their efficiency consequences and the transactions costs of institutions which incorporate them. We argue in this paper that this balance is best achieved through decentralized, monitored
implementation of country targets, with fair burden sharing in achieving these targets assured through realistic transfers of capital and technology from the developed to the developing world.

A key focus of this paper is the magnitude of the resource transfers required in order to satisfy various "equity constraints". We show that the benefits of even modest cooperation can be quite substantial in efficiency terms. Thus, a key tradeoff emerges in terms of the balance between the size of the GEF required to lubricate cooperation and the magnitude of the efficiency gains associated with projects funded through the GEF. We consider various levels of cooperation, beginning with the non-cooperative, business-as-usual solution and ending with the (set of) full information, first-best cooperative solution(s). Using our model framework, we illustrate for 1989 data that a relatively modest-sized GEF, if efficiently administered, is sufficient to attain most of the benefits of the fully cooperative solution. The key to efficiency lies in evoking sufficient cooperation among nations to allow the identification of GHG mitigation projects which, at the margin, should be funded. This identification requires essentially that nations share with the GEF administration their country plans for GHG mitigation and the marginal abatement costs of specific projects in these country plans. The actual implementation of these plans and projects would be carried out in decentralized fashion at the country level. Whether nations will be willing to cooperate in this fashion will, we argue, depend on their perception of equitable burden sharing in meeting whatever the agreed global mitigation level is.

The results of our review of the antecedents of cooperation and of our theoretical framework may be summarized as follows. The central feature of institutional design to implement the Climate Change Convention must be to assure both cooperation and efficiency through decentralized implementation of agreed global and country targets, with fair burden sharing in achieving these targets assured through realistic transfers of capital and technology from the developed to the developing world.
# Table of Contents

Executive Summary ................................................................. i

Introduction .............................................................................. 1

1. Issues Relating to Global Climate Change and Its Mitigation .......... 3
   1.1 Background to the Global Climate Change Problem .................. 3
   1.2 Issues Framing Policy Responses to Global Climate Change .......... 7
   1.3 Design of a Fair Mechanism for Reducing GHG Emissions .......... 9

2. Modelling Equity and Efficiency in Global Climate Change .......... 11
   2.1 The Benchmark Noncooperative Solution .............................. 14
   2.2 A First-Best Framework for Characterizing Cooperative Solutions ...... 15
   2.3 Solutions for Alternative Institutional Designs ..................... 17

3. A Simulation Framework for Studying Cooperative Behavior ........... 22
   3.1 Benchmark Noncooperative Case ....................................... 22
   3.2 A Simulation Framework .................................................. 24

4. Decentralized Implementation Mechanisms .................................. 30
   4.1 Decentralized Implementation ......................................... 30
   4.2 Fairness ....................................................................... 32
   4.3 Outlines of a Possible Institutional Design ........................... 32

5. LDC-Specific Issues .............................................................. 36

6. Conclusions and Directions for Future Research ........................... 38

Appendix 1: Principles of Fairness and Equity Precedents for a Global Climate Change Convention ................................................................. 39
   Principles and Attributes of Fair Allocations .................................. 39
   Precedents for a Climate Change Convention ................................... 42

Appendix 2: Technical Appendix .................................................. 47
   Proof of Proposition 1 ................................................................ 47
   Characterizing the First-Step Cooperative Solution with Strategic Behavior ............. 47

Appendix 3: Simulation Framework Details ........................................ 51
   Results ............................................................................... 51
   Country Level Data ................................................................ 55

References ............................................................................... 61
Introduction

Growing awareness and increasing concern about the accumulation of greenhouse gases (GHGs) has led to a series of initiatives (such as the Rio summit last year) towards a global accord on the mitigation of global climate change. As in the case of the Montreal Protocol for the elimination of CFC’s, an important issue associated with such an accord is the allocation of resources globally to achieve this mitigation in the most efficient and equitable manner.

This paper identifies several issues relating to the design of institutions to implement economically efficient and equitable approaches to monitoring and mitigating the effects of Greenhouse Gases (GHGs), such as CO$_2$ and CH$_4$, on the global environment and the global economy. We build on previous World Bank sponsored research (Allen et al., 1992) in the context of implementing the Montreal Protocol and the stratospheric ozone depletion problem. This earlier research emphasized institutional design for global efficiency, but was also driven by important equity and participation constraints. The present research continues to emphasize both efficiency and equity, but we focus as well on fundamental differences between the implementation of the Montreal Protocol and a corresponding international convention on global climate change. These differences include the following:

1. **Magnitude**: The sheer magnitude of the economic impacts likely to be under discussion will be considerably higher, so that the consequences of policies, including those directed at equitable burden sharing, will not be just "at the margin", but will entail significant changes in business as usual scenarios.

2. **Scientific Uncertainty**: The science of global climate change is fraught with uncertainties, so that issues of monitoring and mitigation and the impact of policy on these will be much more difficult to understand. Coupled with scientific uncertainty are issues of policy uncertainty related to available data, especially in LDCs, on levels of economic activity in sectors using or generating GHGs. This is partially the result of very diffuse sources and sinks for GHGs and the very large number of economic agents involved in these sectors.

3. **Heterogeneous Impacts**: The impacts of GHGs, even assuming a worst case climate warming scenario, will be considerably more heterogeneous than the more uniform impacts of ozone depleting substances. Some countries could benefit while others could face catastrophic consequences.

Given the above conditions, the nature of the economic instruments likely to be effective for coping with GHGs will be different than those associated with the Montreal Protocol. Nonetheless, some important aspects of the ozone problem carry over. Also, many characteristics of earlier proposals (e.g., Allen et al. [1992]) on decentralized solution approaches to the ozone problem have relevance for the GHG problem, namely those concerned with global efficiency, technology transfer of best practices, and the importance of welfare-neutral or welfare-improving policies at the country level to promote decentralized implementation of global climate change mitigation programs.

The bulk of this paper is focussed on the development of an economic framework to both inform the design of and to evaluate alternative institutional mechanisms for global GHG abatement. This framework is built around a group of countries or country groups with heterogeneous preferences and incomes, and we investigate alternative outcomes when countries carry on with "business-as-usual", (non-cooperatively) maximizing their individual welfare, allocating resources for consumption and GHG-reducing investment accordingly, and when they cooperate in global efforts to mitigate global climate
change. Our focus is on seeking out opportunities for cooperation through international resource transfers and the re-allocation of these resources such that all countries are made better off through cooperation. More so than in the case of the Montreal Protocol, an important element of a cooperative global solution to the GHG problem is the seeking out of projects that are the most efficient from a global standpoint, and ensuring that these projects are implemented through international resource transfers. Thus, for example, the OECD countries might find it more cost effective to invest in GHG abatement projects in developing countries, and fund a pool of resources to put such a program into effect. On the other hand, as in the case of the Montreal Protocol, transfers also play an important role on the equity dimension, since they are an important lubricant for cooperation. The framework that we develop provides a useful basis for examining alternative equity-driven "constraints" on a purely economic solution. Several of these constraints are examined in the paper.

We proceed as follows. The next section discusses relevant scientific/technological and socio-economic issues associated with the global climate change problem. We also summarize the nature of the policy debate on global climate change and its relationship to equity and efficiency. Section 2 develops a two-stage model in which countries or regions are assumed to make investments (in GHG conservation) and monetary transfers in stage 1, before an uncertain state of the world is revealed in stage 2. The investments and resulting GHG emissions from each country are understood to be subject to some "equity constraints", that are agreed on before any actions are undertaken (i.e., prior to stage 1 decisions). The questions we address are: what will be the impact of various "equity constraints" on stage 1 investments and transfers, on overall efficiency, and on GHG emissions (the latter being a surrogate for GHG impact). In Section 3, we illustrate the concepts of Section 2 through a detailed example. Using actual country data for all the countries of the globe, we develop a simulation framework to analyze the impact of alternative proposals that have been advanced for sharing the burden of mitigating global climate change, in the context of the comprehensive economic model developed in this paper. In Section 4, we discuss the decentralized implementation of various equity-efficiency designs, as developed in Section 2. Section 5 focuses specifically on issues associated with GHG abatement in developing countries, including participation of these countries in a global accord and the allocation of resources for GHG abatement projects in these countries. A final section presents concluding remarks, discusses limitations of this research and directions for future research.
1. Issues Relating to Global Climate Change and Its Mitigation

In this section, we first discuss the background to the global climate change problem, focussing in particular on the scientific questions that have a major impact on the design of effective economic institutions for dealing with the problem. Thereafter we briefly discuss various alternatives that have been proposed for addressing the problem and some financial implications of these. We also review the issues that have framed various policy responses to the global climate change problem, and summarize the potential impact of equity considerations in arriving at a global accord to reduce net GHG emissions.

1.1 Background to the Global Climate Change Problem

The earth’s atmosphere maintains the habitability of the planet partly by a natural ‘greenhouse effect’ that traps incoming solar energy. The principal greenhouse gases are water vapor, carbon dioxide (CO₂), methane (CH₄), Chlorofluorocarbons (CFCs), and Nitrous Oxide (N₂O). These gases are transparent to the short wavelengths of incoming solar radiation, but trap long wavelength infra-red radiation from the Earth. Since the industrial revolution, anthropogenic emissions appear to have altered this natural climatological mechanism. Principally, emissions of CO₂ from fossil fuels, CH₄ from rice paddies and landfills, and CFCs have increased atmospheric greenhouse gas concentrations, thereby contributing to a rise of about 0.5°C in mean global temperature since 1880. According to the National Academy of Sciences (1992), if emissions are allowed to proceed unchecked, we can expect mean global temperatures to rise 1°C - 5°C within the 21st century.

Due solely to growth in the use of fossil fuels, emissions of carbon dioxide have grown at roughly 3% per year since the industrial revolution to today’s global emissions levels of around 6 Gigatons of carbon/year. Since carbon is also stored in biomass that alternately consumes and restores CO₂ to the atmosphere in a balanced annual growth cycle, deforestation releases net CO₂ into the atmosphere. Though the annual carbon exchanged between the atmosphere and plants and forests, about 120 Gigatons, is much larger than emissions due to fossil fuels, it is net emissions into the atmosphere that determine changing atmospheric concentrations. Atmospheric CO₂ concentrations have increased from about 280 ppm (parts per million by volume of dry air) in pre-industrial times to over 350 ppm in 1996 (MacCracken et al., 1990). Though energy use is responsible for about 70% of annual CO₂ emissions, deforestation contributes another 20% (Stern, 1989). Carbon dioxide is responsible for roughly half of the annual contributions to the greenhouse effect. Methane from rice paddies and landfills and CFCs also contribute 18% and 14%.

Mean global temperature is a complicated function of the incoming solar energy, the thermal energy stored in the oceans and land masses, the changing concentrations of greenhouse gases, as well as other transient phenomena. It is evident that mean global temperature has increased about 0.5°C over this century. What is not evident is whether this trend is within the natural variation of mean global temperatures over a 100-year period, or if it is significantly outside of the natural "background noise". According to Dr. James Hansen of NASA’s Goddard Institute for Space Studies, the standard deviation of mean global temperature over a 100 year period is roughly 0.2°C. It is his claim that "CO₂ warming should rise above the noise level of natural climate variability in this century" (Hansen, et al., 1981).

In addition to warmer mean global temperatures, other probable consequences of climate change include: more mean global precipitation; drier, hotter summers in the interiors of temperate continents; and
rising sea levels (NAS, 1987). Due to the rapidity of the predicted climate change (unprecedented in the geological record), the risk of low probability-high consequence weather events, such as droughts and floods, can be expected to increase as we enter the 21st century. However, due to inherent difficulties in modelling global climate systems that are extremely complex, interactive, and non-linear, consensus has not yet emerged on the regional effects of climate change. Global trends certainly give cause for concern, but consequences for any specific location or constituency are far from clear.

**Issues of Scientific Uncertainty**

Climate models are of two types: radiative forcing models and general circulation models. **Radiative forcing models** predict the time dependent path toward a final equilibrium temperature based on physical principals such as incident solar radiation, reflectivity of surfaces, absorption of energy at different wavelengths by trace gases, and simple process lag coefficients (designed to capture the damping effects of thermal storage capacities in the oceans, polar ice caps, and land masses).

Observations of mean temperature changes and trace gas concentrations over the past 100 years have given geophysicists and meteorologists a means to calibrate their climate prediction models. If the models are fairly accurate 'predictors' of past temperatures, this enhances their general credibility as predictors of future climates. Radiative forcing climate models that include a 50 year lag time and a 4°C equilibrium temperature rise in response to a doubling of CO₂ concentrations are the best fit to data on atmospheric greenhouse gas concentrations and actual mean temperature trends since 1880 (MacCracken et al., 1990). Refinements that account for additional phenomena such as volcanoes, sun-spot activity, and mixed layer and thermocline action in the oceans are able to explain temperature trends remarkably well (Hansen, et al., 1981).

Radiative forcing models project that a broad range of 1°C - 5°C rise in mean global temperatures is likely within the 21st century (National Academy of Sciences, 1992). If the radiative forcing models are correct, emissions of greenhouse gases to date have already committed the global atmosphere to a mean temperature rise of 1°C to 3°C within the next century.

However, there are many aspects of the global climate that are poorly understood and are not easily accounted for in the radiative forcing framework. These phenomena include the effects of clouds, circulation of gases at different levels of the atmosphere, and the effects of changing circulation patterns in the oceans. In addition, radiative forcing models give no insight into regional climate change that might be expected. A few large **general circulation models** (GCMs) have been developed to account for circulation and non-linear interactions of the atmosphere, clouds, oceans, ice sheets, and biota. As GCMs are in their infancy, there is little agreement on the details of their projected future climates. However, there are some broad regional projections that are beginning to converge between models (mentioned below). The major GCMs built in the United States have been developed at NASA’s Goddard Institute for Space Studies (GISS), NOAA’s Geophysical Fluid Dynamics Laboratory (GFDL), and the National Center for Atmospheric Research (NCAR). A representative run of the GFDL model indicates that a doubling of atmospheric carbon dioxide concentrations could lead to a number of consequences including a heightened risk of catastrophic floods in Bangladesh, China, and Indonesia and increasing probability and duration of droughts in the central grain growing regions of the United States and the Soviet Union.

There are a number of controversies in the construction of GCMs that are not expected to be resolved any time soon. Questions about the effects of clouds has a long track record in the weather prediction community. Predictions of most GCMs are highly sensitive to assumptions about the role of
clouds in mitigating or enhancing climate perturbations. Modelling the heat and carbon exchange between the atmosphere and oceans is also fraught with uncertainty. The roles of the jet stream and the El Niño effect -- shifting ocean circulation patterns first detected in 1972 (Kellogg and Schware, 1981) -- serve to complicate the matter further. The overall implication is that, even though some marginal patterns are emerging that are common to some of the GCMs, prediction of both global and regional impacts of global climate change is fraught with uncertainty.

Projected Impacts of Global Climate Change

Three major assessments have been undertaken to use the results of GCMs for projecting potential regional impacts of global climate change. The National Academy of Sciences projected a number of probable physical impacts to emerge within the 21st century from a doubling of CO$_2$ or its radiative equivalent (NAS, 1987). The panel projected CO$_2$ doubling impacts in the following physical categories:

(i) global mean surface warming of 1.5°C - 4.5°C;

(ii) increase in global mean precipitation and in high latitudes of the northern hemisphere;

(iii) long-term, mid-latitude summer continental dryness and warming; and

(iv) a rise in the mean sea level of 10 to 30 cm due to thermal expansion of the oceans and a reduction in sea ice.

Drawing on similar GCM results, the IPCC evaluated the probable regional effects of a continuation of current emissions trends into the 21st century. The following regional impacts resulting from the model were reported by the panel to be very likely by the year 2020:

(i) **Central North America:** Warming between 3°C and 4°C in winter and 2°C to 3°C in summer; precipitation staying below 20% in winter and 10% in summer; and soil moisture would decrease in summer by 10-15%.

(ii) **South East Asia:** Warming ranges from 1°C to 2°C throughout the year with no precipitation changes in winter and 5% to 15% increase in summer; summer soil moisture increase by 5% to 10%.

(iii) **Sahel:** Warming ranges from 1°C to 2°C with marginal increase in summer precipitation and decrease in soil moisture.

(iv) **Southern Europe:** Warming of roughly 2°C in winter and 2°C to 3°C in summer; precipitation in winter increasing marginally but summer precipitation decreasing by 5% to 15%; summer soil moisture would be lowered by 10% to 25%.

(v) **Australia:** Warming 1°C to 2°C in summer and 2°C in winter; summer precipitation rise 10%. Changes in soil moisture are unknown. There are large variations at the sub-continental level within this area.” (Mohnen et al., 1990).

The EPA mounted an heroic effort to translate similar broad physical and regional projections into specific expected impacts on different sectors of the economy within five regions of the United States
(EPA, 1990). The study assessed the probable impacts of climate change and sea level rise on: (i) water resources; (ii) agriculture; (iii) ecosystems - forests, watersheds, lakes, climatological zones, etc.; (iv) human health; and (v) urban infrastructure. Though there is a wide variation in the range of potential impacts and the state of the data and the science does not allow the projection of probable economic losses at the sectoral level in each region.

In sum, climate change prediction is an inexact science, but broad patterns in the models are emerging that have caused even the most conservative reviewers to take notice. Consensus has formed on further mean global temperature increases and mean sea level rise due to thermal expansion of the oceans. A few regional patterns are emerging from the GCMs, but due to systemic uncertainties, these patterns do not validate the predictions. It is likely that the 21st century will experience rapid climate change in response to anthropogenic influences. It is not yet clear whether this rapid change will seriously alter the capabilities of local environments to provide goods and services demanded by future societies.

Alternatives for Dealing with Global Climate Change

The policy options that can be employed to minimize climate change in response to emissions of trace gases from human activities can be classified as: (i) engineering countermeasures; (ii) adaptation; and (iii) prevention.

Engineering countermeasures

Technologies to reduce CO₂ emissions are currently under research and development. Clean combustion technologies (CCT) use advanced thermodynamic processes to increase the efficiency of fossil fuel use. Current boiler designs for both coal and oil-based electricity generation obtain thermal efficiencies of 30% to 35%. CCT can achieve efficiencies of 40% to 45% which can result in 25% reductions in CO₂ emissions. Other advanced technologies, such as fuel cells and magnetohydrodynamics (MHD), might achieve efficiencies in the range of 45% to 60%, thus reducing CO₂ emissions by 50%. However, these technologies are currently very expensive. Another approach, carbon sequestration, is aimed at developing technologies to remove carbon from the flue gas stream of fossil fuel plants. However, they require a 50% derating which means twice as much coal or oil must be consumed to generate the same amount of electricity. In addition, a current constraint to the wide adoption of such systems is posed by the fact that no workable disposal scheme has yet been developed to securely dispose of massive amounts of carbon dioxide without running the risk that much of the CO₂ would eventually seep into the atmosphere. The Electric Power Research Institute (EPRI) estimates that carbon sequestration systems could double current electricity costs (Kane and South, 1989).

Adaptation

Certain policy responses provide a good hedge against climate change by maintaining diverse water supplies, food sources, and fuels. Policies included in this approach seek to maintain biological diversity, stimulate inter-cropping, and build diverse international economic ties. Explicit development of compensation mechanisms are a forward-looking component of adaptation strategies.

Prevention

A large share of the current global climate change policy discussion, both national and international, is focussed on selecting an appropriate bundle of preventive options. Policies in the
prevention arsenal are aimed at reducing GHG emissions by stimulating substitution by cleaner fuels (e.g. nuclear or natural gas displacing coal), encouraging conservation, and increasing the efficiency of energy supply and use. These policies include: Corporate Average Fleet Economy Standards (CAFE); performance standards for industrial equipment and household appliances; emissions regulations on particular industrial sectors; systems of tradable emissions certificates such as those under provisions in the Clean Air Act; taxes and subsidies to encourage conservation, switching, and investments in energy efficiency; and public information campaigns.

Financial Implications

Nordhaus (1991) surveyed a number of studies that estimate the cost of controlling emissions of GHG. Estimates in these studies (engineering, macroeconomic, and general equilibrium) ranged from $5 to $342 per ton of carbon equivalent for global reductions from 10% to 80% of current emissions. A computable general equilibrium model that explicitly models the distribution of costs among four distinct world regions (Whalley and Wigle, 1991) estimated that it would cost roughly $430 per ton of carbon equivalent to reduce emissions by 50% from current levels over a 40 year period. These cost estimates are considerable, amounting to between 1% and 5% of total regional output.

1.2 Issues Framing Policy Responses to Global Climate Change

Even if it is not possible to quantify all of the costs and benefits of each policy option, a cost-benefit approach to global climate change policy evaluation is appropriate because it forces all trade-offs to be made explicit. There are three possible policy responses to the kinds of impacts summarized above: (i) do nothing and adapt as the impacts emerge; (ii) invest in preventive measures to reduce emissions; and (iii) invest in adaptive relationships and structures. A reasonable approach for evaluating trade-offs between these options is to first establish acceptable levels and rates of warming. Once these targets are determined, "the overall aim should be to minimize the sum of the policy and private costs for any given level of warming" (Barbier and Pearce, 1990). The setting of international targets is a critical step, because nations will have different views of acceptable levels and rates of warming.

Two characteristics of global climate change complicate the evaluation: discounting and irreversibility. The high degree of uncertainty in predicting future climate change results in a very high expected value of new information (quasi-option value) in the policy evaluation process. However, irreversibility and long time-lags of climate change processes work against the "do nothing" approach as a strategy for resolving uncertainty. As societies subscribe to a 'wait and see' approach, emissions in the interim commit the planet to additional warming which, in turn, increases the risks of low probability-high consequence weather events increases the extent of required adaption.

The other complicating factor is how to treat discounting across generations when supply-side environmental capacities are changing. Future societies will demand services from the environment. However, the capacity of the ecosystem to provide the demanded services may be impaired by rapid climate change. Traditional discounting methods do not appropriately account for this possible supply-side loss. Under the assumption that society is risk-averse, current societies are willing to pay a premium in return for reduced expected loss by future generations. Barbier and Pearce suggest that one way to get around the discounting problem is to use this risk premium (option value) as a measure of how much to invest in global climate change mitigation policies. This investment can be viewed as an indirect
compensation to future generations. "If global climate change results in an irreversible and non-substitutable loss of capital, then indirect compensation is the best means of ensuring inter-generational equity. Cost-effective preventive and adaptive measures today, coupled by increased research and knowledge of climatic change, are the best compensatory investments for the future" (Barbier and Pearce, 1990).

As the global atmosphere is essentially a commons used by many nations with a wide variation of endowments and interests, effective approaches to climate change will require coordinated action through international agreement. Analysis of the most promising policy options that are under consideration in ongoing international discussions are briefly presented below.

Carbon Dioxide Emission Limits

Within the spirit of this forward-looking cost-benefit approach, a number of energy economists have put significant effort into evaluating the costs and benefits of carbon dioxide emission limits. The most seminal work has recently been published by Manne and Richels (1990). Using an energy technology model linked with a macroeconomic model, Manne and Richels are able to evaluate impacts of various policy packages in terms of resulting shortfalls from potential GDP. A key result is that if U.S. carbon dioxide emissions are limited to the current 1990 rate of 1.37 Gigatons per year through the year 2000 and then reduced to 80% of this level by the year 2020, the resulting cost is roughly $3.6 trillion in present value terms to the United States economy. This represents approximately 5% of the total annual U.S. macroeconomic consumption through the next century (Hogan, 1990). Though these targets are severe, there are even more ambitious emission reduction targets embodied in some legislation currently under consideration. This cost estimate assumes that alternative technologies will not be readily available in the near future. When Manne and Richels incorporate more hopeful assumptions about the development of advanced technologies and autonomous energy efficiency improvements, total present value costs of their targets fall to as little as $0.8 trillion. On the basis of these results, Manne and Richels recommend an ambitious research program to develop advanced energy technologies. A critique of this model by Williams indicates that these emission-limit targets could actually be met at substantially lower cost, and possibly even net benefit, by following a much more broadly-based research program including energy efficiency improvements in end-use devices (Williams, 1990). The differences between these policy recommendations and those of Manne and Richels is indicative of the broader divergence of views between 'technological optimists' and the more conservative 'engineering paradigm' (Lave, 1990).

This model is also used to estimate that an equilibrium equivalent carbon tax of roughly $250/ton of carbon would be sufficient to limit emissions at 1990 levels. In another study, Nordhaus finds that a carbon tax of between $3 and $37/ton could result in a 10% to 25% reduction from uncontrolled carbon dioxide emission trends (Nordhaus, 1991). In the cost-benefit framework of Barbier and Pearce, the objective is to compare various emission targets in terms of cost-effectiveness. However, without a corresponding benefit calculation, the relative attractiveness of the two different emissions targets cannot be evaluated.

Using a similar general equilibrium approach, John Whalley and Randall Wigle (1991) evaluated the regional incidence of economic costs resulting from a carbon tax designed to cut projected emissions in half worldwide. According to this study, the most efficient tax is one imposed and retained by energy-consuming countries. In this case, annual global welfare losses average about 2.1% of economic production. Losses would be twice as high if energy producers imposed and retained the carbon tax or if the tax were levied by a world agency which then allocated revenues in proportion to population. The
highest losses result from a regime that imposes an equal per capita emissions ceiling that would allow developing countries to expand emissions but would be tightly binding on industrialized countries. The incidence of welfare losses vary widely across geo-political groups depending upon which approach is taken.

**The Promise of Energy Efficiency**

Another approach receiving considerable attention by energy economists is reducing emissions by improving the efficiency of both energy supply technologies and end-use devices. Since 1973, major reductions in energy intensity (primary energy consumption relative to real GDP) were realized in OECD countries primarily in response to increases in the real cost of energy. It is widely recognized that the capital plant installed in most developing countries is often less efficient than technologies developed in OECD countries in the 1970's. For this reason, some analysts have identified an enormous untapped potential for efficiency gains that could serve to reduce carbon dioxide emissions without a GDP penalty. Because the greatest gains in efficiency improvements are to be had in the developing world, and at least cost, it may well be that the most cost-effective global strategy for reducing carbon dioxide emissions is to invest heavily in these improvements (Kats, 1990). Inefficiency of energy use in developing countries is often assessed as a result of inappropriate planning and inefficient pricing. Subsidized retail prices, common in developing countries, do not give individual consumers appropriate incentives to invest in efficiency since they don't bear the true economic costs of their consumption decisions. Allen and Christensen (1990) have proposed a win-win global strategy which would couple reform toward rational pricing policies with a shift in international technical assistance to improve energy efficiency. Policy-makers in the developing world are hard-pressed to respond to urgent domestic economic needs without the additional burden of safeguarding the global commons. Since energy efficiency improvements hold the promise of stimulating economic growth while simultaneously reducing emissions, a fundamental shift in multilateral lending toward energy efficiency should be in the direct interest of developing country economic planners and global environmental concerns.

1.3 **Design of a Fair Mechanism for Reducing GHG Emissions**

The problem of reducing GHG emissions is greatly complicated by several of its attributes:

- uncertainty in impacts
- asymmetry in the projected impacts
- unequal allocation of initial conditions in use of the global atmosphere as a commons resource
- unequal ability to shoulder the burden of emissions reductions
- changes from the status quo (free access) are viewed as losses

---

1 See Appendix 1 for a discussion of fairness principles and equity precedents.
While all nations have a stake in the use of the commons resource, the rights of national sovereignty imply that no international body can exist with monitoring or enforcement powers. Therefore participation in any agreement is voluntary and subject to renegotiation.

Basically, the stylized problem here is to design incentives which will be effective in reaching efficient levels of global GHG concentrations resulting from country-specific emissions and sinks. These incentives may be expected to include both investment incentives, for GHG mitigation measures undertaken by individual countries, as well as compensation to certain countries to promote their cooperation in this effort. As we will show below, it is critical for efficiency that both investments and compensation be determined cooperatively. And here is where concepts of equity may be central, in that perceived equity has long been noted as an essential ingredient for cooperation (e.g., Barrett (1992, p. 50), Kleindorfer et al. (1993, chapter 7)). In the next section, we formulate this stylized problem and characterize various solutions to it, including the cooperative first-best solution, a noncooperative solution, and various equity-constrained second-best solutions. The objective of this formal analysis is to capture concisely the interactions between the nature of the global negotiation process, its expected outcomes and the incentives which countries face for cooperating with a global initiative to reduce GHGs.
2. Modelling Equity and Efficiency in Global Climate Change

In the spirit of the economic design literature, we investigate alternative institutional approaches to reducing GHGs as follows:

1. We first establish the benchmark scenario of business-as-usual (BAU), in which countries non-cooperatively allocate their income to consumption and GHG-reducing investment to maximize their individual welfare, without regard to any global consequences.

2. We next determine appropriate cooperative actions (including investments and transfer payments) at the global level, aimed at improving the welfare of all countries through cooperation.

3. We then examine efficient institutional designs to implement these actions, subject to constraints on information availability, individual rationality (sovereignty in this context), transaction costs, equitable burden sharing etc. These constraints lead to the joint desiderata of cooperative planning and decentralized implementation.

We begin by developing in this section a two-stage model of global interactions associated with reducing GHG emissions. Each country faces a number of tradeoffs in confronting the issues of global climate change. The essential features of the model are as follows. First, we reflect the consequences of global GHG emissions and the uncertainty of global climate change on each country. These effects may be quite different from one country to the next. Second, we reflect the cost of investments in technologies or activities directed toward reducing GHG emissions by the country. Resources used for this purpose could clearly be devoted to other productive purposes in the country and the economic consequences of diverting their use to reducing GHG emissions is reflected in the model as a reduction in current consumption.

The buildup of GHGs in the atmosphere is a dynamic process and should be so modelled. We take the simplest dynamic model, a two-stage model, preceded by a pre-planning bargaining stage. At stage 0 we assume the global community decides on the framework (if any) it will use for coordinating its efforts to reduce GHGs. At stage 1, each country makes investments to either reduce GHG emissions or to set up the possibility of mitigating the effects of these in stage 2. Further investments and mitigation measures are undertaken in stage 2 after uncertainty about the extent and consequences of GHGs on global climate change is resolved. Forward and options contracts may be signed between various countries at stage 0 and the results of these contracts are realized in stage 2. Thus, the model has the structure shown in Figure 1 below.

We use the following notation:

\[ \theta = \text{country index, where the set of all countries is denoted } \Theta \]

\[ x(\theta) = \text{investment by country } \theta \text{ to reduce GHGs at stage 1} \]

\[ X = \{ x(\theta) \mid \theta \in \Theta \}, \text{the vector of all country investments} \]

\[ y(\theta) = \text{consumption by country } \theta \text{ at stage 1} \]
Figure 1: Model Structure

\[ Y = \{ y(\theta) \mid \theta \in \Theta \}, \text{the vector of all country consumptions} \]

\[ I(\theta) = \text{income for country } \theta \text{ in stage 1} \]

\[ \omega = \text{uncertain state of the world, realized at stage 2, where we assume that } \omega \in \mathbb{R}^* \]

\[ F(\omega) = \text{probability distribution on the states of the world} \]

\[ s(\theta) = \text{monetary transfer payment to country } \theta \text{ at stage 1} \]

\[ S = \{ s(\theta) \mid \theta \in \Theta \}, \text{the vector of all ex ante transfers} \]

Let \( g(x(\theta), y(\theta); \theta) \) (which may be thought of as the "GHG impact function" for country \( \theta \)) denote the total GHGs (measured in units of global climate change potential) generated by country \( \theta \) in stage 1, and let the total GHGs generated in all countries be denoted by \( G(X, Y) \) so that

\[ G(X, Y) = \sum_{\theta \in \Theta} g(x(\theta), y(\theta); \theta). \]  \hspace{1cm} (1)

We assume throughout that, for each \( \theta \), \( g(x, y, \theta) \) is increasing in consumption and decreasing in mitigation investments, i.e., \( g_x < 0, g_y > 0 \). We also assume that \( g(\cdot, \theta) \) is jointly convex in \((x, y)\), so that investments in \( x \) have a declining marginal impact on (reducing) \( G \) and consumption has an increasing marginal impact on \( G \).

We assume the following aggregate welfare function, denoted \( U(\theta) \), for country \( \theta \):
\[ U(X,Y,\omega; \theta) = V(G(X,Y),y(\theta),\omega; \theta), \quad \theta \in \Theta \]  

so that U depends on X only through aggregate GHG emissions G. We will assume that V is decreasing in G,\(^2\) increasing in y and jointly concave in G and y. Given these assumed properties of G and V, it is straightforward to show that, for each \( \omega \) and \( \theta \), V is concave in \((X, Y)\), from which it follows that, for each \( \theta \in \Theta \), the expected value of V over \( \omega \) is concave in \((X, Y)\).\(^3\)

We will also be interested in characterizing the Pareto-efficient outcomes to the collective consumption-investment problem associated with the above country welfare functions \( U(\theta) \). The set of Pareto (or first-best) outcomes is important both as an efficiency benchmark as well as in understanding various "cooperative" solutions, described more fully below, to the global problem of GHG mitigation.

For this purpose, we will define a (weighted utilitarian) global welfare function \( W \) as

\[ W(X,Y) = E_\omega \left\{ \sum_{\theta \in \Theta} \eta(\theta) U(X,Y,\omega; \theta) \right\} \]  

where \( \eta(\theta) \) satisfy:

\(^2\) We will consider below the case where certain countries are strictly better off (i.e., V is increasing in G) as GHGs increase.

\(^3\) To see that V is concave in \((X, Y)\) for every \( \omega \) and \( \theta \), let \((X', Y')\) and \((X'', Y'')\) be arbitrary feasible investment and consumption vectors, and for \( \alpha \in [0,1] \), let \((X, Y)\) be the arbitrary convex combination

\[ (X, Y) = \alpha(X', Y') + (1-\alpha)(X'', Y''). \]

Since G is convex, we have

\[ G(X, Y) \leq \alpha G(X', Y') + (1-\alpha)G(X'', Y'') \]

Thus, since V is decreasing in G, we have

\[ V(G(X,Y),y(\theta),\omega; \theta) \geq V(\alpha G(X', Y'), (1-\alpha)G(X'', Y''), \alpha y'(\theta) + (1-\alpha)y''(\theta), \omega; \theta) \]

so that, since V is concave in \((G, y)\), we have finally the desired result:

\[ V(G(X,Y),y(\theta),\omega; \theta) \geq \alpha V(G(X', Y'),y'(\theta),\omega; \theta) + (1-\alpha) V(G(X'', Y''),y''(\theta),\omega; \theta) \]
\[ \eta(\theta) \geq 0; \quad \sum_{\theta \in \Theta} \eta(\theta) = 1. \] (4)

Since, as noted, the expected utility functions \( E\{V(\cdot;\theta)\} \) are concave, the Pareto set of allocations from any convex feasible set are given by the argmax \( W_\eta \) as the weights \( \{\eta(\theta) \mid \theta \in \Theta\} \) vary over the feasible set defined by (4).\(^4\)

U may be thought of as the net economic benefits realized from the country’s activities in stages 1 and 2. We assume that investments \( x(\theta) \) in GHG reduction and consumption \( y(\theta) \) are related by the following budget constraint:

\[ I(\theta) = x(\theta) + y(\theta) - s(\theta) \] (5)

Thus, investments in GHG reduction will necessarily reduce consumption \( y(\theta) \) unless offset by transfers \( s(\theta) > 0 \) to \( \theta \) from other countries.\(^5\) For feasibility, we require the following restrictions on transfers among countries:

\[ \sum_{\theta \in \Theta} s(\theta) = 0. \] (6)

2.1 The Benchmark Noncooperative Solution

As noted above, we develop here the benchmark (BAU) noncooperative solution based on uncoordinated actions by individual countries. To characterize this noncooperative solution, we use the Nash equilibrium concept for the associated game in which each country attempts to maximize (2) subject to (5), with \( s(\theta) = 0 \). The problem in this case for country \( \theta \) will be:

\(^4\) Note that the traditional approach to defining the Pareto set is to set individual country reservation expected utility levels for all but one country and then maximize the remaining country’s expected utility over feasible allocation vectors \( (X, Y) \) and compensation vectors \( S \) and \( T \) (if compensation is allowed). As these reservation utility levels are varied, the Pareto set is generated. The present approach, using the weighted welfare function (3), is more congenial to the analysis, but it is entirely equivalent, where the weight \( \eta(\theta) \) corresponds to the dual variable associated with country \( \eta \)'s reservation utility level in the traditional approach. The reader will also note that many of these cooperative solutions will be unacceptable from the standpoint of the stated objectives of global cooperation, i.e. to minimize GHG emissions, since they also reallocate resources for consumption. However, this general formulation is convenient for characterizing the subset of solutions that will meet all necessary criteria, and we will examine specific cases of interest later.

\(^5\) Because income can always be productively invested in reducing GHGs, with strict improvements in welfare resulting therefrom, it is clear that the budget constraint (5) will hold as an equality at optimum.
\[
\text{Maximize } E_{\omega} \left\{ V(G(X, Y), y(\theta), \omega; \theta) \right\} 
\]
subject to:
\[
l(\theta) = x(\theta) + y(\theta) \tag{8}
\]

Substituting (8) into (7), country \( \theta \) is assumed to solve the following problem, taking other country decisions as given:
\[
\text{Maximize } E_{\omega} \left\{ V(G(X, I - X), l(\theta) - x(\theta)), \omega; \theta) \right\} 
\]

Thus, the following first-order conditions characterize the Nash noncooperative equilibrium:\(^6\)

\[
\begin{align*}
x(\theta) \frac{\partial EV(\theta)}{\partial x(\theta)} &= 0; \\
\frac{\partial EV(\theta)}{\partial x(\theta)} &= E_{\omega} \left\{ [g_1(\theta) - g_2(\theta)]V_c(\theta) + V_{x(\theta)}(\theta) \right\} \leq 0; \quad \forall \theta \in \Theta 
\end{align*} \tag{10}
\]

2.2 A First-Best Framework for Characterizing Cooperative Solutions

By a first-best solution, we mean a Pareto allocation \((X, Y, S)\) for the above country welfare functions and constraints, i.e. a solution which cannot be improved upon for all countries simultaneously. From the above, the Pareto solutions \((X, Y)\) must be solutions to the following problem for some feasible weighting vector \(\{\eta(\theta) \mid \theta \in \Theta\}\):

\[
\text{Maximize } E_{\omega} \left\{ \sum_{\theta \in \Theta} \eta(\theta)V(G(X, Y), y(\theta), \omega; \theta) \right\} 
\]
subject to (5)-(6), where \(E_{\omega}\) is the expectation at stage 1 with respect to the distribution \(F(\omega)\). Thus, the first-best solution is effected by putting all resources in the hands of a central planning authority, which is assumed to solve (11) with no transactions costs.

Since (5) holds as an equality at the solution to (11), we may eliminate \(y(\theta)\) by substituting (5) into (11). The resulting problem of interest is then:

---

\(^6\) A noncooperative equilibrium exists by the usual arguments.
Maximize \( \mathbb{E}_\omega \left\{ \sum_{\omega \in \Theta} \eta(\theta) V(G(X, I - X + S), I(\theta) - x(\theta) + s(\theta), \omega; \theta) \right\} \) \hspace{1cm} (12)

subject to (6). From the Lagrangian \( \mathcal{L}^c \) for this problem we obtain the following first-order conditions:

\[
\frac{\partial \mathcal{L}^c}{\partial x(\theta)} = 0;
\]

\[
\frac{\partial \mathcal{L}^c}{\partial x(\theta)} = \mathbb{E}_\omega \left\{ \left[ g_x(\theta) - g_y(\theta) \right] \sum_{\zeta} \eta(\zeta) V_c(\zeta) - \eta(\theta)V_y(\theta) \right\} \leq 0; \quad \forall \theta \in \Theta
\]

and

\[
\frac{\partial \mathcal{L}^c}{\partial s(\theta)} = \mathbb{E}_\omega \left\{ g_y(\theta) \sum_{\zeta} \eta(\zeta)V_c(\zeta) + \eta(\theta)V_{y0}(\theta) \right\} - \mu = 0; \quad \forall \theta \in \Theta
\]

where \( \mu \) is the dual variable associated with (6). When \( x(\theta) > 0 \), (12) implies that the change in global benefits associated with transferring a monetary unit from consumption to investment for GHG reduction in country \( \theta \) must just equal the marginal cost \( \mathbb{E}_\omega \{ \eta(\theta)V_y(\theta) \} \) in lost consumption.

Assuming for the moment that \( x(\theta) > 0 \), we can compare (10) obtained earlier for the non-cooperative case with (13) above. We see that (10) implies a similar benefit-cost equality to that discussed above for (13). In the noncooperative case, however, country \( \theta \) equates the marginal loss in consumption benefits to the benefits for itself of transferring a monetary unit in that country from consumption to investment. By contrast, for Pareto efficiency, marginal consumption losses are equated to global benefits of increased investment in mitigating GHGs.

Comparing the noncooperative solution with the first-best solution, we obtain the following result on the benefits of cooperation, which is proved in the Appendix.

**Proposition 1**: Let superscripts \( C \), respectively \( NC \), denote the solutions to the cooperative, first-best problem \( (12) \) (subject to (6)) and the noncooperative problem \( (9) \).

i. The noncooperative solution is Pareto inefficient in the sense that there are weighting vectors \( \{ \eta(\theta) \mid \theta \in \Theta \} \) such that the corresponding cooperative solutions \( (X(\eta), Y(\eta)) \) leave every country better off than under the noncooperative solution.

ii. The level of aggregate GHG emissions \( G(X^C, Y^C) \) achieved under any cooperative solution is efficient in the sense that it is the minimum aggregate emission level achievable from total mitigation investments \( \sum x^C(\theta) \). That is, for the cooperative solution:

\[
G(X^C, Y^C) = \text{Minimum} \left\{ G(X, Y) \mid \sum_{\theta \in \Theta} x(\theta) \leq \sum_{\theta \in \Theta} x^C(\theta) \right\}
\]
Unless all countries have identical preferences $V(\theta)$ and identical emission technologies $g(\theta)$, the noncooperative solution is not efficient in the sense that lower aggregate GHG emissions can be achieved from the total mitigation investments $\sum x^{NC}(\theta)$, i.e.

$$G(X^{NC}, Y^{NC}) > \text{Minimum} \left\{ G(X, Y^{NC}) \left| \sum_{\theta \in \Theta} x(\theta) \leq \sum_{\theta \in \Theta} x^{NC}(\theta) \right. \right\}$$

2.3 Solutions for Alternative Institutional Designs

Proposition 1 indicates how the essential focus of institutional design in improving efficiency in GHG mitigation efforts. First, the Proposition indicates that increased cooperation itself can lead to increased efficiency, with respect to both consumption and investment patterns. The second part of the Proposition notes, in particular, that the most basic level of cooperation could involve simply increasing the efficiency of investments in mitigation activities by focusing on the best alternatives for GHG mitigation investments globally. In this section, we explore the theoretical foundations of these different approaches to institutional design. We consider two classes of designs, with or without transfer payments among countries. The next section will illustrate these issues by simulating the performance of these various institutional designs in the context of the theory developed here in conjunction with 1989 country data.

A primary focus of this research is on ways in which cooperation can be achieved to enhance solutions obtained by each country acting unilaterally in a fully non-cooperative fashion. As we noted in the introduction, conditions for global cooperation that ensure equity are likely to be very important in order to achieve the benefits of a cooperative solution. Furthermore, in addition to being a "lubricant for cooperation", as noted in Section 1, there may also be moral arguments in favor of equitable burden sharing.

Turning to the specifics, we consider the impact of several types of equity-driven conditions that we overlay on the basic solutions developed above. The development here is entirely in the spirit of asking what can be done to make all nations better off relative to the BAU non-cooperative benchmark (see OECD [1992] for arguments for and against these various equity concepts).

2.3.1 Solutions with No Transfer Payments

a. Benchmark Non-Cooperative

The non-cooperative solution developed in section 2.1 provides the benchmark against which all other solutions will be compared.

b. Negotiated Reduction Targets

With negotiated reduction targets, all countries would agree ex ante to impose on themselves an explicit constraint on GHG emissions of the form $g(\theta) \leq k(\theta)$, where $k(\theta)$ might, for example, be the 1989
emission level. Various forms of this constraint have been considered as approaches to climate change mitigation (e.g. see Grubler and Nakicenovic, 1992). These might take the form of restricting each country to a particular level of GHG emission per capita, or per unit of GNP. In the former case, for example, this would amount to appending to the first-best, to the bargaining solution, or to the noncooperative solution constraints of the following form:

\[
g(\alpha(\theta), \gamma(\theta), \theta) \leq \gamma\left(\frac{I(\theta)}{N(\theta)}\right)
\]

(15)

where \( \gamma(\cdot) \) is a nonincreasing function of per capita income \( I(\theta)/N(\theta) \). We will consider the impact of such a constraint in the simulation framework developed in the next section.

Because of the difficulty of measuring GHG outputs, this constraint might be imposed on inputs, or on outputs in particular sectors (e.g., electric power). Alternatively, countries might choose to impose taxes on GHG emitting consumption, with the proceeds of these taxes being directed towards investment in mitigating the effects of GHG. Taxes on consumption could take the form:

\[
x(\theta) \geq \tau(\theta)I(\theta), \quad \theta \in \Theta.
\]

(16)

where the tax rate \( \tau(\theta) \) could be an increasing function of per capita income levels \( I(\theta)/N(\theta) \), where \( N(\theta) \) is the population in country \( \theta \). If \( \tau(\theta) = 0 \) for some countries, then the effect would be to impose targeted taxes only on certain countries (those for which \( \tau(\theta) > 0 \)). Again, these constraints would reduce aggregate unconstrained welfare, assuming cooperation, but might be required to assure cooperation.

2.3.2 Solutions with Transfer Payments

a. Cooperative Reallocation of GHG Investments (without strategic adjustment)

In this case, countries will reallocate among themselves the total pool of funds committed by individual countries for GHG investments, \( \sum_\theta x(\theta) \), in order to achieve the highest "bang for buck". However, in anticipation of such reallocations, countries are assumed not to strategically adjust their consumption and investment decisions. The problem may be expressed in the form:

\[
\text{Minimize} \quad G(X, Y) = \sum_{\theta \in \Theta} g(x(\theta), \gamma(\theta); \theta)
\]

(17)

such that

\[
\sum_{\theta \in \Theta} x(\theta) \leq \sum_{\theta \in \Theta} \bar{x}(\theta)
\]

(18)

which at optimum equates the marginal product of GHG investment \( g_c(\theta) \) across countries. Note that the pre-committed level of investment \( x(\theta) \) could simply be the level of investment planned by the country in the benchmark non-cooperative case and that cooperation even at this minimal level could occur only among a sub-set of the countries.
This case is presented here to illustrate the benefits of cooperation even at a minimal level, rather than as a realistic institutional design. We consider next how this concept may be embodied within a workable scheme.

b1. **Cooperative Reallocation with a Global Environmental Facility (without strategic adjustment)**

The scheme of cooperative reallocation of investment considered above may be institutionalized through the Global Environmental Facility (GEF). Those countries whose pre-committed levels of GHG investment exceed the optimal level determined by cooperative reallocation would transfer the surplus of funds to the GEF. The GEF would, in turn, use these funds to "top off" GHG mitigation investments in those countries where the optimal level of investment exceeds the available funds. Typically, as in the case of the global allocation of funds for CFC-reducing investments, one would expect the developed countries to use the GEF to transfer resources to developing countries to be invested in high-payoff projects in these countries.

As the simulation framework developed in the next section illustrates, global cooperation in this way presents an opportunity for all countries to emerge winners -- the developed countries through winning the cooperation of developing nations and access to high-payoff projects in these countries, and the developing countries through additional resources received for investment.

b2. **Cooperative Reallocation with a Global Environmental Facility (with strategic adjustment)**

The cooperative solution in "a" and "b1" above assumes that countries will not strategically re-adjust their committed levels of own investment and consumption in anticipation of transfers from the GEF. This is likely to be difficult to avoid in practice. However, even with such strategic re-adjustment, this reallocation of funds would dominate the non-cooperative solution.

We characterize cooperative reallocation with strategic adjustment in the appendix for the analytical example developed in the next section. The welfare implications of this case are illustrated through the simulation framework presented in section 3.

c. **Bargaining Theoretic Solutions**

Here equity is taken to mean that countries commit themselves to some type of "collective bargaining", with or without compensation. Any such commitment would clearly entail an understanding of the rules and procedures governing bargaining, deadlocks, defaults, etc. We model the outcome of this type of embodied equity here through Nash Bargaining Theory. The results are likely to be robust to other, similar theories of bargaining (see, e.g., the discussion in Kleindorfer et al. (1993)). But it should be noted that there is still a great deal of research to be done to understand the process and outcomes which bargaining in the context of global climate change is likely to yield.

In terms of the above model, and using Nash Bargaining Theory as a descriptive model of the outcome of bargaining, the results of global coalition bargaining may be represented as the solution of the following problem:
\[
\text{Maximize } \max_{x,y,s} \left[ E_\omega U(G,y(\theta),\omega;\theta) - U_0^{NC}(\theta) \right] \\
\] (19)

subject to the balancing equation (4) and to:

\[
E_\omega \{U(G,y(\theta),\omega;\theta)\} \geq U_0^{NC}(\theta); \quad \theta \in \Theta; \\
\sum_{\theta \in \Theta} s(\theta) = 0; \quad X \geq 0; \quad Y \geq 0. \\
\] (20)

where \( U_0^{NC}(\theta) \) is the default payment for country \( \theta \) if country \( \theta \) does not join in the consensual bargaining solution, i.e., if country \( \theta \) defects from the global coalition. A plausible value for \( U_0^{NC}(\theta) \) would be the expected utility for country \( \theta \) at the noncooperative solution described above. The above formulation assumes that transfer payments are possible as well as agreements about levels of investment and consumption. An alternative formulation would have either no transfer payments (i.e., \( s(\theta) \) would be constrained to equal 0 in the solution to the above bargaining problem) or transfer payments of a particular sort (see, for example, the discussion below).

Concerning the solution to the above, the outcome to the Nash Bargaining Problem is known to be efficient. It would therefore enjoy the same properties described in general in Proposition 1. As is well known, the essence of this solution is that global surplus above the default option is maximized and shared in proportion to the default payoffs. Countries with larger default payoffs (i.e., higher \( U_0^{NC}(\theta) \)) therefore receive higher expected utilities than other countries at the bargaining solution. A host of variations on this theme are, of course, possible. These would follow the bargaining theoretic literature and would include: imperfect information by countries about the preferences and default options of other countries, asymmetric bargaining power, bargaining delay costs, ambiguity effects, etc. The main idea is, however, clear from the above.

Bargaining solutions may be operationalized by compensation rules. One example which has been discussed is that developed countries contribute a fixed percentage of their GNP to developing countries for investments in energy conservation and other global climate change risk mitigation measures. Magnitudes in the range of 0.1% of GNP have been suggested in this regard. The effect of this type of rule would be to append constraints of the following sort (possibly determined through bargaining), while continuing to assume non-cooperative behavior in other respects:

\[
(1 - \alpha)I(\theta) = x(\theta) + y(\theta), \quad \theta \in \Theta^{DC} \\
I(\theta) + s(\theta) = x(\theta) + y(\theta), \quad \theta \in \Theta^{DC} \\
\sum_{\theta \in \Theta^{DC}} s(\theta) = \alpha \sum_{\theta \in \Theta^{DC}} I(\theta) \\
\] (22)

(23)
where $\Theta^{DC}$ (resp., $\Theta^{LDC}$) are the set of developed (resp., developing) countries. Thus, the first constraint requires a transfer of $-s(\theta) = \alpha I(\theta)$ to the GEF for developed countries, and the second constraint is the balance equation requiring all transfers to developing countries to equal the balance in the GEF.

The above forms do not, of course, exhaust the kinds of institutional arrangements that are possible for cooperation and arriving at cooperative outcomes. From a policy perspective, the key issue is to understand what the transactions costs of monitoring and enforcing various such arrangements might be and what their impact would be in promoting cooperation among the global coalition. We will explore these questions in greater detail through the simulation framework developed in the next section.
3. A Simulation Framework for Studying Cooperative Behavior

In this section, we will first develop an analytical example which follows the general framework developed above. Thereafter, using 1989 data for all countries, we will develop a simulation framework based on the analytical example to examine further the consequences of various alternatives for cooperative behavior.

Assume the following specifications for the relevant functions:

\[ g(x(\theta), y(\theta), \theta) = \alpha(\theta) \frac{y(\theta)}{x(\theta)} \]  \hspace{1cm} (24)

\[ G(X, Y) = \sum_{\theta \in \Theta} g(x(\theta), y(\theta), \theta) = \sum_{\theta \in \Theta} \alpha(\theta) \frac{y(\theta)}{x(\theta)} \]  \hspace{1cm} (25)

\[ V(G(X, Y), y(\theta), \omega; \theta) = t(\theta) \log y(\theta) - h(\omega) \gamma(\theta) G(X, Y) \]  \hspace{1cm} (26)

where \( \alpha(\theta), t(\theta) \) and \( \gamma(\theta) \) are positive real numbers for each \( \theta \in \Theta \), and where \( \gamma(\theta) h(\omega) \) represents the impact of \( G \) on country \( \theta \) in state of the world \( \omega \). We denote the expected value of \( h(\omega) \) by \( h \) and the expected value of \( \gamma(\theta) h(\omega) \) by \( \gamma \).

3.1 Benchmark Noncooperative Case

In the noncooperative case, the welfare maximizing problem for country \( \theta \) becomes:

\[ \text{Maximize} \ E_\omega \left\{ V(G(X, Y), y(\theta), \omega; \theta) \right\} \]  \hspace{1cm} (27)

subject to:

\[ l(\theta) = x(\theta) + y(\theta) \]  \hspace{1cm} (28)

Substituting (28) into (27) yields the following unconstrained maximization problem:

\[ L^{nc} = t(\theta) \log \left( l(\theta) - x(\theta) \right) - \gamma(\theta) h(\omega) \sum_{\zeta \in \Theta} \alpha(\zeta) \frac{(l(\zeta) - x(\zeta))}{x(\zeta)} \]  \hspace{1cm} (29)

The first-order condition for this non-cooperative problem is:
\[
\frac{\pi(\theta)}{l(\theta) - x(\theta)} - \frac{\gamma(\theta) \bar{h} \alpha(\theta) \pi(\theta)}{x(\theta)^2} = 0, \quad \theta \in \Theta.
\] 

(30)

This can be solved to yield:

\[
x(\theta) = \frac{\beta(\theta)}{\pi(\theta)} l(\theta)
\]

(31)

where

\[
\beta(\theta) = -\frac{\alpha(\theta) \bar{h}(\theta)}{2} + \sqrt{\left(\alpha(\theta) \bar{h}(\theta)\right)^2 + 4 \pi(\theta) \alpha(\theta) \bar{h}(\theta)} > 0 \quad \forall \theta
\]

(32)

Thus,

\[
y(\theta) = \left(1 - \frac{\beta(\theta)}{\pi(\theta)}\right) l(\theta)
\]

(33)

which is positive since \(\beta(\theta) < t(\theta)\) by (33). We can determine the relevant quantities.

**Aggregate GHG Emissions**

\[
G(X, Y) = \sum_{\theta \in \Theta} \alpha(\theta) \frac{y(\theta)}{x(\theta)}
\]

(34)

\[
= \sum_{\theta \in \Theta} \alpha(\theta) \left(\frac{\pi(\theta) - \beta(\theta)}{\beta(\theta)}\right)
\]

**Country \(\theta\) Welfare**

\[
E_a \{U(X, Y, \omega; \theta)\}
\]

\[
= t(\theta) \log y(\theta) - \bar{h}(\theta) G(X, Y)
\]

(35)

\[
= t(\theta) \log \left[\left(\frac{\pi(\theta) - \beta(\theta)}{\pi(\theta)}\right)l(\theta)\right] - \bar{h}(\theta) \sum_{\zeta \in \Theta} \alpha(\zeta) \left(\frac{\pi(\zeta) - \beta(\zeta)}{\beta(\zeta)}\right)
\]
Aggregate Investment in GHG Reduction

\[ \sum_{\theta \in \Theta} x(\theta) = \sum_{\theta \in \Theta} \left( \frac{\beta(\theta)}{\pi(\theta)} \right) I(\theta) \]  

(36)

Aggregate Consumption

\[ \sum_{\theta \in \Theta} y(\theta) = I - \sum_{\theta \in \Theta} \left( \frac{\beta(\theta)}{\pi(\theta)} \right) I(\theta) \]  

(37)

where

\[ I = \sum_{\theta \in \Theta} I(\theta) \]  

(38)

3.2 A Simulation Framework

In this simulation framework, we classify countries in six groups according to income as in the 1991 World Development Report. India and China, owing to their size, are treated as a separate group as are economies in transition (countries of the former Soviet Union and Central Europe). Emissions data are from World Resources 1992-1993 (WRI 1992). For purposes of this paper, we account only for industrial CO\(_2\) emissions. However, industrial CO\(_2\), net CO\(_2\) emissions from land use changes, CH\(_4\), CFCs, and the IPCC index of combined radiative forcing potential from all of these sources are reported in Appendix 3.

Before reporting our results, a caveat is in order. While we model GHG reduction scenarios (e.g., a "30% reduction scenario"), it should be emphasized that the results we obtain are only intended to be qualitatively valid. To obtain quantitatively valid estimates of costs and benefits associated with specific release trajectories would require detailed information on supply curves for each country. Clearly, we have not included a detailed estimate of such supply curves here. Our intent is to demonstrate the effects of various levels of cooperation and the efficiency impact of different equity constraints which may be required to assure such cooperation.

The general framework presented in this paper models the behavior of individual countries and assumes that each country, \( \theta \in \Theta \), chooses to spend its resources on consumption, \( y(\theta) \), and investments in reducing GHG emissions, \( x(\theta) \), to maximize its own expected welfare, \( E_{\theta} [V(G(X,Y), y(\theta), \omega; \theta)] \). In this simulation, we operationalize this framework by using actual data and a number of simplifying assumptions. The assumption that industrial CO\(_2\) emissions rise linearly with GNP: \( g(x,y;\theta) = \alpha y(\theta) / x(\theta) \) is supported by the data (displayed in the figure below). The following linear model explains 89% of the variance in 1989 industrial CO\(_2\) emissions between countries:

\[ \ln g(\theta) = -0.40 + 1.09 \ln y(\theta) \]  

(39)
Cooperative Institutional Arrangements

2. Cooperative reallocation of investments

The "First Step" cooperative solution models a re-allocation by the global coalition of global resources that would have been devoted to GHG reduction in the non-cooperative outcome to all country groups to minimize global GHG emissions. In this "First Step", redistributed resources are assumed to augment (diminish) investments in GHG reduction and not to augment (diminish) consumption, relative to the benchmark case. Results show that all country groups are equally better off with this type of reallocation relative to the benchmark case. This results from a more effective allocation of global investments in GHG emission reductions while consumption remains unchanged for each country group.

A "Sophisticated Response" is modeled in the next scenario. Here, all country groups are allowed to choose y and x to maximize expected welfare, given the vector of resource transfers from the global coalition determined in the "First Step Cooperative Solution", but subject to the constraint that positive transfers from the global coalition can be used only for investments in GHG reduction. Under these conditions, investments that would have been made in GHG reduction in a non-cooperative world by all non-OECD country groups are entirely displaced by the resource transfers. Conversely, OECD countries fund all investments in GHG reduction and spend roughly 2.5% of GNP on domestic GHG reduction and transfers. Consequently, expected utility increases for all country groups except the OECD.

This outcome in which the OECD pays for all investments in GHG reduction leads naturally to the next scenario. Here, the OECD maximizes expected welfare by investing in GHG reductions in all

---

First Step Cooperative Solution (Change in Expected Utility)

![Graph showing changes in expected utility across different income groups]

- Low Income
- India & China
- Low-Middle
- Upper-Middle
- Transition
- High Income

- First step coop solution
- Sophisticated response
- OECD's best
country groups to the point at which the marginal benefit from investments in each country group is equal to the marginal benefit of consumption in OECD countries. As before, transfers can only be used for investments in GHG reduction. In this case, the OECD increases its total resources devoted to domestic GHG reduction and transfers to roughly 2.6% of GNP. The resulting investments serve to reduce global GHG emissions further and, thereby, make all country groups better off.

An Explicit GEF Solution

3. 30% reductions from 1989 emissions financed by a tax on OECD countries

The "First Step" cooperative solutions indicate that resource transfers in a cooperative world would be entirely financed by OECD countries. In this scenario, we examine what level of tax on OECD countries would be necessary to reach a particular target of GHG emissions reductions. Tax, τ, is levied on OECD countries to finance the GEF, GEF = τ GNP_{OECD}, to be distributed to all other country groups, θ_{LDC}, through Z to minimize G(X+Z,Y). The GEF objective modeled here is to reduce global GHG emissions by 30% from the non-cooperative outcome. We model "First Step", "Sophisticated Response", and "Sophisticated GEF" solutions with assumptions that parallel those given above. This could be seen as an Executive Committee's problem to determine τ and efficiently allocate GEF resources through transfers z(θ) to LDCs such that Σ z(θ) = τ GNP_{OECD} to reach a specified level of GHG reductions globally (here 30%).

In the "First Step" solution, all non-OECD countries are equally better off relative to the non-cooperative solution. The OECD is also better off owing to reduced global GHG emissions. The tax

![30% reductions financed by the GEF](image_url)

(Change in Expected Utility)
necessary to achieve this level of reductions is only 0.13% of GNP from OECD countries. This level of
tax must be interpreted cautiously. As stated in the caveat above, model assumptions of cost functions
and GHG emission technologies are extremely limited as they are embedded in the form of the assumed
utility function and fit to actual 1989 emissions. Hence, the absolute levels of taxes reported here have
little merit, but make sense only relative to levels determined in the following scenarios.

Allowing a "Sophisticated Response" to the transfers determined above, all developing countries
divert their own resources to consumption. Relative to the "First Step" solution, this results in an increase
in global GHG emissions and consequent decreases in expected utility for all country groups (except
economies in transition).

In the "Sophisticated GEF" solution, the Executive Committee anticipates this response and adjusts
\( \tau \) to achieve its objective of 30% reductions in \( G(X,Y) \). In this variant, all countries are better off than
in the non-cooperative base case. However, the tax necessary to achieve 30% reductions is roughly double
that determined in the "First Step" solution (see details in Appendix 3).

Equity Constraints

4.  \textit{Equi-proportional 30\% reductions from 1989 emissions}

Equi-proportional rules are common in international environmental agreements. Such rules provide
powerful focal points for discussions as they signal that each signatory country is expected to "pull its own
weight" in terms of, say, equal emission reductions as a percent of status quo levels. In this scenario, we
model the expected welfare of each country group relative to the non-cooperative benchmark case if all
countries choose \( x(\theta) \) and \( y(\theta) \) to maximize expected welfare under an equi-proportional emissions
reduction constraint: \( g(\theta) \leq 70\% \) of \( g(\theta)_{1989} \). As shown, even with this constraint binding on all country
groups, all country groups appear to be better off than under the unconstrained non-cooperative outcome.
This is so even as each country group spends substantially more on GHG reduction (relative to
unconstrained non-cooperative investments). This result is due to the reduction in global GHG emissions:
\( G(X,Y) \) is 30\% lower than in 1989. Note that this is the case even with consumption weights, \( t(\theta) \), five
orders of magnitude greater than GHG weights, \( y(\theta) \), in the welfare function.

5.  \textit{Equal per capita emission rights to achieve 30\% reductions from 1989 emissions}

Another equity principle that has been put forward in climate change discussions is the concept
of equal emission rights per capita. We model such a rule that assigns emission rights on an equal per
capita basis, does not allow trade in these emission rights, and attempts to achieve 30\% reductions in
\( G(X,Y) \). In this scenario, all countries maximize their own welfare under the constraint that \textit{per capita}
emissions cannot exceed 70\% of \( G(X,Y)_{1989} / N_{1989} \). The constraint is not binding on poor countries, but
does bind higher income LDCs, transition economies and OECD countries (see detailed results in
Appendix 3). Since the constraint is not binding on low income economies, total \( G(X,Y) \) is reduced far
more than the 30\% reductions target. Results indicate that a strict application of such a rule would not
be acceptable to higher income countries as they would do better in the non-cooperative solution. In
addition, it appears that there would be substantial gains to trade in emission rights under such a rule.
Future extensions of this model might estimate the value of traded rights in a general equilibrium solution.
6. **Nash bargaining solution with \( EU(x(\theta), y(\theta), w; \psi) \text{nc} \) as threat point**

The last equity constraint we model is a "Nash Bargaining Solution" described in Section 2.3, with threat points given by the noncooperative solution and allowing transfer payments among countries. The transfer payments may be thought of as flowing through a GEF as in our earlier examples. However, it should be noted that the Nash Bargaining Solution allows for these transfer payments to be used for both GHG mitigation as well as consumption. As a result, we see that the welfare of non-OECD countries is decidedly enhanced at the Nash Bargaining Solution. As noted in section 2.3, the outcome is also Pareto efficient so that, in particular, GHG investments are used efficiently. Given that this solution allows explicit transfers for consumption, it is arguably less realistic as a feasible institutional design than other designs illustrated above which allow transfers only for GHG mitigation investments.

The results (see details in Appendix 3) show all country groups (except the OECD) doing extremely well relative to the non-cooperative solution and relative to the other solutions above. Transfers from OECD countries are 3 to 8 times greater than in the cooperative solutions above. Nonetheless, the OECD still is better off than in the non-cooperative world, owing to a substantial reduction in emissions.
4. Decentralized Implementation Mechanisms

We briefly consider here the issue of how the global community should design institutions for monitoring GHG emissions and for funding GHG mitigation projects and programs. Our basic notion for this design problem is similar to the framework we developed earlier for the Montreal Protocol (Allen et al. [1992]). This framework assumes that a Global Environmental Facility (GEF) has been set up, under the governance of an Executive Committee, for funding projects and programs in developing countries. Moreover, each signatory country to the International Climate Change Convention is assumed to obligate the country to meet certain target limits on GHG emissions, possibly with the financial assistance of the GEF. For this type of institution to function without excessive transactions costs, it should be clear that a guiding principle must be decentralization of implementation.

It should be noted that we are not exploring in detail here the intra-country implementation issues. These will be very important, both in terms of sharing best practices as well as in assuring efficient intra-country implementation procedures, through, for example, emissions trading in the power sector, or industrial pollution regulation. This, however, is not the focus of this research (in which we assume that the functions $g(t)$ are "best effort" or "efficient-frontier" GHG emissions for each country).

To promote global cooperation, it is also clear from the preceding arguments that the implementing institutions assure that fair burden sharing is evident to all participants. Let us discuss these two issues—decentralization and fairness—separately.

4.1 Decentralized Implementation

At this juncture, we are just at the beginning of understanding the problems of designing institutions for decentralized implementation of GHG reduction, with the key issues being:

- Heterogeneity of sources and sinks;
- Information barriers and transactions costs;
- Lack of control or lack of responsiveness to price mechanisms;
- National sovereignty, heterogeneity of interests, and problems of enforcement.

These issues point to difficulties in monitoring results and, given the costs of GHG mitigation, to difficulties in assuring cooperative compliance with country targets. Thus, the key issue for design will be to focus on monitoring, sharing of information and, with this, efficient decentralization of implementation. Decentralization can occur at two levels:

1. Between the Executive Committee representing the global community and individual countries (the global level);
2. Within individual countries (the national level).
Decentralization at the national level has been extensively analyzed and various schemes, most notably tradable permits and taxes, have been developed to achieve target reductions in GHGs in various sectors efficiently. These alternative approaches themselves have yet to be examined fully in an empirical setting, and it seems likely that no single scheme will be optimal for every country (see Wheeler [1992]). Thus, decentralization at the national level should be understood in terms of both differing sectoral targets for GHG mitigation, but also differing effectiveness of alternative policy instruments in achieving these sectoral targets in different countries. Thus, the key issue is that each country commits itself to a well-intentioned effort to achieve fair targets for GHG reduction. How they achieve this will be country specific, although sharing of best practices and new technologies across countries should be facilitated (see below).

Decentralization at the global level implies that each country would be allocated (or would accept) a certain "target" or permitted level of GHGs and would be given autonomy to decide how this target level is to be achieved. As in the case of the Montreal Protocol, each country would develop a Country Plan indicating baseline projects and incremental costs for achieving its target reduction level. The target level itself has been the subject of intense debate (see Barrett [1992] for a discussion of alternative target-setting procedures). However set, in order for this scheme to work, the following two criteria must be met:

1. The global community should be able to measure the emissions and whether or not the permitted level has been achieved;
2. The global community should be able to impose (at least moral if not financial) sanctions on noncompliant countries.

A third desirable characteristic of efficient decentralized implementation is that the shadow price of GHG reduction in each country and sector be estimable so that a rough efficiency benchmark (viz., equalized marginal abatement costs) is evident to all participating countries. Using market mechanisms at the national level could enhance significantly the estimation of understanding marginal abatement costs in each country. For example, in the electric power sector if an efficiently functioning emissions trading market were present, the market price for an emissions permit for GHGs would represent the cost of a unit reduction in GHGs in that sector. The challenge is to link sectors such as electric power, which are more easily monitored and controlled, with other sectors, such as agriculture and manufacturing, where the total GHG emissions and the cost of reducing these will be considerably more difficult to estimate on an ongoing basis. In these sectors, from both a national as well as a global perspective, it seems likely that a variety of country-specific instruments and projects will be required to achieve efficient GHG mitigation in the implementation of Country Plans.

Once country plans have been developed, the financing of these in developing countries from the GEF can be accomplished by a two-phase bidding scheme similar to that proposed for CFC reduction in Allen et al. [1992]. In the first phase, incremental costs of country plans are estimated and tracked, and some agreed portion of these costs are financed in an on-going manner from the GEF, with strong monitoring of results required of all countries. In the second phase, projects for GHG reduction which show strong comparative efficiencies (as measured by the marginal abatement cost of the project) are chosen for accelerated funding. For this to work well, monitoring of results in achieved conservation and GHG reduction is clearly central, as noted in Allen et al. [1992]. Where monitoring is more difficult (as in agricultural sources such as rice paddies and livestock where the large number of economic agents involved will make monitoring of compliance to standards a very difficult matter) the uncertainty in monitoring results will partially erode the overall benefits obtainable by the Global Coalition and therefore
the desirability of funding projects in these areas. All of these caveats underline the importance of cooperative activity by each signatory country, including sharing of best practices, and funding through the GEF of those mitigation options in countries and sectors which have the best "bang per buck" in terms of cost per GHG emission reduction.

4.2 Fairness

In achieving perceived fairness, any institutional design must begin with the characteristics we discussed earlier on the determinants of fairness. We may summarize these under several categories relevant to the institutional design question at issue here:

Acceptability and Feasibility—Grandfathering

To assure a sense of continuity with the past, and thus with prima facie feasibility, the design will almost certainly require some form of grandfathering to assure a gradual introduction of targets for each country which fits with the country’s history.

Acceptability for the Future—Grandchildrering

To assure opportunities for growth, especially for countries which are currently disadvantaged, the design must assure room for change so that future generations in developing countries may have the possibility of achieving a reasonable standard of living. If targets are set only with the past in mind, and with no flexibility for change, then growth opportunities will be thwarted. Countries, seeing this, will not likely wish to participate in a Global Climate Change Convention.

Information Sharing on Best Practices—Monitoring

A fundamental determinant of cooperation and of efficiency is information sharing and communication. This allows both monitoring of best available mitigation opportunities across countries, as well as the transfer of best available technologies. Beyond the mere static efficiency issues here, however, it should be noted that a spirit of openness and participation is central to cooperation.

Efficiency and Decentralized Implementation

Efficiency itself helps to promote trust and cooperation. When clear inefficiencies are present, both groups and individuals see little point in contributing their best efforts. Decentralization is important, as noted above, for assuring efficiency; it is also important in creating an atmosphere of trust and autonomy for individual country efforts.

4.3 Outlines of a Possible Institutional Design

Let us now sketch the outlines of an institutional design which partially meets the above desiderata. The basic features of this design are the following:

- Voluntary acceptance of GHG targets and monitoring procedures for each country;
• Development and (partial financing for LDCs) of country plans along the lines of the Montreal Protocol (as spelled out above);

• Beyond the indicated funding of LDC country plans, individual project funding in specific countries may be funded utilizing a portion of GEF funds to further enhance efficiency; such funding would be in the spirit of accelerating the accomplishment of country plans by funding when country-specific projects which have significant comparative economies as measured by their relatively low marginal costs of GHG reduction.

Concerning targets, consider the following scheme for setting initial targets for country $\theta$ for year $t$:

\[
E_t^\theta \leq E_t^\theta (1 - \alpha_t^\theta) + EP_t^\theta, \quad t \geq T_0^\theta, \tag{40}
\]

where

\begin{align*}
E_t^\theta &= \text{Allowed baseline GHG emissions for country } \theta \text{ in year } t; \\
E_t^0 &= \text{Base year (e.g., 1990) for benchmarking GHG emissions for country } \theta \text{ (the base year may differ for different groups of countries);} \\
EP_t^\theta &= \text{Additional/permitted GHG emissions for country } \theta \text{ in year } t; \\
\alpha_t^\theta &= \text{An increasing function of } t \text{ for } t \geq T_0^\theta; \\
T_0^\theta &= \text{Initial year for beginning GHG reduction for country } \theta.
\end{align*}

The sense of the above is that there would two terms determining the target emission level of GHGs for each country; the first would be some percent of base year emissions in the country, and the second would be some additional level of GHG emissions which is intended to allow for growth (grandchildrening) of relative emissions in certain countries over time. By staging the initial year for beginning GHG reduction efforts (with presumably developing countries having a later $T_0$ than developed countries) and by changing the dynamics of change through $\alpha$, various trajectories of aggregate target emissions can be achieved with differing consequences for different groups of countries.

We have in mind that the additional/permitted GHG emissions for country $\theta$ would be set according to a scheme like the following:

\[
EP_t^\theta = \left( \frac{V_t^\theta}{\sum_{i \in \Theta} V_t^i} \right) E_t^G \tag{41}
\]

where $V_t^\theta$ represents some measure of the desirability of providing additional permits to country $\theta$ at time $t$. $V_t^\theta$ might be of the form:

33
\[ V_i^\theta = \sum_{k=1}^{K} \beta_k X_k^\theta, \quad (42) \]

where \( E_t^0 \) represents the aggregate level of additional permits to be issued in year \( t \), where \( \beta_k \) are positive weights associated with a set of \( K \) factors measuring country \( \theta \)'s fair access to additional permits, where the factors \( X_k^\theta \) would be such factors as:

- Population per unit GDP (i.e., the inverse of per capita income);
- Population per unit of GHG emissions in year \( t \);
- Some measure of the vulnerability of country \( \theta \) to global climate change, e.g., as measured by the percentage of its exposed coastal areas below a certain sea level.

The sense of (42) is that the higher \( V_i^\theta \) is for country \( \theta \) relative to other countries, the higher will be its allotted additional permits, with total additional permits constrained to be equal to \( E_t^0 \) in year \( t \). Note that if we set

\[ E_t^0 = \sum_{\theta \in \Theta} \alpha_t^\theta E_t^\theta, \quad (43) \]

then by (40)-(43) the aggregate allowed emissions in year \( t \) (assuming that all countries have passed the starting gate \( T_0^\theta \)) will be

\[ \sum_{\theta \in \Theta} E_t^\theta \leq \sum_{\theta \in \Theta} E_{t-1}^\theta, \quad (44) \]

so that the proposed scheme can be tuned to cap total emissions at some base year level. Of course, adjustments in the parameters of this scheme would accommodate other total emission levels.

In addition to the target-setting scheme above, if monitoring were sufficiently clear to promote trades, it is possible that global trading of the allotments to each country (either their total allotment or just their additional permitted allotment) could be allowed to further promote efficiency. If monitoring were not accurate, then of course there would be little incentive for any country to buy such permits.

Finally, as we have noted, an essential ingredient of cooperation and feasibility is transfer payments through the GEP. This would take place in two ways: first, through funding of country plans (with each developed country paying an agreed, prenegotiated share \( \phi(\theta) \) of its GDP into the GEP) and second through targeted funding to accelerate the implementation of projects showing with the largest comparative advantage. Thus, in terms of our earlier model, the transfer payments in year \( t \) would be of the form:
s(θ) = \phi(\theta) f(\theta), \theta \in \Theta^{DC}; \quad s(\theta) \geq 0, \theta \in \Theta^{LDC};

where the level of transfer payments to LDCs would depend on both the country plan of the LDC and the number of projects in that country selected for accelerated implementation. The percentage of the total GED disbursements in any given year dedicated to acceleration projects is a major issue deserving of further analysis.

The above sketch is intended to convey the spirit of an institutional design which would capture the essential elements of fairness, while also assuring some levers to the Executive Committee for monitoring and promoting efficiency. This general form of the design problem would, of course, need to be coupled with an appropriate forum for negotiation to determine the details of this design.
5. **LDC-Specific Issues**

In the context of a global accord on global climate change and GHG abatement, the developing countries differ from the rest of the global community along several dimensions. Of these, the following are among the more important:

- Constraints due to lack of resources to invest in GHG mitigation
- Equity issues relating to reduced responsibility for historical GHG emissions which have contributed to the current buildup, and making the trade-off between GHG-reducing investment and critical programs for economic growth
- Weak institutional frameworks for implementing GHG projects and monitoring their success.

Despite the scarcity of resources for GHG-related investment, the participation of the developing countries is key to a successful global climate change accord. With the majority of the world’s population and the fastest rates of growth in fossil-fuel usage and GHG emissions, the role of the developing countries will be most critical in determining the ability of the global community to reign in GHG emissions. Furthermore, the developing countries, being in an earlier stage of the growth phase, have significantly greater relative potential for curtailingments in GHG emissions, both through retrofitting-type interventions in existing projects and through changes to future projects.

While the developing countries are emerging as significant energy users and emitters of GHGs, much of the current accumulation of GHGs is the result of emissions by the industrialized countries. Hence, the argument has been made that the developing countries cannot be held responsible for the current problems associated with this accumulation or asked to spend their limited resources fixing it.

Significant concerns arise, also, relating to the efficiency with which GHG mitigating projects can be implemented in developing countries. While many developing countries are embracing privatization as a solution to the problems created by many decades of public ownership of essential economic sectors, GHG mitigating projects are fundamentally different because they could be viewed as threats and encumbrances rather than opportunities for growth, since individual companies will reap but a fraction of the total benefit of these projects and will, in any event, have alternative uses for the funds which will bring them greater private benefit. Hence, companies undertaking these projects will seek compensation for doing so. This creates a whole host of issues relating to monitoring and regulation which need to be addressed. These areas have been largely overlooked in the current privatization wave.

The Montreal Protocol on Substances that Deplete the Ozone Layer (MP) is possibly the closest precedent to a future accord on global climate change, and provides considerable insight into the differential treatment of developing countries in a global treaty. Signatories to the MP have committed themselves to a complete phase-out of ODSs within specific time limits.

The Montreal Protocol differentiates between developing countries and the rest of the global community in two ways:

1. By allowing the developing countries more time to meet their obligations under the Protocol, to phase out ozone-depleting substances.
Despite the technical possibility and the economic desirability of an accelerated response from the LDCs, the MP did not originally require the LDCs to phase-out as rapidly as developed countries. Instead, the protocol allowed the LDCs a "grace period" of ten years on both the starting baselines and the targets, in order to delay the burden on these countries. This was conceivably because the LDCs had only a small although still rapidly growing fraction of ODS use and because it would not have been equitable to ask them to divert scarce development resources to remedying a global problem principally created by the developed world. (LDCs currently contribute only about 18 per cent of total ODS emissions, although their share of cumulative emissions would be even less due to the late start LDCs had in ODS use.)

2. By creating a pool of resources (financial and technical) through contributions from the developed countries (called the Interim Multilateral Fund (IMFMP)).

Through the IMFMP, the Protocol guarantees reimbursement of the incremental costs associated with implementing country plans designed to meet Protocol obligations. Once again, both the creation of the IMFMP and disbursements from it are guided by the recognition that most of the benefits of these phase-out projects accrue to the global community at large, whereas the country undertaking the measures bears the cost.

These measures incorporated in the MP clearly indicate that financing decisions for global environmental activities will be guided by criteria beyond the usual cost-benefit and efficiency criteria of environmental economics, including criteria such as affordability and international equity. (See Munasinghe (1990) for a discussion.) These projects, therefore, are significantly different from the conventional lending activities of international development lending agencies such as the World Bank, and involve a range of new issues which require the creation of appropriate incentives for cooperation by private and public sector participants in both developed and developing countries.

A resource pool that is similar to the IMFMP is a near certainty in the case of a global climate change accord. From an economic standpoint, our previous analysis has demonstrated the importance of investing in globally efficient projects, and it is clear that many of these projects currently exist and will emerge in the developing countries. Thus, developed countries such as the U.S. and Japan may find it economically advantageous (applying a "bang-for-buck" criterion) to invest funds earmarked for GHG mitigation in LDC projects.

Thus, a resource pool for environmental investment in the developing countries makes good economic sense. However, it can also be justified from an equity standpoint, as illustrated most vividly by the Montreal Protocol. Once again, the analysis presented in section 2 clearly reveals the impact of various equity "constraints" on an economic efficiency framework. Hence, our approach combines these economic-efficiency and equity elements.

As noted above, the development of appropriate institutional mechanisms to efficiently channel these resources and ensure that they are put to good use poses a special challenge. The Montreal Protocol provides little guidance in this regard since it only provides for reimbursement of incremental costs incurred by the developing countries, instead of explicit economic incentives for individual countries and in-country agencies to use funds efficiently. Cost reimbursement does not provide the essential economic "lubricant" for countries to be proactive in coming up with projects or making sure they are well implemented. As a consequence, many MP related projects have been stalled by the complexities of monitoring individual projects and the heavy transaction costs associated with micro-management.
6. Conclusions and Directions for Future Research

The key focus of this paper has been on the benefits of cooperation in an effort to mitigate global climate change. As our results have demonstrated, there appear to be several cooperative outcomes which are more efficient in terms of GHG reduction and welfare improving for all countries, relative to the business-as-usual non-cooperative outcome. It is important that the global community strive for these outcomes.

We have also focused on the key interaction between principles of fairness and efficiency in implementing decentralized institutional designs for global GHG reduction. We have pointed out that perceived fairness is required to assure cooperation and, with it, efficiency. A number of critical drivers of perceived fairness have been discussed, including acceptability, information sharing on best practices and available technologies, grandfathering, feasibility, efficiency, and volunteerism. In the absence of cooperation, both static efficiency and dynamic efficiency and innovation will be sacrificed. On the other hand, such cooperation cannot come at the expense of large transactions costs resulting from misplaced central planning. Nor can it come by attempting to extract large transfer payments for non-GHG related projects. The central feature of institutional design to implement the Climate Change Convention must therefore be to assure both cooperation and efficiency through decentralized implementation of fair targets, with fair burden sharing in achieving these targets assured through realistic transfers of capital and technology from the developed to the developing world.

As we have noted, a central issue which we can begin to address at this juncture is continuing research on monitoring systems which will be able to assess the net GHG emissions from particular sectors and particular countries. Until this monitoring problem is resolved, it will be difficult to assure fairness and effectiveness in implementing decentralized sectoral or national targets for GHG reduction.

Other fruitful areas for research on the institutional design question seem to be the following:

- The analysis of effective policy implementation approaches and incentives to promote efficient (win-win) conservation measures which conserve GHG-rich resources.

- A targeted analysis of the energy sector with both conservation and efficiency in mind, including coordinating energy and environmental concerns with resource options, regulatory policy, privatization initiatives and other economic instruments.

- Assessment of the performance of decentralized instruments such as tradable emission rights, monitoring, regulated competitive structures, and incentive regulation. The assessment should couple both theory and empirical assessment, including simulation, experimental assessments and field studies.

- Empirical and theoretical research on the efficiency properties of alternative global institutional designs which meet the prima facie requirements of equity laid out in this paper. On both the theoretical and empirical sides, this could begin with a more detailed study of the efficiency consequences of various imposed equity constraints as discussed in Sections 2 and 3.
Appendix 1: Principles of Fairness and Equity Precedents for a Global Climate Change Convention

Principles and Attributes of Fair Allocations

The practice and literature of microeconomics and welfare economics have been primarily concerned with efficiency. In situations that require the agreement of claimants to a good, however, it may be necessary to choose an allocation that is considered "fair", even if this allocation falls short of first-best efficiency, as defined in the usual willingness-to-pay terms of Pareto efficiency and social welfare. This general observation has been developed by Okun (1975) into the thesis that there may be a tradeoff between equity and efficiency. Note that when the focus is on the allocation of access to a commons resource that, in the absence of an agreement, would be overused and degraded due to free-ridership and externalities, both fairness and efficiency can be seen to be complementary. Thus, to the extent that fairness is necessary to achieve agreement, one may view fairness or equity in the present context as an essential ingredient in institutional design.

Economic methods are designed to guide the allocation of resources into activities that will use them most efficiently and produce the highest value for society as a whole. Though efficiency plays a role in determining fair or equitable allocations of commons property, context and precedent may be even more important. Since these "local" characteristics matter to people in deciding what is fair in each case, it has been difficult to include fairness and equity considerations within economic models of behavior that are based on general principles. Some of the fairness principles that are commonly appealed to in supporting arguments for alternative policies are discussed in this section.

Fairness as Proportionality

The principle of proportionality states that returns should be allocated in proportion to investment or contribution. This principle has ancient roots and was invoked by Aristotle in his principle of a just distribution as one in which shares are proportioned to desert or merit. This equity principle is the basis of many modern methods including the "polluter pays principle". However, this principle requires that contribution be measurable and goods be divisible. Relative contribution is not an easy matter to determine in many divorce proceedings or toxic waste Superfund sites. An appeal to the proportionality principle makes little sense when the good is indivisible: the allocation of kidneys for transplant, competing claims on an unsharable territory, locating a waste facility, or deciding who will be discharged from the military during a demilitarization.

Fairness as Utilitarianism

The utilitarian principle specifies that goods should be distributed to maximize the sum of individual utilities or some proxy thereof. This is essentially Bentham’s "greatest good" principle by which goods are allocated to the individuals who will derive the greatest good (in terms of increased utility) from receiving them. Though originally put forward as a concept that would allow society’s welfare to be maximized, the utilitarian principle requires that we measure utility on a cardinal scale and add these measures across individuals. Interpersonal utility comparisons are replete with difficulties. But even if it were possible to construct cardinal utility measures that could be summed across individuals to approximate the "good of society", the utilitarian program could clearly result in some baldly inequitable
outcomes. Maximizing the good of society might require that a terrible sacrifice be visited on some individuals to purchase an incremental benefit for others.

Progressivity in personal income tax and in the rate at which nations contribute to the United Nations is based not only on increased ability to pay with income, but also on an assumption of the theory of the consumer -- declining marginal benefit of income with increasing income. This assumption means that a dollar's worth of consumption can raise the welfare of a poor person more than it could raise the welfare of a wealthy person. This concept, with roots in classic utilitarianism and neoclassical economics, could be one basis for arguing that countries that are most well off should shoulder more of the burden than those that are less well off in any mechanism designed to reduce emissions of GHGs.

Fairness According to the Rawlsian Maximin Principle

The maximin principle was proposed to counter the shortcomings of utilitarianism. Due to Rawls (1971), this principle states that economic design should have as a fundamental objective the maximization of the welfare of the least well-off groups in society. Rawls proposed this principle as one that would emerge if risk averse parties were to agree on some principle for distributing a good before they knew what roles they would play, that is, from behind a "veil of ignorance".

The Rawlsian principle is typically based on observable allocations of welfare producing inputs, such as income, rather than the unobservable amount of utility that is derived from the inputs and it embodies a certain "safety net" protecting the least well off. This principle arguably answers some of the foremost criticisms of utilitarianism. However, just as one implication of utilitarianism might be considered unjust, that a few should suffer for the good of the whole, it is not clear that the maximin alternative is any better, as it might lead to substantial sacrifices by most of society for the benefit of a few disadvantaged people.

Fairness and the Pareto Efficiency Criterion

A Pareto efficient distribution of resources in an economy is one in which there is no way to reallocate resources to make someone in the economy better off without making at least one other person worse off. Here, it is assumed that an individual derives welfare from the share of the resources that she receives alone. Pareto efficiency is subject to the constraint that no one should be made worse off than under some given reference point, usually the status quo distribution. Thus, like the maximin principle, the Pareto Criterion includes a sort of "safety net" in the form of the initial distribution as the minimum that each agent should receive.

It is useful to note that modern welfare analysis in general and the Pareto Criterion in particular are generalizations of the utilitarian principle. For example, under appropriate assumptions, the set of efficient or Pareto allocations are obtained by maximizing a weighted sum of individual utilities (rather than a simple sum as in Bentham's original utilitarian principles). A key difference between the Pareto principle and the utilitarian principle is that the set of all Pareto points is put forth as having merit and not any particular point in this efficient set.

---

7 This principle might play a role in designing an equitable institution to deal with GHG emissions. However, initial conditions (past and present emissions) are known. Hence, any appeal to "veil of ignorance" arguments might have little weight in swaying entrenched interests. Nonetheless, the notion of maximizing the welfare of the worst-off (say in terms of GDP/capita) could be seen as a compellingly noble objective.
Envy-free, (Incrementally) Superfair Distributions

Superfairness is a fairness principle developed in an explicitly economic framework (Baumol 1986). A distribution is said to be envy-free if every agent is at least as well off with her allocation as she would be with anyone else's. A distribution is said to be superfair when no class of individuals envies the allocation assigned to individuals of any other class. Incremental superfairness limits attention to the distribution of the good at hand by ruling out consideration of other sources of envy such as talent, height, or wealth. Envy-freeness does not require interpersonal comparisons of utility, but rather only that each person evaluate how much utility he or she would get from the allocations of others relative to his or her own allocation. Unlike distributions according to utilitarianism or the maximin principle, envy-free distributions do not require a high degree of information on the part of a social planner and could result from a decentralized mechanism.

Consider a problem of fair division of a divisible set of goods starting from an equal split (everyone's initial allocation is identical) with trading allowed. Under standard assumptions, the resulting distribution would not only be Pareto efficient but would also be envy-free. However, the concept of envy-freeness is inherently limited to situations characterized by equal endowments or equal claims on a common good and is not easily generalized to situations in which players have different initial claims or endowments of the good to be distributed (Young, 1993). In the case of equal claims, an equal split reference point is trivially envy-free. But if claims are not equal, the identification of an envy-free baseline or default option is not straightforward.

The "Kantian" Allocation Rule

Immanuel Kant's Categorical Imperative states that one should act as if the maxim of one's act were to become a universal law of nature. In the context of climate change, this moral principle might imply that each nation should abate emissions at a level that is at least as large as the uniform abatement level it would like to see all nations adopt (Barrett, 1992). Since the Categorical Imperative allows broad context dependencies and individual interpretations, while yet providing a general basis for comparative discourse, it is arguably a reasonable meta-rule for economic design of fair institutions and rules.

Elements of Fairness

Summarizing, there are several distinct concepts that underlie the fairness principles above and that form the assumptions of most arguments for just distribution (see Rescher (1966), Yaari and Bar-Hillel (1984) and Young (1993)):

- **Egalitarianism:** This concept is appealed to in arguments for inalienable rights that are non-transferable and is fundamental to certain democratic institutions such as "one person one vote".

- **Help the Needy:** Distribution to those who have greatest need, or who live below a subsistence level or who are vulnerable, is the concept that motivated the maximin principle. The flip side of this principle is "Give when you are able." This concept is also the basis of such commonplace social institutions as a progressive income tax, income rules for public housing and food stamps, need-based financial assistance for higher education, etc.
- **Reward the Able**: Reward according to endowment (of talent or ability) is the fundamental notion behind a meritocracy (and most scholarships). Private endowment (or status quo holdings of property) is commonly interpreted to legitimate property rights.

- **Reward Effort**: Reward according to effort, productivity, or contribution is the foundation of the principle of proportionality.

- **Reward Prudence**: Reward those who have been prudent over time in stewarding resources or who are attempting to help themselves. The flip side of this principle is that those who find themselves vulnerable through no fault of their own are worthy of assistance.

Organizations or arguments for a particular distribution commonly appeal to a combination of these five elements of fairness. Since legitimate claims to commons property are often grounded in different measures of fairness, society often weights distribution schemes either explicitly or implicitly in allocating institutions. In addition, the following two characteristics of allocating institutions contribute directly to whether resulting decisions are seen as fair:

- **Acceptability**: The outcome should be acceptable to all participants. A minimally acceptable allocation requires that no claimant be worse off than under the initial allocation.

- **Due Process**: Any rule that is adopted to decide on which projects shall be funded or how much should be spent on any given country’s sectoral program should be applied consistently across countries without special exceptions or preferences.

**Precedents for a Climate Change Convention**

The importance of the status quo, the concept of equal rights to use a commons resource, and the focal point of equi-proportionality can be seen in many international agreements that serve as precedents for a climate change convention. In this section, we briefly review a selection of international conventions that provide insightful precedents to a global agreement on climate change.


Due to the advancement of deep sea mining technology in the early 1970’s, the mining of nodules on the seabed rich in manganese, cobalt and other metals became possible. As the high seas do not belong to any nation, the United Nations Conference on the Law of the Sea (UNCLOS) adopted a general principle that the seabed is a "global commons" in which all countries have a stake. The problem of how to fairly allocate this common property was essentially a problem of assigning rights to these goods between the group of industrialized nations that had the technology to mine the deep seabed and the developing countries that did not.\(^8\) The solution that was adopted is a variant of the divide and choose

---

\(^8\) The Law of the Sea provides a reasonable precedent for a convention on climate change. Treating the seabed as a global commons, each nation is entitled to a share of the resources. As no mining had begun, all nations began from the same status quo, but there was wide variation in the ability to mine the
game. Any mining company that wishes to mine a site must divide the proposed site into two plots and submit this proposal to an International Seabed Authority. A coalition of developing countries, called the "Enterprise", is then allowed to choose which of the two plots it shall take. The entire site is then to be mined with the proceeds from the Enterprise’s plot going to the developing country coalition. In this way, developing countries are able to have fair access to the profits obtained from this global resource.

All nations in the UN system participated in framing the Law of the Sea Convention. As a precedent for negotiations on a climate change convention, it is significant that the formation of the International Seabed Authority which is charged with technology transfer and profit-sharing, was necessary to obtain the agreement of a coalition of seventy-seven developing countries (the Group of 77). Also significant is the fact that the two nations with the most advanced seabed mining technology, the United States and the United Kingdom, are not party to the agreement. As of 1992, 51 nations had signed the convention which will enter into force when 60 nations accede (Bergesen, et al., 1992).

The Law of the Sea negotiations also led to agreements on fishing rights in territorial and international waters and set up an International Whaling Commission. The agreements and institutions that emerged from UNCLOS define and are charged with allocating fishing and whaling rights and quotas, ie., they allocate access to a commons renewable resource. As the global atmosphere may be similarly characterized as a commons renewable resource, UNCLOS fishing and whaling agreements may provide some compelling precedents for a climate change convention. As these aspects of UNCLOS are not reviewed here, an investigation of these agreements and the discussions that led to them would be a fruitful avenue for future research.

The Montreal Protocol on Substances that Deplete the Ozone Layer

The institutional arrangements that were set up under the Montreal Protocol on Substances that Deplete the Ozone are briefly reviewed in Section 5. Three highlights are: i) allowable levels of production and consumption of ozone depleting substances (ODS) are reduced in a phased schedule as a percentage of baseline levels. ii) The phase-out schedule is less stringent for developing countries than for industrialized countries. iii) The signatories to the Protocol also set up a fund, the Interim Multilateral Fund, to transfer resources from industrialized to developing countries to fairly distribute the burden of phasing out ODS. Very briefly, these arrangements emerged from discussions that were initiated with the Vienna convention: a weak framework convention that allowed parties to be involved in international monitoring efforts. The opening of a hole in the ozone layer over Antarctica provided the conditions that made the stronger Montreal Protocol possible. Further evidence of reductions in the ozone column over countries in the northern hemisphere made a faster phase-out under the London accord possible. At each stage, successive resolution of scientific uncertainty was followed by appropriate policy commitments. The evolution of the protocol and the influence of the interests on the arrangements that emerged set a powerful precedent for the ongoing international discussions on climate change. Future research that reviews the protocol’s history and highlights the relative importance of arguments based on the status quo,

depth seabed. Similarly, all nations are clearly entitled to a share of the global atmosphere and there is wide variation in ability to shoulder the burden of reducing harmful emissions. Unlike the Law of the Sea, however, the status quo use of the atmosphere varies widely between countries and there is no agreement on whether legitimate claims on use of the atmosphere should be determined by GNP, population, land area, or past emissions.

43
equal rights, and equi-proportionality from the perspective of each major stakeholder group could be very illuminating in the context of the conceptual framework set out in this paper.

The Basel Convention on the International Movement of Hazardous Wastes

The Basel Convention which controls transboundary movement and disposal of hazardous and toxic wastes came into force in May 1992. Under the Convention, movements of hazardous wastes between signatories and non-signatories are banned unless countries have a bilateral agreement that meets the terms of the Convention. A number of African countries have signed the Bamako Convention that prohibits the importation of any hazardous waste. Austria requires domestic handlers of hazardous waste to ensure that host countries adhere to the Austrian standards of disposal. Signatories to the Basel Convention are considering adopting language similar to that of Austria which would give more flexibility than the outright ban at the center of the Basel Convention. Though 95% of the world’s hazardous waste (300-400 million tons/year according to UNEP) is generated in industrialized countries, the convention has not been ratified by the US, Japan or any of the EC countries except France.

Convention on Long Range Transborder Air Pollution (LRTAP)

Before the 1972 Conference on the Human Environment in Stockholm, the governments of Norway and Sweden became concerned about rising acidity of lakes and rivers. Armed with scientific evidence of this trend, they sought reductions in sulfur dioxide emissions from their European neighbors at the conference. At that time, there were broad uncertainties about the causal links between sulfur emissions, dispersion and transport, atmospheric acidification, wet and dry acid deposition and effects on fresh water, forests and crops. The concept of "critical load", ranking watersheds in terms of resilience to acid deposition, was yet to emerge. As such, most delegates to the conference were skeptical of claims of damage in Scandinavia due to SO$_2$ emissions in neighboring countries. The conference did agree, however, on the principle that nations are responsible to ensure that activities within their control do not harm the environments of other nations. After the Stockholm Conference, the OECD initiated a number of studies of transboundary pollution, including the Co-operative Program for Monitoring and Evaluation of the Long-Range Transmission of Air Pollution in Europe (EMEP). Using data collected by monitoring stations throughout Europe, by 1977 this program was able to estimate pollution deposition in each country and allocate national responsibility. Nonetheless, there was still a great deal of uncertainty about the nature and extent of environmental damage caused by acid deposition and whether reductions in SO$_2$ emissions presented a cost-effective means to reduce these uncertain impacts.

Thus, transborder pollution was identified as a problem that could lead to substantial, heterogeneous environmental and economic impacts. With uncertainty about these impacts and appropriate policy responses, the stage was set for discussions under the United Nations Economic Commission for Europe (ECE) that led to the framework Convention on Long Range Transborder Air Pollution of 1979 (LRTAP).

In 1975, the Soviet Union proposed a high-level East-West meeting to pursue a legally binding international convention dealing with energy or environmental matters. Apparently, the Soviet Union wished to continue the process of détente, but to move the process away from arms control or human rights (Levy 1992). After the first EMEP report in 1977, the Scandinavian countries proposed an air pollution convention for ECE countries that contained binding commitments for reductions in SO$_2$ emissions. Other European countries were not aware of any domestic acidification problems and, as noted above, were skeptical of Scandinavian claims that acid deposition presented a severe ecological threat.
They were certainly not ready to sign on to binding SO\textsubscript{2} reduction commitments. To obtain their support, the language of the proposed convention was substantially weakened so that no country was required to make binding commitments to meet explicit reduction targets though all signatories accede to the principle that "transborder air pollution should be reduced as much as is economically feasible" (Levy 1992). Though only Norway and Sweden were seriously concerned with the effects of acid rain, 32 nations and the European Community signed the convention in 1979. Most signatories did so because the commitments were not costly, showed that they were good citizens, and to further détente. Germany held out the longest in opposition to the convention, apparently concerned that accession to the convention might set a precedent leading to future liability for damages in Scandinavia. The process that served to bring Germany into this convention, and may serve to enforce international environmental agreements in general, is called "Tote-board diplomacy" (Levy 1992). As the lone holdout, Germany was faced with external pressures from its allies and domestic pressures from environmental interest groups. As long as Germany held out, it could not credibly claim that the nation was behaving as a responsible citizen in working cooperatively on international environmental issues. Tote-board diplomacy has also served to ensure that nations meet their commitments under several protocols to the framework convention signed in the 1980s.

The Executive Body of the LRTAP, comprised of government officials from signatory countries, meets annually to review progress and make policy decisions. Meetings are open to international organizations, non-governmental organizations, and industry. Formally, each country has veto power since all decisions are made by consensus. However, since the agreement of only 16 of the 33 parties to the convention is required to pass any resolution or protocol, the veto is rarely used. Parties that do not agree can legitimately choose not to participate. In addition to providing an institutional structure for a continual negotiation process, the executive body acts as a forum for reviewing: i) emission trends; ii) national strategies; iii) national policy measures; and iv) administrative structures in each signatory country (ECE 1992). This function provides information on performance toward meeting commitments, the "tote-board", that is used by domestic interest groups to move the negotiating process.

Three protocols have been added to the framework convention since 1979. In 1985 twenty parties committed to reducing SO\textsubscript{2} emissions by 30% from 1980 levels by 1993. Three of the largest European polluters -- the United Kingdom, Poland, and Spain -- refused to sign, as did the United States. In 1988 twenty-six parties committed to freeze nitrogen oxide emissions at current levels. A proposal to reduce NO\textsubscript{x} emissions by 30%, pushed for by hard-line environmental states, could not obtain enough support to pass. In late 1991, a protocol that loosely commits states to control volatile organic compounds was signed by twenty-one parties. Domestic industry and environmental interest groups had broad access to the policy-making process and lobbied hard for their positions in the debate over each of these protocols.

LRTAP provides an important precedent for the climate change discussions. Uncertainty in the science of assessing environmental damage and heterogeneity of impacts are common to both. The weak institutional structure adopted under LRTAP, a framework convention oriented toward scientific research and broad principles, provided a forum for strong consensus-building efforts that have yielded firm commitments to pollution reduction. Policies to attain commitments are not specified in LRTAP protocols, but national policies and progress are merely monitored by the Executive Body. Participating nations are free to design efficient policies to meet their commitments that are appropriate for their own situation. However, the protocols that have emerged treat all signatories identically in that they all agree to the same proportional reduction targets. Though this may be inefficient for the entire coalition, equal treatment appears to be a very robust criterion to get agreement.
In the United States, legislation designed to reduce power plant emissions using market instruments has been recently introduced. Under Title IV of the Clean Air Act of 1990, power plants are assigned annual SO\textsubscript{2} emission rights proportional to emissions over a previous three year period (1985-1987) which can then be traded. As of 1995, plants emitting more than 2.5 pounds of SO\textsubscript{2}/mmBTU will be issued tradable permits equal to 2.5 lb SO\textsubscript{2} times their average annual fuel consumption over the baseline period. Similarly, by the year 2000 most plants with emissions in excess of 1.2 lb/mmBTU will be allocated allowances at that rate times their baseline fuel consumption. Assigning the initial allocation of allowances on the basis of past emissions is called "grandfathering" and is an explicit recognition that the status quo matters in designing a scheme to reduce emissions industry-wide. Trading allows the entire electric power industry to most efficiently meet the reduction targets. The notion of grandfathering, however, sidesteps the question of whether the distribution of emissions in base period was equitable. The regulatory framework under which the electric power industry operates in the United States is currently undergoing rapid changes in many states. It is still too early to tell if emissions permits will actually be traded in enough volume to result in a stable market. Another option open to electric utilities to meet the Clean Air Act requirements is to purchase power from other generators by wheeling through the transmission lines of other companies (almost as a common carrier). An investigation of this possibility is explored in Villani (1993).
Appendix 2: Technical Appendix

Proof of Proposition 1

(i) The fact that the Nash noncooperative solution characterized by (10) is Pareto inefficient follows from the original Kuhn-Tucker approach to vector optimization problems. Let \( v \in \Theta \) be any country and consider the following problem:

\[
\text{Maximize}_{x \in \mathbb{R}^n} E_v \left[ V(G(x, I - x + S, I(v) - x(v) + s(v), \omega; v)) \right]
\]

subject to (6) and:

\[
E_v \{ V(\theta) \} \geq E_v \{ V^{NC}(\theta) \}, \quad \forall \theta \in \Theta \setminus \{v\}
\]

where \( V^{NC}(\theta) \) represents the payoff for country \( \theta \) from any noncooperative solution. A feasible solution to A.1-A.2 is clearly the given Nash noncooperative solution which satisfies both A.2 as well as (6) (note that (12) implies \( s(\theta) = 0 \) for all \( \theta \)). So much verifies that the solution to A.1-A.2 weakly dominates the noncooperative solution. Actually, by assigning Lagrange multipliers to the constraints A.2, it is easily verified that any solution to the necessary and sufficient conditions obtained for A.1-A.2 cannot be a solution to the first-order conditions (10) for any weighting vector satisfying (4). Thus, the solution to A.1-A.2 strictly dominates the noncooperative solution, as claimed.

(ii) The fact that resources are used efficiently in mitigating GHGs under the cooperative solution is evident from the structure of the problem. Assuming the country leads directly to a contradiction since aggregate welfare is always decreasing in total emissions \( G \) and increasing in consumption. Thus, if aggregate emissions can be lowered without affecting consumption (i.e. without using additional mitigation investments) they will be at the cooperative solution. An alternative method of seeing the same result is to note from (13) and (14) that the marginal emissions \( g_\theta(\theta) \) are equal across countries \( \theta \) for which \( x^C(\theta) > 0 \), which is the necessary and sufficient condition for minimizing total emissions using a fixed investment pool.

To see that the noncooperative solution is inefficient (when not all countries are identical) requires only an examination of the first-order conditions (10). If not all countries have identical preferences and emissions technologies, then (10) implies that the just mentioned condition of equalized marginal emissions will not obtain. Clearly, lower total emissions could be achieved by transferring some mitigation resources from one country to another to equalize marginal emissions.

Characterizing the First-Step Cooperative Solution with Strategic Behavior

1. GEF Problem

The contribution \( s(\theta) = -\phi I(\theta) \) from each of the developed countries \( \theta \in \Theta^{DC} \) is determined once \( I(\theta) \) is known and \( \phi \) is agreed upon. The job of the coalition reduces to efficiently allocating resources from the
GEF thus collected, $\sum s(\theta) \mid \theta \in \Theta^{DC}$, in GHG reducing investments in the LDC's. For the analytical example, the GEF's problem may be expressed as:

$$\text{Min} \sum_{\theta \in \Theta^{DC}} \alpha(\theta) \frac{y(\theta)}{x(\theta) + s(\theta)}$$ \hspace{1cm} A.3

subject to:

$$\sum_{\theta \in \Theta^{DC}} s(\theta) = \phi \sum_{\theta \in \Theta^{DC}} I(\theta)$$ \hspace{1cm} A.4

Here $x(\theta)$ and $y(\theta)$ are the declared levels of investment and consumption by country $\theta$. Note that this formulation implies that the transfer $s(\theta)$ goes directly into investment.

This yields the following Lagrangian for the GEF:

$$L^G = \sum_{\theta \in \Theta^{DC}} \alpha(\theta) \frac{y(\theta)}{x(\theta) + s(\theta)} + \lambda^G \left[ \sum_{\theta \in \Theta^{DC}} s(\theta) - \phi \sum_{\theta \in \Theta^{DC}} I(\theta) \right]$$ \hspace{1cm} A.5

and the first order condition:

$$- \alpha(\theta) \frac{y(\theta)}{(x(\theta) + s(\theta))^2} + \lambda^G = 0 \hspace{1cm} \theta \in \Theta^{LDC}$$ \hspace{1cm} A.6

A.4 and A.6 will yield the efficient level of $s(\theta) = s^*(x(\theta); \ldots)$, i.e. as a function of the declared investment $x(\theta)$ by country $\theta$.

2. **Country Problem**

Given non-cooperative behavior, the welfare maximizing problem for country $\theta$ becomes:

$$\text{Maximize} \ E_\omega \{ V(G(X^{LDC} + S^*), X^{DC}, y(\theta), \omega; \theta) \}$$ \hspace{1cm} A.7

subject to:

$$I(\theta) + s^*(\theta) = [s^*(\theta) + x(\theta)] + y(\theta) \hspace{1cm} \text{for} \ \theta \in \Theta^{LDC}$$ \hspace{1cm} A.8

$$(1-\phi) I(\theta) = x(\theta) + y(\theta) \hspace{1cm} \text{for} \ \theta \in \Theta^{DC}$$

---

9 i.e. the declared levels of investment and consumption in the non-cooperative solution without transfers, where $I(\theta) = x(\theta) + y(\theta)$. 

48
a) In the case of the developed countries, we obtain the following unconstrained maximization problem:

\[ L^{DC} = t(\theta) \log((1-\phi) I(\theta) - x(\theta)) \]

\[ - \gamma(\theta) \prod_{\xi \in \Theta^{EC}} \alpha(\xi) \left( \frac{(1-\phi) I(\xi) - x(\xi)}{x(\xi)} \right) - \sum_{\xi \in \Theta^{EC}} \alpha(\xi) \left( \frac{I(\xi) - x(\xi)}{x(\xi) + s^*(\xi)} \right) \]

The first-order condition for the DC's is:

\[ \frac{\gamma(\theta) \prod \alpha(\theta) (1-\phi) I(\theta)}{(1-\phi) I(\theta) - x(\theta)} = 0, \quad \theta \in \Theta^{DC}. \]

This can be solved to yield:

\[ x(\theta) = \left( \frac{\beta(\theta)}{I(\theta)} \right) (1-\phi) I(\theta) \]

where

\[ \beta(\theta) = - \frac{\alpha(\theta) \gamma(\theta)}{\gamma(\theta) + \sqrt{(\alpha(\theta) \gamma(\theta))^2 + 4 \gamma(\theta) \alpha(\theta) \gamma(\theta)}} > 0 \quad \forall \theta \in \Theta^{DC} \]

Thus,

\[ \gamma(\theta) = \left( 1 - \frac{\beta(\theta)}{I(\theta)} \right) (1-\phi) I(\theta) \]

which is positive since \( \beta(\theta) < t(\theta) \) by A.12. Note that the transfer \( s(\theta) \) causes the country to scale down both investment and consumption, but not much is possible "strategically" since \( I(\theta) \) is public information and \( \phi \) is pre-negotiated.

b) In the case of the LDC's, we obtain the following unconstrained maximization problem:

\[ L^{LDC} = t(\theta) \log(I(\theta) - x(\theta)) \]

\[ - \gamma(\theta) \prod_{\xi \in \Theta^{EC}} \alpha(\xi) \left( \frac{(1-\phi) I(\xi) - x(\xi)}{x(\xi)} \right) - \sum_{\xi \in \Theta^{EC}} \alpha(\xi) \left( \frac{I(\xi) - x(\xi)}{x(\xi) + s^*(\xi)} \right) \]
The first-order condition for the LDC’s is:

\[
\frac{i(\theta)}{(l(\theta) - x(\theta))} + \frac{\gamma(\theta)\Pi \alpha(\theta)(l(\theta) + s^*(\theta))}{(x(\theta) + s^*(\theta))^2} = 0, \quad \theta \in \Theta^{LDC}. \quad \text{(A.15)}
\]

A.6 can be expressed in the form

\[
- \alpha(\theta) \frac{(l(\theta) - x(\theta))}{(x(\theta) + s(\theta))^2} + \lambda^G = 0; \quad \theta \in \Theta^{LDC} \quad \text{(A.16)}
\]

A.15 and A.16, together with A.4, characterize the optimal levels \(s^*(\theta), x^*(\theta)\) and therefore \(y^*(\theta)\).
Appendix 3: Simulation Framework Details

Results

<table>
<thead>
<tr>
<th></th>
<th>Low Income</th>
<th>India&amp;China</th>
<th>Low-Middle</th>
<th>Upper-Middle</th>
<th>Transition</th>
<th>High Income</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>population 89 (millions)</td>
<td>990</td>
<td>1,946</td>
<td>682</td>
<td>330</td>
<td>411</td>
<td>800</td>
<td>5,167</td>
</tr>
<tr>
<td>GNP 89 (US$ billions)</td>
<td>288</td>
<td>673</td>
<td>883</td>
<td>1,012</td>
<td>899</td>
<td>14,804</td>
<td>16,559</td>
</tr>
<tr>
<td>Industrial CO2 89 (T millions)</td>
<td>367</td>
<td>3,041</td>
<td>1,413</td>
<td>1,163</td>
<td>4,878</td>
<td>9,722</td>
<td>20,584</td>
</tr>
<tr>
<td>GNP/capita 89</td>
<td>289</td>
<td>346</td>
<td>1,295</td>
<td>3,067</td>
<td>2,187</td>
<td>18,505</td>
<td></td>
</tr>
<tr>
<td>Industrial CO2/capita 89</td>
<td>0.37</td>
<td>1.56</td>
<td>2.07</td>
<td>3.52</td>
<td>11.87</td>
<td>12.15</td>
<td></td>
</tr>
<tr>
<td>alpha(theta)</td>
<td>0.23</td>
<td>15.67</td>
<td>3.39</td>
<td>2.30</td>
<td>40.60</td>
<td>213.72</td>
<td></td>
</tr>
<tr>
<td>i(theta)</td>
<td>GNP</td>
<td>288</td>
<td>673</td>
<td>883</td>
<td>1,012</td>
<td>899</td>
<td>14,804</td>
</tr>
<tr>
<td>t(theta)</td>
<td>600,000 - 10*GNP</td>
<td>597,120</td>
<td>593,270</td>
<td>591,170</td>
<td>589,680</td>
<td>591,010</td>
<td>451,960</td>
</tr>
<tr>
<td>gamma(theta)</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>gamma-bar</td>
<td>h-bar*gamma</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Low Income</th>
<th>India&amp;China</th>
<th>Low-Middle</th>
<th>Upper-Middle</th>
<th>Transition</th>
<th>High Income</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. NON-COOPERATIVE SOLUTION</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>y(theta)</td>
<td>287.82</td>
<td>669.55</td>
<td>880.89</td>
<td>1,010.00</td>
<td>891.58</td>
<td>14,485.55</td>
<td>18,225.40</td>
</tr>
<tr>
<td>x(theta)</td>
<td>0.18</td>
<td>3.45</td>
<td>2.11</td>
<td>2.00</td>
<td>7.42</td>
<td>318.45</td>
<td>333.60</td>
</tr>
<tr>
<td>Xo</td>
<td>0.06%</td>
<td>0.51%</td>
<td>0.24%</td>
<td>0.20%</td>
<td>0.83%</td>
<td>2.15%</td>
<td>1.80%</td>
</tr>
<tr>
<td>g(x,y)</td>
<td>367.00</td>
<td>3,041.00</td>
<td>1,413.00</td>
<td>1,163.00</td>
<td>4,878.00</td>
<td>9,722.00</td>
<td>20,584.00</td>
</tr>
<tr>
<td>E(U(.theta))</td>
<td>3,360,516</td>
<td>3,839,590</td>
<td>3,988,100</td>
<td>4,060,035</td>
<td>3,994,144</td>
<td>4,309,603</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low Income</td>
<td>India&amp;China</td>
<td>Low-Middle</td>
<td>Upper-Middle</td>
<td>Transition</td>
<td>High Income</td>
<td>Sum</td>
</tr>
<tr>
<td>------------------------</td>
<td>------------</td>
<td>-------------</td>
<td>------------</td>
<td>--------------</td>
<td>------------</td>
<td>-------------</td>
<td>-----------</td>
</tr>
<tr>
<td>2a. FIRST STEP COOPERATIVE SOLUTION (allocation of Xnc to minimize G(X,Y) @ fixed Ync)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>y(\theta)</td>
<td>267.82</td>
<td>669.55</td>
<td>880.89</td>
<td>1,010.00</td>
<td>891.58</td>
<td>14,485.55</td>
<td>18,225.40</td>
</tr>
<tr>
<td>x(\theta)</td>
<td>1.24</td>
<td>15.80</td>
<td>8.42</td>
<td>7.43</td>
<td>29.34</td>
<td>271.37</td>
<td>333.60</td>
</tr>
<tr>
<td>s(\theta)</td>
<td>1.07</td>
<td>12.35</td>
<td>6.31</td>
<td>5.43</td>
<td>21.92</td>
<td>(47.08)</td>
<td>0.00</td>
</tr>
<tr>
<td>g(x,y)</td>
<td>52.26</td>
<td>664.11</td>
<td>354.08</td>
<td>312.34</td>
<td>1,233.57</td>
<td>11,408.70</td>
<td>14,025.07</td>
</tr>
<tr>
<td>E(U) - E(U)nc</td>
<td>6,559</td>
<td>6,559</td>
<td>6,559</td>
<td>6,559</td>
<td>6,559</td>
<td>6,559</td>
<td></td>
</tr>
</tbody>
</table>

| 2b. SOPHISTICATED RESPONSE TO TRANSFERS (free up own resources for consumption) |
| y(\theta)              | 268.00     | 673.00      | 883.00     | 1,012.00     | 899.00     | 14,439.49   | 18,194.49 | Y         |
| x(\theta)              | 1.07       | 12.35       | 6.31       | 5.43         | 21.92      | 317.43      | 364.51    | X         |
| s                      | 1.07       | 12.35       | 6.31       | 5.43         | 21.92      | (47.08)     | 0.00      | S         |
| g(x,y)                 | 60.98      | 854.04      | 473.52     | 427.87       | 1,664.86   | 9,722.00    | 13,203.36 | G(X,Y)    |
| E(U) - E(U)nc          | 7,748      | 10,429      | 8,795      | 8,545        | 12,279     | 5,941       |           |           |

<p>| 2c. HOW WELL CAN THE OECD DO? (subject to transfers being used only for GHG reduction) |
| y(\theta)              | 288.00     | 673.00      | 883.00     | 1,012.00     | 899.00     | 14,414.07   | 18,159.07 | Y         |
| x(\theta)              | 1.46       | 18.54       | 9.87       | 8.70         | 34.49      | 316.87      | 399.93    | X         |
| s                      | 1.46       | 18.54       | 9.87       | 8.70         | 34.49      | (73.06)     | 0.00      | S         |
| g(x,y)                 | 44.67      | 568.79      | 302.85     | 267.10       | 1,058.20   | 9,722.02    | 11,953.62 | G(X,Y)    |
| E(U) - E(U)nc          | 8,987      | 11,569      | 10,035     | 9,785        | 13,519     | 6,384       |           |           |</p>
<table>
<thead>
<tr>
<th></th>
<th>Low Income</th>
<th>India &amp; China</th>
<th>Low-Middle</th>
<th>Upper-Middle</th>
<th>Transition</th>
<th>High Income</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>3a. Roughly 30% REDUCTIONS FROM GLOBAL 1989 CO2 EMISSIONS (financed by OECD countries: GEF = tau * GNP(OECD))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GEF distributed (via vector Z) to LDCs to minimize G(Xnc + Z, Ync)</td>
<td>0.132% tau</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>y(τau)nc</td>
<td>287.82</td>
<td>669.55</td>
<td>880.89</td>
<td>1,010.00</td>
<td>891.58</td>
<td>14,465.06</td>
<td>18,205.91</td>
</tr>
<tr>
<td>x(τau)nc</td>
<td>0.18</td>
<td>3.45</td>
<td>2.11</td>
<td>2.00</td>
<td>7.42</td>
<td>318.45</td>
<td>333.60</td>
</tr>
<tr>
<td>z(θeta)</td>
<td>0.52</td>
<td>5.35</td>
<td>2.58</td>
<td>2.14</td>
<td>8.92</td>
<td>0.00</td>
<td>(19.50)</td>
</tr>
<tr>
<td>x(θeta)</td>
<td>0.69</td>
<td>8.79</td>
<td>4.69</td>
<td>4.14</td>
<td>16.34</td>
<td>318.45</td>
<td>353.09</td>
</tr>
<tr>
<td>g(x,y)</td>
<td>93.86</td>
<td>1,192.78</td>
<td>635.96</td>
<td>560.98</td>
<td>2,215.58</td>
<td>9,708.91</td>
<td>14,408.08</td>
</tr>
</tbody>
</table>

3b. SOPHISTICATED RESPONSE BY LDCs: (free up own resources for consumption) | 0.132% tau |               |            |              |            |             |         |
| y(τau)               | 288.00     | 673.00        | 883.00     | 1,012.00     | 899.00     | 14,465.48   | 15,221.48 | Y       |
| x(τau)               | 0.00       | 0.00          | 0.00       | 0.00         | 0.00       | 318.03      | 318.03   | Xown    |
| z(θeta)              | 0.52       | 5.35          | 2.58       | 2.14         | 8.92       | (19.50)     | 0.00     | Z       |
| x(θeta)              | 0.52       | 5.35          | 2.58       | 2.14         | 8.92       | 318.03      | 337.52   | X       |
| g(x,y)               | 126.20     | 1,972.67      | 1,159.22   | 1,085.87     | 4,093.08   | 9,722.00    | 18,159.05 | G(X,Y)  |
| E(U) - E(U)nc        | 2.792      | 5.474         | 3.840      | 3.589        | 7.323      | 1,829       |          |         |

3c. LEVEL OF TAX FOR 30% REDUCTIONS GIVEN SOPHISTICATED RESPONSE | 0.236% tau |               |            |              |            |             |         |
<p>| y(τau)               | 288.00     | 673.00        | 883.00     | 1,012.00     | 899.00     | 14,451.20   | 18,206.20 | Y       |
| x(τau)               | 0.00       | 0.00          | 0.00       | 0.00         | 0.00       | 317.80      | 317.80   | Xown    |
| z(θeta)              | 0.70       | 8.88          | 4.73       | 4.17         | 16.52      | (35.00)     | 0.00     | Z       |
| x(θeta)              | 0.70       | 8.88          | 4.73       | 4.17         | 16.52      | 317.80      | 352.60   | X       |
| g(x,y)               | 93.22      | 1,187.30      | 632.17     | 557.52       | 2,208.87   | 9,719.64    | 14,397.72 | G(X,Y)  |
| E(U) - E(U)nc        | 6,653      | 9,235         | 7,601      | 7,350        | 11,085     | 5,113       |          |         |</p>
<table>
<thead>
<tr>
<th></th>
<th>Low Income</th>
<th>India&amp;China</th>
<th>Low-Middle</th>
<th>Upper-Middle</th>
<th>Transition</th>
<th>High Income</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y(\theta) )</td>
<td>287.75</td>
<td>668.08</td>
<td>879.99</td>
<td>1,099.15</td>
<td>888.44</td>
<td>14,353.23</td>
<td>18,086.64</td>
</tr>
<tr>
<td>( x(\theta) )</td>
<td>0.25</td>
<td>4.92</td>
<td>3.01</td>
<td>2.85</td>
<td>10.56</td>
<td>450.77</td>
<td>472.36</td>
</tr>
<tr>
<td>( g(x,y) )</td>
<td>256.90</td>
<td>2,128.70</td>
<td>989.10</td>
<td>814.10</td>
<td>3,414.60</td>
<td>6,805.40</td>
<td>14,408.80</td>
</tr>
<tr>
<td>( E(U) - E(U)_{nc} )</td>
<td>6.018</td>
<td>4.873</td>
<td>5.570</td>
<td>5.677</td>
<td>4.088</td>
<td>2.028</td>
<td>G(X,Y)</td>
</tr>
<tr>
<td>70% of ( g(x,y)_{nc} )</td>
<td>256.90</td>
<td>2,128.70</td>
<td>989.10</td>
<td>814.10</td>
<td>3,414.60</td>
<td>6,805.40</td>
<td>14,408.80</td>
</tr>
</tbody>
</table>

5. **EQUAL EMISSION RIGHTS PER CAPITA TO ACHIEVE 30% REDUCTIONS FROM GLOBAL 1989 CO2 EMISSIONS**  
   (non-cooperative solution: no transfers and no trading of emission rights)

<table>
<thead>
<tr>
<th></th>
<th>Low Income</th>
<th>India&amp;China</th>
<th>Low-Middle</th>
<th>Upper-Middle</th>
<th>Transition</th>
<th>High Income</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y(\theta) )</td>
<td>287.82</td>
<td>669.55</td>
<td>880.89</td>
<td>1,099.48</td>
<td>868.25</td>
<td>13,509.74</td>
<td>17,225.72</td>
</tr>
<tr>
<td>( x(\theta) )</td>
<td>0.18</td>
<td>3.45</td>
<td>2.11</td>
<td>2.52</td>
<td>30.75</td>
<td>1,294.26</td>
<td>1,333.28</td>
</tr>
<tr>
<td>( g(x,y) )</td>
<td>365.99</td>
<td>3,037.56</td>
<td>1,411.47</td>
<td>920.24</td>
<td>1,146.12</td>
<td>2,230.90</td>
<td>9,112.29</td>
</tr>
<tr>
<td>( E(U) - E(U)_{nc} )</td>
<td>11,471</td>
<td>11,468</td>
<td>11,470</td>
<td>11,165</td>
<td>4,202</td>
<td>20,049</td>
<td>G(X,Y)</td>
</tr>
<tr>
<td>Equal/cap rights Sum = 70% of 89</td>
<td>2,783.04</td>
<td>5,426.65</td>
<td>1,901.64</td>
<td>920.24</td>
<td>1,146.12</td>
<td>2,230.90</td>
<td>14,408.60</td>
</tr>
</tbody>
</table>

6. **NASH BARGAINING SOLUTION** (numerically computed with \( E(U) \) non-coop as threat point)

<table>
<thead>
<tr>
<th></th>
<th>Low Income</th>
<th>India&amp;China</th>
<th>Low-Middle</th>
<th>Upper-Middle</th>
<th>Transition</th>
<th>High Income</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y(\theta) )</td>
<td>327.63</td>
<td>704.65</td>
<td>913.03</td>
<td>1,040.29</td>
<td>922.28</td>
<td>14,225.01</td>
<td>19,133.47</td>
</tr>
<tr>
<td>( x(\theta) )</td>
<td>1.70</td>
<td>20.74</td>
<td>10.98</td>
<td>9.65</td>
<td>38.20</td>
<td>344.26</td>
<td>425.53</td>
</tr>
<tr>
<td>( s(\theta) )</td>
<td>41.53</td>
<td>51.78</td>
<td>41.01</td>
<td>37.94</td>
<td>61.48</td>
<td>(233.73)</td>
<td>0.00</td>
</tr>
<tr>
<td>( g(x,y) )</td>
<td>43.58</td>
<td>531.98</td>
<td>281.59</td>
<td>247.62</td>
<td>980.09</td>
<td>8,831.83</td>
<td>10,916.69</td>
</tr>
<tr>
<td>( E(U) - E(U)_{nc} )</td>
<td>87,382</td>
<td>39,473</td>
<td>30,852</td>
<td>27,092</td>
<td>29,672</td>
<td>1,496</td>
<td>127,963,465</td>
</tr>
</tbody>
</table>

Product Sum
<table>
<thead>
<tr>
<th>Country</th>
<th>Group</th>
<th>Industrial CO₂ ('000 Tons)</th>
<th>CH₄ ('000 Tons)</th>
<th>CFCs ('000 Tons)</th>
<th>CO₂ equiv (IPCC index)</th>
<th>Population (millions)</th>
<th>GNP/cap (US$)</th>
<th>GNP (US$ bill)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afghanistan</td>
<td>1</td>
<td>6,273</td>
<td>480</td>
<td></td>
<td>16,353</td>
<td>16.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bangladesh</td>
<td>1</td>
<td>14,114</td>
<td>6,900</td>
<td></td>
<td>159,014</td>
<td>110.7</td>
<td>180</td>
<td>19.93</td>
</tr>
<tr>
<td>Benin</td>
<td>1</td>
<td>667</td>
<td>54</td>
<td></td>
<td>1,801</td>
<td>4.6</td>
<td>380</td>
<td>1.75</td>
</tr>
<tr>
<td>Bhutan</td>
<td>1</td>
<td>33</td>
<td>40</td>
<td></td>
<td>873</td>
<td>1.4</td>
<td>190</td>
<td>0.27</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>1</td>
<td>520</td>
<td>170</td>
<td></td>
<td>4,090</td>
<td>8.8</td>
<td>320</td>
<td>2.82</td>
</tr>
<tr>
<td>Burundi</td>
<td>1</td>
<td>176</td>
<td>34</td>
<td></td>
<td>890</td>
<td>5.3</td>
<td>220</td>
<td>1.17</td>
</tr>
<tr>
<td>Cambodia</td>
<td>1</td>
<td>451</td>
<td>1,100</td>
<td></td>
<td>23,551</td>
<td>8.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central African Republic</td>
<td>1</td>
<td>204</td>
<td>100</td>
<td></td>
<td>2,364</td>
<td>3.0</td>
<td>390</td>
<td>1.17</td>
</tr>
<tr>
<td>Chad</td>
<td>1</td>
<td>202</td>
<td>220</td>
<td></td>
<td>4,822</td>
<td>5.5</td>
<td>190</td>
<td>1.05</td>
</tr>
<tr>
<td>Comoros</td>
<td>1</td>
<td>51</td>
<td>11</td>
<td></td>
<td>282</td>
<td>0.5</td>
<td>460</td>
<td>0.21</td>
</tr>
<tr>
<td>Equatorial Guinea</td>
<td>1</td>
<td>106</td>
<td>1</td>
<td></td>
<td>127</td>
<td>0.4</td>
<td>330</td>
<td>0.13</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>1</td>
<td>2,565</td>
<td>1,400</td>
<td></td>
<td>31,965</td>
<td>49.5</td>
<td>120</td>
<td>5.94</td>
</tr>
<tr>
<td>Gambia, The</td>
<td>1</td>
<td>183</td>
<td>16</td>
<td></td>
<td>561</td>
<td>0.8</td>
<td>240</td>
<td>0.20</td>
</tr>
<tr>
<td>Ghana</td>
<td>1</td>
<td>3,521</td>
<td>120</td>
<td>1</td>
<td>11,914</td>
<td>14.4</td>
<td>390</td>
<td>5.62</td>
</tr>
<tr>
<td>Guinea</td>
<td>1</td>
<td>1,000</td>
<td>300</td>
<td></td>
<td>7,360</td>
<td>5.6</td>
<td>430</td>
<td>2.41</td>
</tr>
<tr>
<td>Guinea-Bissau</td>
<td>1</td>
<td>147</td>
<td>72</td>
<td></td>
<td>1,859</td>
<td>1.0</td>
<td>180</td>
<td>0.17</td>
</tr>
<tr>
<td>Guyana</td>
<td>1</td>
<td>660</td>
<td>27</td>
<td></td>
<td>1,227</td>
<td>0.8</td>
<td>340</td>
<td>0.27</td>
</tr>
<tr>
<td>Haiti</td>
<td>1</td>
<td>725</td>
<td>90</td>
<td></td>
<td>2,615</td>
<td>6.4</td>
<td>360</td>
<td>2.30</td>
</tr>
<tr>
<td>Indonesia</td>
<td>1</td>
<td>137,726</td>
<td>6,500</td>
<td>1</td>
<td>280,099</td>
<td>178.2</td>
<td>500</td>
<td>89.10</td>
</tr>
<tr>
<td>Kenya</td>
<td>1</td>
<td>5,192</td>
<td>640</td>
<td>0</td>
<td>18,632</td>
<td>23.5</td>
<td>360</td>
<td>8.46</td>
</tr>
<tr>
<td>Lao P D R</td>
<td>1</td>
<td>227</td>
<td>370</td>
<td></td>
<td>7,997</td>
<td>4.1</td>
<td>180</td>
<td>0.74</td>
</tr>
<tr>
<td>Lesotho</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.7</td>
<td>470</td>
<td>0.80</td>
</tr>
<tr>
<td>Liberia</td>
<td>1</td>
<td>773</td>
<td>63</td>
<td>0</td>
<td>2,096</td>
<td>2.5</td>
<td>450</td>
<td>1.13</td>
</tr>
<tr>
<td>Madagascar</td>
<td>1</td>
<td>901</td>
<td>680</td>
<td>0</td>
<td>15,181</td>
<td>11.3</td>
<td>230</td>
<td>2.60</td>
</tr>
<tr>
<td>Malawi</td>
<td>1</td>
<td>634</td>
<td>73</td>
<td></td>
<td>2,167</td>
<td>8.2</td>
<td>180</td>
<td>1.48</td>
</tr>
<tr>
<td>Mali</td>
<td>1</td>
<td>425</td>
<td>310</td>
<td></td>
<td>6,935</td>
<td>8.2</td>
<td>270</td>
<td>2.21</td>
</tr>
<tr>
<td>Mauritania</td>
<td>1</td>
<td>3,023</td>
<td>140</td>
<td></td>
<td>5,963</td>
<td>1.9</td>
<td>500</td>
<td>0.95</td>
</tr>
<tr>
<td>Mozambique</td>
<td>1</td>
<td>1,205</td>
<td>130</td>
<td></td>
<td>3,935</td>
<td>15.3</td>
<td>80</td>
<td>1.22</td>
</tr>
<tr>
<td>Group</td>
<td>Industrial CO2 ('000 Tons)</td>
<td>CH4 ('000 Tons)</td>
<td>CFCs ('000 Tons)</td>
<td>CO2 equiv (IPCC index)</td>
<td>Population (millions)</td>
<td>GNP/cap (US$)</td>
<td>GNP (US$ bill)</td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>---------------------------</td>
<td>----------------</td>
<td>-----------------</td>
<td>------------------------</td>
<td>----------------------</td>
<td>---------------</td>
<td>---------------</td>
<td></td>
</tr>
<tr>
<td>Myanmar</td>
<td>1</td>
<td>5,009</td>
<td>3,200</td>
<td>72,209</td>
<td>40.8</td>
<td>180</td>
<td>3.31</td>
<td></td>
</tr>
<tr>
<td>Nepal</td>
<td>1</td>
<td>934</td>
<td>1,000</td>
<td>21,934</td>
<td>18.4</td>
<td>290</td>
<td>2.15</td>
<td></td>
</tr>
<tr>
<td>Niger</td>
<td>1</td>
<td>1,008</td>
<td>230</td>
<td>5,838</td>
<td>7.4</td>
<td>250</td>
<td>28.45</td>
<td></td>
</tr>
<tr>
<td>Nigeria</td>
<td>1</td>
<td>79,263</td>
<td>3,700</td>
<td>0</td>
<td>156,963</td>
<td>113.8</td>
<td>250</td>
<td>28.45</td>
</tr>
<tr>
<td>Pakistan</td>
<td>1</td>
<td>60,973</td>
<td>3,400</td>
<td>6</td>
<td>167,611</td>
<td>109.9</td>
<td>370</td>
<td>40.66</td>
</tr>
<tr>
<td>Rwanda</td>
<td>1</td>
<td>381</td>
<td>46</td>
<td>0</td>
<td>1,247</td>
<td>6.9</td>
<td>320</td>
<td>2.21</td>
</tr>
<tr>
<td>Sierra Leone</td>
<td>1</td>
<td>671</td>
<td>97</td>
<td>0</td>
<td>2,708</td>
<td>4.0</td>
<td>220</td>
<td>0.88</td>
</tr>
<tr>
<td>Solomon Islands</td>
<td>1</td>
<td>101</td>
<td>1</td>
<td>0</td>
<td>182</td>
<td>0.3</td>
<td>580</td>
<td>0.18</td>
</tr>
<tr>
<td>Somalia</td>
<td>1</td>
<td>960</td>
<td>760</td>
<td>0</td>
<td>16,920</td>
<td>6.1</td>
<td>170</td>
<td>1.04</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>1</td>
<td>4,034</td>
<td>540</td>
<td>0</td>
<td>15,374</td>
<td>16.8</td>
<td>430</td>
<td>7.22</td>
</tr>
<tr>
<td>Sudan</td>
<td>1</td>
<td>3,338</td>
<td>1,200</td>
<td>0</td>
<td>28,538</td>
<td>24.5</td>
<td>540</td>
<td>13.23</td>
</tr>
<tr>
<td>Tanzania</td>
<td>1</td>
<td>2,099</td>
<td>740</td>
<td>0</td>
<td>17,639</td>
<td>23.8</td>
<td>130</td>
<td>3.09</td>
</tr>
<tr>
<td>Togo</td>
<td>1</td>
<td>627</td>
<td>34</td>
<td>0</td>
<td>1,341</td>
<td>3.5</td>
<td>390</td>
<td>1.37</td>
</tr>
<tr>
<td>Uganda</td>
<td>1</td>
<td>879</td>
<td>210</td>
<td>0</td>
<td>5,289</td>
<td>16.8</td>
<td>250</td>
<td>4.20</td>
</tr>
<tr>
<td>Viet Nam</td>
<td>1</td>
<td>16,170</td>
<td>3,600</td>
<td>0</td>
<td>93,770</td>
<td>64.8</td>
<td>215</td>
<td>13.93</td>
</tr>
<tr>
<td>Zaire</td>
<td>1</td>
<td>3,822</td>
<td>290</td>
<td>0</td>
<td>9,912</td>
<td>34.5</td>
<td>260</td>
<td>8.97</td>
</tr>
<tr>
<td>Zambia</td>
<td>1</td>
<td>2,612</td>
<td>120</td>
<td>0</td>
<td>5,132</td>
<td>7.8</td>
<td>390</td>
<td>3.04</td>
</tr>
<tr>
<td>China</td>
<td>2</td>
<td>2,388,613</td>
<td>40,000</td>
<td>12</td>
<td>3,299,089</td>
<td>1,113.9</td>
<td>350</td>
<td>388.87</td>
</tr>
<tr>
<td>India</td>
<td>2</td>
<td>651,936</td>
<td>36,000</td>
<td>4</td>
<td>1,431,428</td>
<td>832.5</td>
<td>340</td>
<td>283.05</td>
</tr>
<tr>
<td>Algeria</td>
<td>3</td>
<td>46,492</td>
<td>970</td>
<td>1</td>
<td>72,735</td>
<td>24.4</td>
<td>2,230</td>
<td>54.41</td>
</tr>
<tr>
<td>Angola</td>
<td>3</td>
<td>4,065</td>
<td>340</td>
<td>1</td>
<td>12,105</td>
<td>9.7</td>
<td>610</td>
<td>5.92</td>
</tr>
<tr>
<td>Argentina</td>
<td>3</td>
<td>118,157</td>
<td>3,800</td>
<td>3</td>
<td>215,576</td>
<td>31.9</td>
<td>2,160</td>
<td>68.90</td>
</tr>
<tr>
<td>Belize</td>
<td>3</td>
<td>180</td>
<td>2</td>
<td>0</td>
<td>222</td>
<td>0.2</td>
<td>1,720</td>
<td>0.32</td>
</tr>
<tr>
<td>Bolivia</td>
<td>3</td>
<td>5,064</td>
<td>360</td>
<td>0</td>
<td>12,624</td>
<td>7.1</td>
<td>620</td>
<td>4.40</td>
</tr>
<tr>
<td>Botswana</td>
<td>3</td>
<td>1,700</td>
<td>97</td>
<td>0</td>
<td>3,737</td>
<td>1.2</td>
<td>1,690</td>
<td>1.92</td>
</tr>
<tr>
<td>Cameroon</td>
<td>3</td>
<td>5,774</td>
<td>230</td>
<td>0</td>
<td>10,604</td>
<td>11.6</td>
<td>1,000</td>
<td>11.60</td>
</tr>
<tr>
<td>Cape Verde</td>
<td>3</td>
<td>77</td>
<td>2</td>
<td>0</td>
<td>119</td>
<td>0.4</td>
<td>780</td>
<td>0.28</td>
</tr>
<tr>
<td>Country</td>
<td>Group</td>
<td>Industrial CO2 ('000 Tons)</td>
<td>CH4 ('000 Tons)</td>
<td>CFCs ('000 Tons)</td>
<td>CO2 equiv (IPCC index)</td>
<td>Population (millions)</td>
<td>GNP/cap (US$)</td>
<td>GNP (US$ bill)</td>
</tr>
<tr>
<td>------------------</td>
<td>-------</td>
<td>----------------------------</td>
<td>----------------</td>
<td>-----------------</td>
<td>------------------------</td>
<td>-----------------------</td>
<td>----------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Chile</td>
<td>3</td>
<td>31,833</td>
<td>270</td>
<td>0</td>
<td>37,503</td>
<td>13.0</td>
<td>1,770</td>
<td>23.01</td>
</tr>
<tr>
<td>Colombia</td>
<td>3</td>
<td>53,831</td>
<td>1,500</td>
<td>2</td>
<td>97,077</td>
<td>32.3</td>
<td>1,200</td>
<td>38.76</td>
</tr>
<tr>
<td>Congo</td>
<td>3</td>
<td>1,773</td>
<td>21</td>
<td>0</td>
<td>2,214</td>
<td>2.2</td>
<td>940</td>
<td>2.07</td>
</tr>
<tr>
<td>Costa Rica</td>
<td>3</td>
<td>2,557</td>
<td>78</td>
<td>0</td>
<td>4,195</td>
<td>2.7</td>
<td>1,780</td>
<td>4.81</td>
</tr>
<tr>
<td>Cote d'Ivoire</td>
<td>3</td>
<td>7,595</td>
<td>200</td>
<td>1</td>
<td>17,668</td>
<td>11.7</td>
<td>790</td>
<td>9.24</td>
</tr>
<tr>
<td>Cuba</td>
<td>3</td>
<td>36,202</td>
<td>310</td>
<td>0</td>
<td>42,602</td>
<td>11.0</td>
<td>2,000</td>
<td>22.00</td>
</tr>
<tr>
<td>Djibouti</td>
<td>3</td>
<td>326</td>
<td>11</td>
<td>0</td>
<td>557</td>
<td>0.4</td>
<td>1,070</td>
<td>0.44</td>
</tr>
<tr>
<td>Dominican Republic</td>
<td>3</td>
<td>6,745</td>
<td>160</td>
<td>0</td>
<td>10,105</td>
<td>7.0</td>
<td>790</td>
<td>5.53</td>
</tr>
<tr>
<td>Ecuador</td>
<td>3</td>
<td>15,216</td>
<td>330</td>
<td>0</td>
<td>22,146</td>
<td>10.3</td>
<td>1,020</td>
<td>10.51</td>
</tr>
<tr>
<td>Egypt</td>
<td>3</td>
<td>79,483</td>
<td>670</td>
<td>3</td>
<td>111,172</td>
<td>51.0</td>
<td>640</td>
<td>32.64</td>
</tr>
<tr>
<td>El Salvador</td>
<td>3</td>
<td>2,362</td>
<td>59</td>
<td>0</td>
<td>3,591</td>
<td>5.1</td>
<td>1,070</td>
<td>5.46</td>
</tr>
<tr>
<td>Fiji</td>
<td>3</td>
<td>678</td>
<td>18</td>
<td>0</td>
<td>1,056</td>
<td>0.7</td>
<td>1,650</td>
<td>1.22</td>
</tr>
<tr>
<td>Guatemala</td>
<td>3</td>
<td>4,071</td>
<td>110</td>
<td>1</td>
<td>12,254</td>
<td>8.9</td>
<td>910</td>
<td>6.10</td>
</tr>
<tr>
<td>Honduras</td>
<td>3</td>
<td>1,979</td>
<td>110</td>
<td>0</td>
<td>4,289</td>
<td>5.0</td>
<td>900</td>
<td>4.50</td>
</tr>
<tr>
<td>Iraq</td>
<td>3</td>
<td>68,898</td>
<td>950</td>
<td>1</td>
<td>94,721</td>
<td>18.3</td>
<td>1,940</td>
<td>35.50</td>
</tr>
<tr>
<td>Jamaica</td>
<td>3</td>
<td>4,899</td>
<td>18</td>
<td>1</td>
<td>11,150</td>
<td>2.4</td>
<td>1,250</td>
<td>3.02</td>
</tr>
<tr>
<td>Jordan</td>
<td>3</td>
<td>9,416</td>
<td>17</td>
<td>1</td>
<td>15,646</td>
<td>3.9</td>
<td>1,640</td>
<td>6.40</td>
</tr>
<tr>
<td>Korea, D P R</td>
<td>3</td>
<td>151,488</td>
<td>1,200</td>
<td>1</td>
<td>176,688</td>
<td>21.0</td>
<td>1,240</td>
<td>26.04</td>
</tr>
<tr>
<td>Lebanon</td>
<td>3</td>
<td>8,720</td>
<td>10</td>
<td>0</td>
<td>8,930</td>
<td>2.7</td>
<td>800</td>
<td>2.96</td>
</tr>
<tr>
<td>Malaysia</td>
<td>3</td>
<td>49,061</td>
<td>890</td>
<td>2</td>
<td>79,497</td>
<td>17.4</td>
<td>2,150</td>
<td>37.58</td>
</tr>
<tr>
<td>Mauritius</td>
<td>3</td>
<td>1,000</td>
<td>4</td>
<td>0</td>
<td>1,084</td>
<td>1.1</td>
<td>1,990</td>
<td>2.19</td>
</tr>
<tr>
<td>Mexico</td>
<td>3</td>
<td>318,702</td>
<td>2,300</td>
<td>5</td>
<td>397,367</td>
<td>84.6</td>
<td>2,010</td>
<td>170.05</td>
</tr>
<tr>
<td>Mongolia</td>
<td>3</td>
<td>10,503</td>
<td>260</td>
<td>0</td>
<td>15,763</td>
<td>2.1</td>
<td>880</td>
<td>21.56</td>
</tr>
<tr>
<td>Morocco</td>
<td>3</td>
<td>22,120</td>
<td>310</td>
<td>1</td>
<td>34,503</td>
<td>24.5</td>
<td>1,030</td>
<td>1.75</td>
</tr>
<tr>
<td>Namibia</td>
<td>3</td>
<td>2,180</td>
<td>87</td>
<td>0</td>
<td>4,007</td>
<td>3.7</td>
<td>800</td>
<td>2.96</td>
</tr>
<tr>
<td>Nicaragua</td>
<td>3</td>
<td>2,730</td>
<td>75</td>
<td>0</td>
<td>4,305</td>
<td>2.4</td>
<td>1,760</td>
<td>4.22</td>
</tr>
<tr>
<td>Papua New Guinea</td>
<td>3</td>
<td>2,250</td>
<td>15</td>
<td>0</td>
<td>2,565</td>
<td>3.8</td>
<td>890</td>
<td>3.38</td>
</tr>
<tr>
<td>Paraguay</td>
<td>3</td>
<td>1,722</td>
<td>310</td>
<td>0</td>
<td>8,232</td>
<td>4.2</td>
<td>1,030</td>
<td>4.33</td>
</tr>
<tr>
<td>Group</td>
<td>Industrial CO2</td>
<td>CH4</td>
<td>CFCs</td>
<td>CO2 equiv</td>
<td>Population</td>
<td>GNP/cap (US$)</td>
<td>GNP (US$ bill)</td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
<td>----------------</td>
<td>-----</td>
<td>------</td>
<td>-----------</td>
<td>------------</td>
<td>---------------</td>
<td>----------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>('000 Tons)</td>
<td>('000 Tons)</td>
<td>('000 Tons)</td>
<td>(IPCC index)</td>
<td>(millions)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peru</td>
<td>21,174</td>
<td>330</td>
<td>0</td>
<td>28,104</td>
<td>21.2</td>
<td>1,010</td>
<td>21.41</td>
<td></td>
</tr>
<tr>
<td>Philippines</td>
<td>40,960</td>
<td>2,400</td>
<td>1</td>
<td>97,233</td>
<td>60.0</td>
<td>710</td>
<td>42.60</td>
<td></td>
</tr>
<tr>
<td>Senegal</td>
<td>3,151</td>
<td>160</td>
<td>0</td>
<td>6,511</td>
<td>7.2</td>
<td>650</td>
<td>4.68</td>
<td></td>
</tr>
<tr>
<td>Swaziland</td>
<td>443</td>
<td>27</td>
<td>0</td>
<td>1,010</td>
<td>0.8</td>
<td>900</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>Syrian Arab Republic</td>
<td>28,154</td>
<td>190</td>
<td>1</td>
<td>38,017</td>
<td>12.1</td>
<td>980</td>
<td>11.86</td>
<td></td>
</tr>
<tr>
<td>Thailand</td>
<td>77,680</td>
<td>6,300</td>
<td>3</td>
<td>227,599</td>
<td>55.4</td>
<td>1,220</td>
<td>67.59</td>
<td></td>
</tr>
<tr>
<td>Tunisia</td>
<td>13,923</td>
<td>90</td>
<td>0</td>
<td>15,813</td>
<td>8.0</td>
<td>1,260</td>
<td>10.08</td>
<td></td>
</tr>
<tr>
<td>Turkey</td>
<td>126,078</td>
<td>880</td>
<td>1</td>
<td>150,431</td>
<td>55.0</td>
<td>1,370</td>
<td>75.35</td>
<td></td>
</tr>
<tr>
<td>Yemen</td>
<td>3,495</td>
<td>106</td>
<td>1</td>
<td>5,721</td>
<td>11.2</td>
<td>650</td>
<td>7.28</td>
<td></td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>16,059</td>
<td>310</td>
<td>1</td>
<td>28,442</td>
<td>9.5</td>
<td>650</td>
<td>5.18</td>
<td></td>
</tr>
<tr>
<td>Brazil</td>
<td>206,957</td>
<td>8,800</td>
<td>6</td>
<td>426,995</td>
<td>147.3</td>
<td>2,540</td>
<td>374.14</td>
<td></td>
</tr>
<tr>
<td>Gabon</td>
<td>7,826</td>
<td>170</td>
<td>0</td>
<td>11,396</td>
<td>1.1</td>
<td>2,960</td>
<td>3.26</td>
<td></td>
</tr>
<tr>
<td>Greece</td>
<td>70,920</td>
<td>360</td>
<td>4</td>
<td>101,972</td>
<td>10.0</td>
<td>5,350</td>
<td>53.50</td>
<td></td>
</tr>
<tr>
<td>Iran, Islamic Republic</td>
<td>166,074</td>
<td>1,500</td>
<td>3</td>
<td>215,193</td>
<td>53.3</td>
<td>3,200</td>
<td>170.56</td>
<td></td>
</tr>
<tr>
<td>Korea, Republic</td>
<td>221,104</td>
<td>1,200</td>
<td>5</td>
<td>275,669</td>
<td>42.4</td>
<td>4,400</td>
<td>186.56</td>
<td></td>
</tr>
<tr>
<td>Libya</td>
<td>37,842</td>
<td>290</td>
<td>0</td>
<td>43,932</td>
<td>4.4</td>
<td>5,310</td>
<td>23.36</td>
<td></td>
</tr>
<tr>
<td>Malta</td>
<td>1,674</td>
<td>8</td>
<td>0</td>
<td>1,842</td>
<td>0.4</td>
<td>5,830</td>
<td>2.04</td>
<td></td>
</tr>
<tr>
<td>Oman</td>
<td>10,259</td>
<td>150</td>
<td>0</td>
<td>13,409</td>
<td>1.5</td>
<td>5,220</td>
<td>7.83</td>
<td></td>
</tr>
<tr>
<td>Portugal</td>
<td>40,912</td>
<td>350</td>
<td>4</td>
<td>71,754</td>
<td>10.3</td>
<td>4,250</td>
<td>43.78</td>
<td></td>
</tr>
<tr>
<td>South Africa</td>
<td>278,468</td>
<td>3,400</td>
<td>7</td>
<td>390,979</td>
<td>35.0</td>
<td>2,470</td>
<td>88.45</td>
<td></td>
</tr>
<tr>
<td>Suriname</td>
<td>1,440</td>
<td>43</td>
<td>0</td>
<td>2,343</td>
<td>0.4</td>
<td>3,010</td>
<td>1.32</td>
<td></td>
</tr>
<tr>
<td>Trinidad and Tobago</td>
<td>18,580</td>
<td>470</td>
<td>0</td>
<td>28,450</td>
<td>1.3</td>
<td>3,230</td>
<td>4.20</td>
<td></td>
</tr>
<tr>
<td>Uruguay</td>
<td>4,749</td>
<td>530</td>
<td>0</td>
<td>15,879</td>
<td>3.1</td>
<td>2,620</td>
<td>8.12</td>
<td></td>
</tr>
<tr>
<td>Venezuela</td>
<td>95,887</td>
<td>1,400</td>
<td>2</td>
<td>137,033</td>
<td>19.2</td>
<td>2,450</td>
<td>47.04</td>
<td></td>
</tr>
<tr>
<td>Albania</td>
<td>9,732</td>
<td>95</td>
<td></td>
<td>11,727</td>
<td>3.0</td>
<td>1,200</td>
<td>3.60</td>
<td></td>
</tr>
<tr>
<td>Bulgaria</td>
<td>106,989</td>
<td>330</td>
<td>1</td>
<td>119,792</td>
<td>9.0</td>
<td>2,320</td>
<td>20.88</td>
<td></td>
</tr>
<tr>
<td>Czechoslovakia</td>
<td>226,347</td>
<td>820</td>
<td>4</td>
<td>267,059</td>
<td>15.6</td>
<td>3,450</td>
<td>53.82</td>
<td></td>
</tr>
<tr>
<td>Group</td>
<td>Industrial CO2 ('000 Tons)</td>
<td>CH4 ('000 Tons)</td>
<td>CFCs ('000 Tons)</td>
<td>CO2 equiv (IPCC index)</td>
<td>Population (millions)</td>
<td>GNP/cap (US$)</td>
<td>GNP (US$ bill)</td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>-----------------------------</td>
<td>-----------------</td>
<td>------------------</td>
<td>------------------------</td>
<td>------------------------</td>
<td>---------------</td>
<td>----------------</td>
<td></td>
</tr>
<tr>
<td>Hungary</td>
<td>5</td>
<td>64,076</td>
<td>410</td>
<td>3</td>
<td>90,305</td>
<td>10.6</td>
<td>2,590</td>
<td>27.45</td>
</tr>
<tr>
<td>Poland</td>
<td>5</td>
<td>440,929</td>
<td>2,500</td>
<td>5</td>
<td>522,794</td>
<td>37.9</td>
<td>1,790</td>
<td>67.84</td>
</tr>
<tr>
<td>Romania</td>
<td>5</td>
<td>212,193</td>
<td>1,500</td>
<td>2</td>
<td>255,439</td>
<td>23.2</td>
<td>3,445</td>
<td>79.92</td>
</tr>
<tr>
<td>USSR (former)</td>
<td>5</td>
<td>3,804,001</td>
<td>34,000</td>
<td>67</td>
<td>4,911,492</td>
<td>288.0</td>
<td>2,000</td>
<td>576.00</td>
</tr>
<tr>
<td>Yugoslavia</td>
<td>5</td>
<td>13,901</td>
<td>750</td>
<td>4</td>
<td>53,143</td>
<td>23.7</td>
<td>2,920</td>
<td>69.20</td>
</tr>
<tr>
<td>Australia</td>
<td>5</td>
<td>257,480</td>
<td>5,000</td>
<td>8</td>
<td>409,464</td>
<td>16.8</td>
<td>14,360</td>
<td>241.25</td>
</tr>
<tr>
<td>Austria</td>
<td>6</td>
<td>51,699</td>
<td>310</td>
<td>3</td>
<td>75,828</td>
<td>7.6</td>
<td>17,300</td>
<td>131.48</td>
</tr>
<tr>
<td>Bahrain</td>
<td>6</td>
<td>12,161</td>
<td>79</td>
<td>0</td>
<td>13,820</td>
<td>0.5</td>
<td>6,360</td>
<td>3.11</td>
</tr>
<tr>
<td>Barbados</td>
<td>6</td>
<td>971</td>
<td>2</td>
<td>0</td>
<td>1,013</td>
<td>0.3</td>
<td>6,350</td>
<td>1.63</td>
</tr>
<tr>
<td>Belgium</td>
<td>6</td>
<td>98,104</td>
<td>450</td>
<td>4</td>
<td>131,046</td>
<td>10.0</td>
<td>16,220</td>
<td>162.20</td>
</tr>
<tr>
<td>Canada</td>
<td>6</td>
<td>455,530</td>
<td>4,100</td>
<td>11</td>
<td>606,233</td>
<td>26.2</td>
<td>19,030</td>
<td>498.59</td>
</tr>
<tr>
<td>Cyprus</td>
<td>6</td>
<td>4,192</td>
<td>6</td>
<td>0</td>
<td>4,318</td>
<td>0.7</td>
<td>7,040</td>
<td>4.89</td>
</tr>
<tr>
<td>Denmark</td>
<td>6</td>
<td>47,009</td>
<td>270</td>
<td>2</td>
<td>64,425</td>
<td>5.1</td>
<td>20,450</td>
<td>104.30</td>
</tr>
<tr>
<td>Finland</td>
<td>6</td>
<td>51,300</td>
<td>180</td>
<td>1</td>
<td>60,953</td>
<td>5.0</td>
<td>22,120</td>
<td>110.60</td>
</tr>
<tr>
<td>France</td>
<td>6</td>
<td>357,163</td>
<td>2,600</td>
<td>24</td>
<td>552,715</td>
<td>56.2</td>
<td>17,820</td>
<td>1,001.48</td>
</tr>
<tr>
<td>Germany</td>
<td>6</td>
<td>641,398</td>
<td>3,680</td>
<td>34</td>
<td>918,360</td>
<td>79.0</td>
<td>16,752</td>
<td>1,323.41</td>
</tr>
<tr>
<td>Iceland</td>
<td>6</td>
<td>1,942</td>
<td>16</td>
<td>0</td>
<td>2,278</td>
<td>0.3</td>
<td>21,070</td>
<td>5.35</td>
</tr>
<tr>
<td>Ireland</td>
<td>6</td>
<td>29,352</td>
<td>430</td>
<td>2</td>
<td>50,128</td>
<td>3.5</td>
<td>8,710</td>
<td>30.49</td>
</tr>
<tr>
<td>Israel</td>
<td>6</td>
<td>32,903</td>
<td>140</td>
<td>3</td>
<td>53,462</td>
<td>4.5</td>
<td>9,790</td>
<td>44.06</td>
</tr>
<tr>
<td>Italy</td>
<td>6</td>
<td>389,747</td>
<td>2,000</td>
<td>25</td>
<td>578,572</td>
<td>57.5</td>
<td>15,120</td>
<td>869.40</td>
</tr>
<tr>
<td>Japan</td>
<td>6</td>
<td>1,040,554</td>
<td>4,100</td>
<td>95</td>
<td>1,684,589</td>
<td>123.1</td>
<td>23,810</td>
<td>2,931.01</td>
</tr>
<tr>
<td>Kuwait</td>
<td>6</td>
<td>31,181</td>
<td>250</td>
<td>1</td>
<td>42,304</td>
<td>2.0</td>
<td>16,150</td>
<td>32.30</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>6</td>
<td>9,266</td>
<td>7</td>
<td>0</td>
<td>9,413</td>
<td>0.4</td>
<td>24,980</td>
<td>9.42</td>
</tr>
<tr>
<td>Netherlands</td>
<td>6</td>
<td>124,990</td>
<td>1,200</td>
<td>6</td>
<td>185,428</td>
<td>14.8</td>
<td>15,920</td>
<td>235.62</td>
</tr>
<tr>
<td>New Zealand</td>
<td>6</td>
<td>26,176</td>
<td>1,100</td>
<td>1</td>
<td>55,149</td>
<td>3.3</td>
<td>12,070</td>
<td>39.83</td>
</tr>
<tr>
<td>Norway</td>
<td>6</td>
<td>46,009</td>
<td>1,300</td>
<td>1</td>
<td>79,182</td>
<td>4.2</td>
<td>22,290</td>
<td>93.62</td>
</tr>
<tr>
<td>Qatar</td>
<td>6</td>
<td>13,308</td>
<td>88</td>
<td>0</td>
<td>15,156</td>
<td>0.4</td>
<td>15,500</td>
<td>6.54</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>6</td>
<td>173,776</td>
<td>1,100</td>
<td>3</td>
<td>214,495</td>
<td>14.4</td>
<td>6,020</td>
<td>86.69</td>
</tr>
<tr>
<td>Group</td>
<td>Industrial CO2 (('000 Tons))</td>
<td>CH4 (('000 Tons))</td>
<td>CFCs (('000 Tons))</td>
<td>CO2 equiv (IPCC index)</td>
<td>Population (millions)</td>
<td>GNP/cap (US$)</td>
<td>GNP (US$ bill)</td>
<td></td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------------------------------</td>
<td>---------------------</td>
<td>-----------------------</td>
<td>------------------------</td>
<td>-----------------------</td>
<td>---------------</td>
<td>---------------</td>
<td></td>
</tr>
<tr>
<td>Singapore</td>
<td>35,860</td>
<td>7</td>
<td>1</td>
<td>41,880</td>
<td>2.7</td>
<td>10,450</td>
<td>28.22</td>
<td></td>
</tr>
<tr>
<td>Spain</td>
<td>203,227</td>
<td>1,500</td>
<td>17</td>
<td>336,668</td>
<td>38.8</td>
<td>9,330</td>
<td>362.00</td>
<td></td>
</tr>
<tr>
<td>Sweden</td>
<td>58,888</td>
<td>270</td>
<td>3</td>
<td>82,177</td>
<td>8.5</td>
<td>21,570</td>
<td>183.35</td>
<td></td>
</tr>
<tr>
<td>Switzerland</td>
<td>39,326</td>
<td>240</td>
<td>2</td>
<td>56,112</td>
<td>6.6</td>
<td>29,880</td>
<td>197.21</td>
<td></td>
</tr>
<tr>
<td>United Arab Emirates</td>
<td>50,944</td>
<td>480</td>
<td>1</td>
<td>66,897</td>
<td>1.5</td>
<td>18,430</td>
<td>27.65</td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>568,451</td>
<td>3,900</td>
<td>25</td>
<td>797,176</td>
<td>57.2</td>
<td>14,610</td>
<td>835.69</td>
<td></td>
</tr>
<tr>
<td>United States</td>
<td>4,869,005</td>
<td>37,000</td>
<td>130</td>
<td>6,409,495</td>
<td>248.8</td>
<td>20,910</td>
<td>5,202.41</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>20,582,772</td>
<td>273,079</td>
<td>573</td>
<td>20,582,772</td>
<td>3,365,229</td>
<td>29,682,860</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Radiative forcing equivalent | 1                              | 21                  | 5,873                 |
| Total CO2 equiv              | 20,582,772                      | 5,734,659           | 3,365,229             | 29,682,860             |

<table>
<thead>
<tr>
<th>Summary Range</th>
<th>CC2 89 (KT)</th>
<th>GHG 89 (IPCC Index)</th>
<th>Pop 89 (millions)</th>
<th>GNP 89 (US$ billions)</th>
<th>GNP/cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Income Developing Economies</td>
<td>366,705</td>
<td>1,237,120</td>
<td>998</td>
<td>288</td>
<td>289</td>
</tr>
<tr>
<td>India &amp; China</td>
<td>3,040,549</td>
<td>4,730,517</td>
<td>1,946</td>
<td>673</td>
<td>346</td>
</tr>
<tr>
<td>Lower Middle Income Developing Economies</td>
<td>1,412,746</td>
<td>2,147,690</td>
<td>682</td>
<td>883</td>
<td>1,294</td>
</tr>
<tr>
<td>Upper Middle Income Developing Economies</td>
<td>1,162,692</td>
<td>1,736,846</td>
<td>330</td>
<td>1,012</td>
<td>3,070</td>
</tr>
<tr>
<td>Economies in Transition</td>
<td>4,878,168</td>
<td>6,231,751</td>
<td>411</td>
<td>899</td>
<td>2,187</td>
</tr>
<tr>
<td>High Income Economies</td>
<td>9,721,912</td>
<td>13,598,736</td>
<td>800</td>
<td>14,804</td>
<td>18,509</td>
</tr>
</tbody>
</table>

20,582,772 29,682,860

**Sources:**
References


World Resources 1992-93, World Resources Institute, Washington, D.C.

