INTERNATIONAL BURDEN SHARING IN GREENHOUSE GAS REDUCTION

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Foreword

In recent years, we have come to recognize that the activities of modern industrial societies place an enormous burden on the environment. For example, the global atmosphere is called on to absorb vast amounts of anthropogenic greenhouse gas emissions. Doing so raises a number of critical questions such as: What are the constraints on the rates and levels of emission releases that would not place in jeopardy the sustainability of socio-economic development and natural ecosystems? How is the burden of mitigation (or adaptation) to possible climate changes and resulting reductions in current (or future) emission levels to be shared? What are appropriate technological options and economic, and other regulatory instruments to achieve such goals?

In view of persistent scientific uncertainties, definitive answers to most of these questions will not be readily at hand in the foreseeable future. Science also can not answer the question of what particular (ethical) model should underly the international burden sharing to face the challenges of mitigation and adaptation to a changing climate. This is the subject of international negotiations and resulting *political* decisions. However, the contribution of science can be to elucidate uncertainty ranges, to quantify the impacts and implications of alternatively suggested burden sharing models in the international negotiation process, and to asses the technological prerequisites and economic consequences of possible policy interventions.

This paper by Arnulf Grübler and Nebojša Nakićenović illustrates such a contribution to the international negotiation process and policy debate. By developing a data base on historical greenhouse gas (GHG) emissions and a model in parametric form, the authors are able to calculate quantitatively the impact of alternative burden sharing criteria. All salient features of the data base and the model are transparent and can be changed easily to perform sensitivity analysis or to respond to new formulations that might emerge from international negotiations.

The quantitative insights gained from an illustrative global control scenario of GHG emissions indicate both areas of possible compromise as well as potential conflicts in future negotiations. The overriding principle of burden sharing (allocation of emission reductions) versus sharing access to the global commons (allocation of emission entitlements) certainly emerges from the analysis as a major source of disagreement from a North–South perspective. Conversely, the comparatively smaller differences in regional/national allocations considering (differentiated) historical versus current responsibility as allocation mechanism are an important analytical finding primarily resulting from the quasi exponential growth path of anthropogenic GHG emissions. This finding could be a source of possible negotiation compromises.

IIASA's Environmentally Compatible Energy Strategies (ECS) Project is analyzing options for mitigating energy-related emissions of greenhouse gases and for adaptation to climate change. Part of the research includes the analysis of different emission reduction allocation schemes, of which this paper is an example. The modular design of the model developed enables to accommodate any other burden sharing model or alternative data sets and model parameters that might emerge from future scientific work or the negotiation process. Other research activities of the ECS Project analyze technological options of GHG mitigation and related economic policy instruments and their impacts. Together these research activities and resulting analytical products in form of the Parametric Framework model described here or the CO_2 mitigation technology inventory CO2DB are intended to provide timely scientific information into a policy process that may be the most complex one yet addressed at the international level.

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Abstract

This report provides an overview of current and historical greenhouse gas (GHG) emissions; examines alternative formulations on how efforts to lower anthropogenic GHG emissions could be shared among regions/countries; evaluates quantitatively the implications of alternative GHG allocation/reduction criteria, particularly from a "North–South" perspective; and describes a combined GHG emission data base and software tool developed for the analysis of GHG allocation regimes: the Parametric Framework.

The Parametric Framework (in *Lotus* format) contains a data set comprising 13 world regions/countries, socio-economic background data, and three different types of greenhouse gases/sources: fossil fuel and industrial carbon dioxide (CO_2) emissions, CO_2 emissions from biota and land-use changes, and anthropogenic methane (CH_4) emissions. Historical emission data span the period 1800 to 1988 for CO_2, and 1950 to 1988 for CH_4. In addition, the numerical routines necessary to calculate the quantitative implications of four alternative GHG allocation criteria (and their variants) are included. The Parametric Framework enables easy and straightforward changes of data, control targets, and other salient parameters of importance in GHG accounting (e.g., global warming potential equivalences between different GHGs).

Four different GHG emission reduction and allocation criteria are analyzed: equal per capita emissions, equal percentage cuts from current emissions to desired target levels ("grandfathering"), cutbacks proportional to past contributions to atmospheric concentration increase on a regional basis (compensation for "natural debt"), and natural GHG sinks adjusted emission reduction. An analysis was made of the quantitative implications of the four GHG emission allocation criteria for 13 world regions, assuming a reduction of global emissions to 4 Gt C (C-equivalent) by the year 2050. Additional sensitivity analyses were performed for each of the criteria.

The most important findings of the analysis include the following: (1) There are two generic classes of allocation criteria: *distributive* – the allocation of emission rights, and *reductive* – the allocation of emission *reduction* requirements. The largest differences in emission allocations are obtained between these two classes, especially when distributive allocation criteria are based on a per capita basis. (2) Differences were smaller within each of the two classes. For example, the reductive allocation criteria *across the board percentage cuts ("grandfathering")* and *cutbacks proportional to past contribution* achieve quite similar regional future emission allocations: (3) The basic principle of the allocation is also more important than the inclusion of different GHGs (comprehensiveness). (4) The smallest variations in emission distribution resulted from altering the reference year compared to which emission reduction ought to be achieved.

Acknowledgments

We gratefully acknowledge the support of the Environmental Policy and Research Division of the World Bank, Washington, DC, for part of the research reported here. In particular, we would like to thank Mohan Munasinghe and Kenneth King for their intellectual encouragement and helpful suggestions which led to this study. Sincere thanks go also to Il'dar Karimov for his skillful contribution to the development of the Parametric Framework.

1. Introduction

Future climate change was one of the central issues during the 1992 UN Conference of Environment and Development (UNCED) held in Rio de Janeiro. Expectations were high that the Global Summit would result in some international agreement to counter the risks of adverse consequences of global climate change. In fact, a Framework Convention on Climate Change negotiated by the Intergovernmental Negotiating Committee (INC) was signed, but without quantitative emission targets and dates. Should binding targets be agreed upon in the future, these would have important distributional consequences. Targets also imply a prior agreement on the degree of comprehensiveness in covering different greenhouse gases, and agreement on the principles for deriving target levels. This paper illustrates the quantitative implications of precisely these central issues surrounding an international agreement.

For several years the prospects of global warming have been on the agenda of the Intergovernmental Panel on Climate Change (IPCC) that has *inter alia* further extended our scientific knowledge in this area and has also developed a number of scenarios describing possible future developments of global GHG emissions. Under a "business-as-usual" scenario GHG emissions increase unconstrained throughout the 21st century leading to nearly a tripling of the equivalent CO_2 concentration in the atmosphere by the year 2100 (*Figure 1.1*). The IPCC (1990) estimates that under such a scenario global mean temperature would increase by 0.3 degrees Celsius per decade to reach a value of about 4 degrees (uncertainty range 3 to 6 degrees) higher than pre-industrial levels by the end of the 21st century. In order to illustrate possible pathways to mitigate the risks of global climate change the IPCC has also developed for the 1990 assessment alternative scenarios leading to a stabilization of atmospheric GHG concentrations (*Figure 1.1*) by the second half of the 21st century as a result of a significant reduction in GHG emissions (*Figure 1.2*). In particular, the Accelerated Policies Scenario (Scenario D in *Figure 1.2*), defines a development path in which current global GHG emissions are approximately halved by the year 2050. In the meantime a new range of emission scenarios have been developed by the IPCC (1992), without however narrowing down the gap between high and low emission paths.

In view of the large degree of scientific uncertainty that surrounds the effects of global warming, the precautionary principle would deem emission

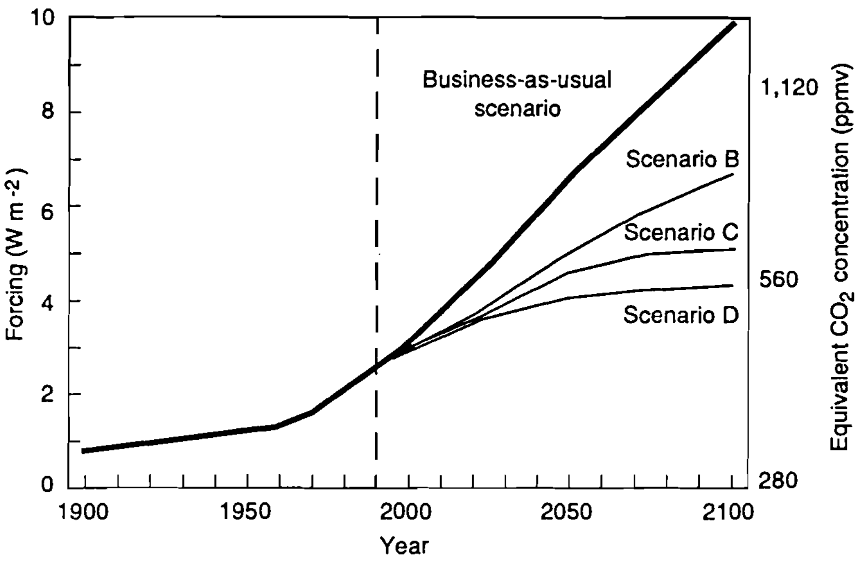

Figure 1.1. Increases of global GHG concentrations (expressed as equivalent CO_2 concentration) and resulting changes in radiative balance (in Watt per m^2) for selected IPCC scenarios. Source: IPCC, 1990.

reductions as a prudent response to the potentially adverse consequences for humanity as a whole. Achieving reductions, and especially drastic ones, is indeed a formidable task considering that developing countries need increases in energy services and other activities that result in GHG emissions. The salient questions are how such reductions might be achieved and by whom, and what the various effects (economic, ecological, distributive, etc.) of such reductions might be. In other words, how is the burden of global emission reduction going to be shared, and what could the criteria be for such burden sharing that would be fair and thus agreeable to all parties.

Of crucial importance in this context is the large disparity between the more developed and the developing countries. The former are responsible for about 80 percent of global emissions but with only 20 percent of world population. More developed countries are also responsible (on a differentiated bases) for the bulk of the historical increase in anthropogenic GHG concentrations. Conversely, developing countries will become more important contributors to future GHG emissions, independent of how high or low global GHG emissions will actually turn out to be.

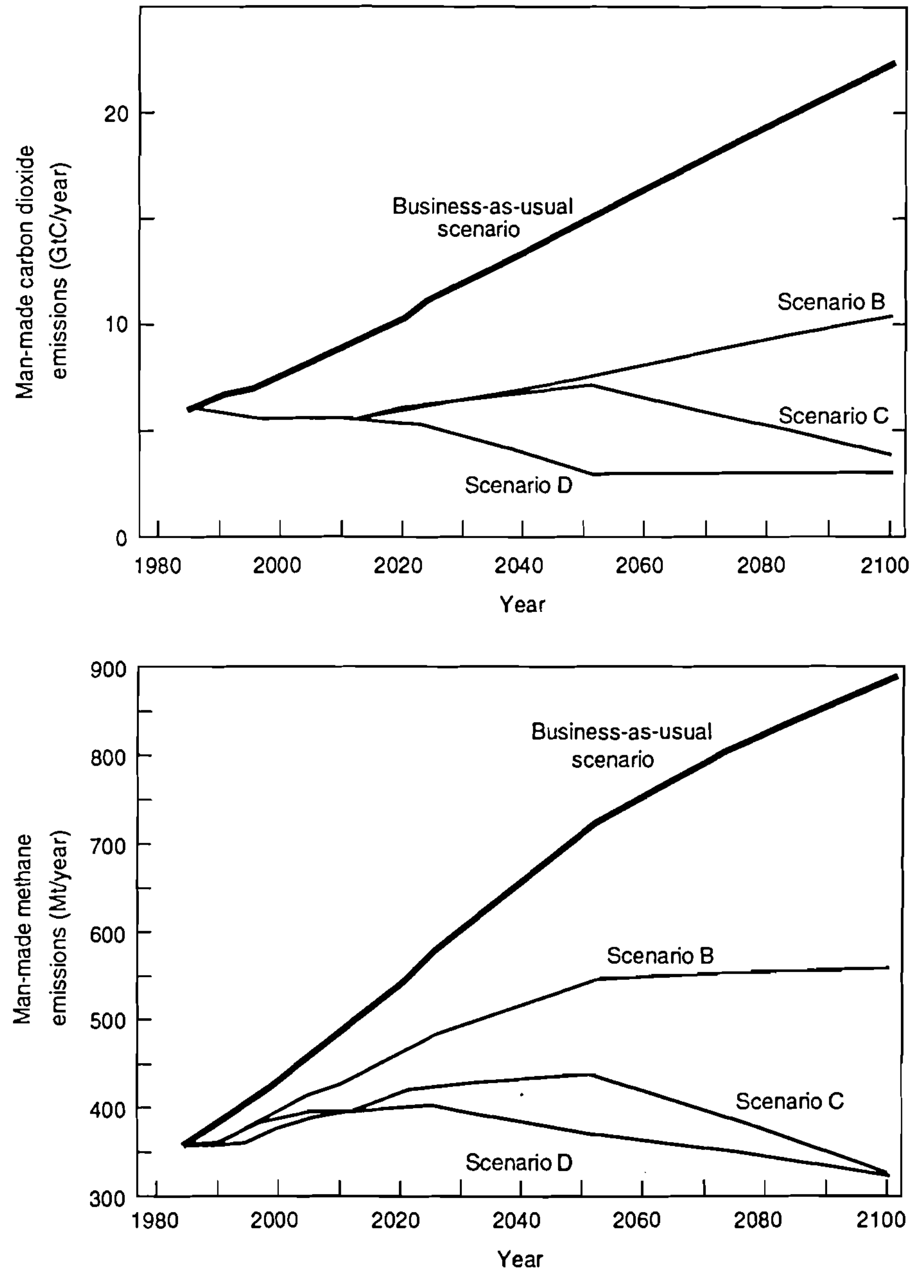

Figure 1.2. Range of IPCC emission scenarios for CO_2 (top) and methane (bottom). Scenarios B, C, and D represent varying degrees of mitigation measures. Source: IPCC, 1990.

In this report we analyze the distributional consequences of four different allocation criteria that have been proposed in the literature.[1] Some of them were also mentioned during the INC process for possible inclusion in the Framework Convention. The criteria examined include equal percentage cuts for all regions, cuts that are proportional to the historical contribution of different regions to GHG concentration increases, equal per capita emissions throughout the world, and the allocation of "natural" sinks of GHGs among different regions. The analysis is based on 13 exhaustive world regions and covers the time period to the middle of the next century. It includes all anthropogenic sources of CO_2 and CH_4. The report is based on the assessments made with the help of the Parametric Framework, a formal model described in Appendix III.

2. Greenhouse Gas Emissions Inventory

Atmospheric trace gases help regulate the temperature regime of the Earth. Incoming solar radiation warms the surface of the planet. Part of the reemitted radiant heat is trapped by trace gases in the atmosphere producing the *greenhouse effect.* Without it, temperature on Earth would be some 30 degrees Kelvin lower and life impossible. This natural greenhouse effect is also involved in governing the temperature balances of the neighboring planets Venus and Mars.

The most important infrared-absorbing greenhouse gases in the Earth's atmosphere are water vapor and carbon dioxide (CO_2), which account for over 90 percent of the natural greenhouse effect. *Table 2.1* summarizes the relative contributions of different gases to the natural and anthropogenic greenhouse effect and gives their respective concentrations and rates of increase. Since the onset of the Industrial Revolution human activities have not only increased the atmospheric concentration of naturally occurring greenhouse gases like CO_2 and methane (CH_4), but have also added new ones such as chlorofluorocarbons (CFCs), which additionally deplete the stratospheric ozone layer. Human activities have altered the concentrations of greenhouse gases both *directly* by anthropogenic emissions of CO_2, CH_4, nitrous oxide (N_2O) and CFCs, and *indirectly* by influencing the complex atmospheric

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[1] For example, Epstein and Gupta (1990); Grubb (1993); Gosh (1991); Hammond *et al.* (1990); Rose and Stevens (1993); Simonis (1992); Smith (1991); Subak and Clark (1990); Wirth and Lashof (1992). For a more quantitative discussion see Argawal and Narain (1991); Fujii (1990); Grubb *et al.* (1992); Grübler und Fujii (1991); Krause *et al.* (1989); Smith *et al.* (1991).

Table 2.1. Greenhouse gases and their effect.

	CO_2	CH_4	N_2O	CFCs	O_3	H_2O
% contribution to greenhouse effect						
Natural (30° K)	23%	2%	2%	-	3%	70%
Anthropogenic 1860–1980 (2–3° K)	60%	14%	3%	9%	10%	4%
Contribution of 1990 emissions over the next 100 years	61%	15%	4%	11%	others: 9%[a]	
Trace gas concentration parts per trillion (10^{12})	10^6 ppt	10^3 ppt	10^3 ppt	ppt		
Pre-industrial	280	800	288	0		
Current	353	1,720	310	280–484[b]		
Increase since 1800	73	920	22	280–484[b]		
(in %)	(26%)	(115%)	(7.6%)	(∞)		
Current increase/yr	1.8	15	0.8	9.5–17[b]		
(in %/yr)	(0.5%)	(0.9%)	(0.25%)	(4%)		
Residence time (years)	50–200	10–14	150	65–130[b]	0.1	-

[a] Including stratospheric water vapor, ozone and HCFCs.

[b] Range corresponds to CFC-11s and CFC-12s respectively.

Source: IPCC, 1990; German Enquête Commission, 1991.

chemistry, including increases in stratospheric water vapor concentrations, depletion of stratospheric ozone (O_3), and increases of ozone concentrations in the lower levels of the atmosphere (increase in tropospheric ozone).

The combined effect of the anthropogenic increase in the concentration of greenhouse gases (GHGs) is estimated to amount to a temperature increase of some 2 to 3 degrees Kelvin over the 1860 to 1980 period. That actual global mean temperature rise was much lower (0.5 degrees K, or perhaps even smaller) can be attributed to a large number of yet insufficiently understood processes like the thermal inertia of the oceans, complex interlinkages and feedbacks between different GHGs, and a variety of counterbalancing trends. For instance, recent findings from the Intergovernmental Panel on Climate Change (IPCC, 1992) indicate that possibly as much as 40 percent of the theoretical additional warming of the northern hemisphere was compensated for by the cooling effect of stratospheric sulfate aerosols resulting from rising emissions of sulfurous compounds from the use of fossil fuels. Previously this was thought to have only local (smog) and regional (acidic precipitation) environmental impacts. Recent IPCC findings (not yet reflected in *Table 2.1*) also indicate that the net warming effect of increasing CFCs concentration may have been balanced by corresponding decreases in stratospheric ozone. Conversely, the future phase out of CFCs under the Montreal and London Protocols may not produce any reduction of global warming due to this complex interplay between the different GHGs (IPCC, 1992).

The effect of changing concentrations of greenhouse gases on climate depends on the respective radiative forcing of the different greenhouse gases, i.e., how a changing concentration of a given GHG modifies the balance between incoming and outgoing radiation of the climate system. There are both *direct* (e.g., changes in the radiative balance through changes in concentration of a particular GHG) and *indirect* effects (e.g., the formation of other radiatively active gases, such as ozone from CH_4 emissions, and influences on the atmospheric residence times of other GHGs). How long these effects will last depends in turn on the residence time of the respective GHG in the atmosphere (*Table 2.1*), before they are absorbed by terrestrial sinks and/or destroyed by chemical reactions in the atmosphere. Combining radiative forcing with atmospheric residence times (particularly for CO_2 still affected by considerable uncertainties in the global carbon cycle) allows a comparison to be made of the "global warming potential" for different GHGs. For instance, in this paper a global warming potential value equivalent to 21 (direct and indirect effects combined) between CO_2 and CH_4 on the basis of the relative mass of the two gases has been adopted. Thus, the emission of one additional kg CH_4 corresponds to 21 kg of additional CO_2 emissions.[2] A sensitivity analysis varying this methane equivalence factor (among other CH_4 accounting variables) is performed in Sections 3.3 and 3.4. Instead of an exogenously fixed residence time for CO_2, a dynamic model is used to

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[2] Note that this factor is based on a mass equivalent, and *not* on a mole equivalent basis. The effect of different assumptions of the equivalence between CO_2 and CH_4 emissions can be easily calculated with the Parametric Framework developed for this report, where the global warming potential mass equivalence of methane is a free parameter value (ranges between 9 and 63 have been presented in the 1990 IPCC report). Generally, increasing the methane equivalence factor will increase the relative importance of methane emissions (and thus of non-industrial emission sources, particularly important in developing countries) compared to CO_2 emissions (dominated by fossil fuel use with larger shares of industrialized countries). There remain serious reservations against using equivalence factors that do not take into account the significant difference in residence time between CO_2 (several decades to centuries) and CH_4 (about one decade). Instantaneous forcing equivalences (Hammond *et al.*, 1990) or similar "Greenhouse Indexes" as for instance used in the 1990 report of the World Resources Institute (WRI) remain highly controversial both in the scientific and policy communities (cf. Argawal and Narain, 1991; Redclift, 1992).

translate emissions to atmospheric concentration increases (for details see Grübler and Fujii, 1991). The methane equivalence factor used here can be compared to the global warming potential of CH_4 relative to CO_2 for a 100-year integration time horizon as presented in the 1990 IPCC report. This value can also be easily changed to any desired value within the Parametric Framework developed for this study.

About three quarters of the potential greenhouse effect from anthropogenic emissions over the 1860 to 1980 period and of current (1990) emissions over the next 100 years (*Table 2.1*) are accounted for by increasing concentrations of two greenhouse gases: carbon dioxide and methane. Considering the comparatively modest contribution of N_2O, which has been revised downwards by a factor of three by the IPCC (Bolin, 1991), and the above discussed possible overall zero-warming balance of increasing CFCs concentrations due to ozone feedbacks, carbon dioxide and methane remain the most dominant anthropogenic greenhouse gases. This is the reason why in the following sections we concentrate on current and historical CO_2 and CH_4 emissions.[3]

Most human activities cause CO_2 and CH_4 emissions and these vary widely in space and over time. Anthropogenic sources include the combustion of fossil fuels, deforestation and land-use changes, agriculture and a variety of industrial processes. Contributions to emissions by greenhouse gas, sector or region vary significantly and change over time. GHG emissions are influenced by differences in population size, climatic conditions, settlement patterns, levels of affluence, and structure of the economy. Furthermore, the type and extent of GHG emissions are frequently the result *inter alia* of: the degree of economic development (e.g., although deforestation is currently primarily a phenomenon in the tropics, it mirrors similar large-scale land transformations that took place in the northern hemisphere many decades to centuries ago); the historical development trajectories (as reflected for instance in differences between spatial and industrial structures even for comparable levels of per capita income); and the type and efficiency of practices and technologies applied both in agriculture, energy, and industry. These complexities have to be borne in mind, especially when comparing different GHG emissions between regions and over time, and in relating emissions to size of population or levels of economic activities.

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[3] An additional reason for not considering N_2O and CFCs emissions are the significant uncertainties in sources and levels of current emissions (N_2O), and in regionally disaggregated historical emission data series (or activity level data from which these could be inferred) for both N_2O and CFCs.

Finally, significant uncertainties in the emission estimates reported here also have to be mentioned. Only fossil fuel CO_2 emission estimates can be considered as quite accurate. For other sources of CO_2 (deforestation and land-use changes) uncertainties in global budgets, and even more so in regional/national estimates, are substantial (sometimes by up to a factor of five). Methane emissions by type of activity and by region are also uncertain. In general, emission estimates inevitably have to combine "hard" data based on detailed statistical sources, consistent data gathering methodologies, and a good understanding of the physical/chemical processes leading to emissions, with uncertain estimates, sometimes even zero-order approximations. For many GHG emission sources data on activities leading to emissions (e.g., activities outside industry or even outside the formal economy like subsistence farming) are lacking, observational records and their interpretation remain fragmented and controversial (like satellite surveys of tropical deforestation), or the linkage between human activities and GHG emissions is poorly understood scientifically (e.g., CH_4 emissions from rice production) and estimated emission factors based on a few observational records (or laboratory experiments) only. In the worst case (as for tropical deforestation) all three uncertainty factors are combined.

The objective of this paper is not to estimate new data sets on historical and present GHG emissions or to preempt the emergence of scientific consensus. Instead, existing data sets available in the public domain and assembled by the authors over the last few years were used primarily to elucidate the impacts and trade-offs inherent in different GHG allocation and emission reduction regimes. Thus, some of the data are inherently uncertain and are provided for illustrative purposes only. Despite the large uncertainties, the data set used in this paper and available in conjunction with the Parametric Framework is useful because it ensures comprehensiveness, consistency, and reflects scientific uncertainties. For example the data set fulfills the following criteria: 1) comprehensive coverage of both historical and current CO_2 and CH_4 emissions at a disaggregation level of 13 regions/countries; 2) global emission budgets consistent with the ranges emerging as scientific consensus, in particular within the IPCC; 3) where uncertainties of both sources and sinks of anthropogenic GHGs result in large ranges of emission estimates, rather conservative, lower range values are adopted. The latter assumption is based on the premise that high emission estimates, in particular from biotic CO_2 sources, are inconsistent with the current consensus of the size of the respective sinks and the measured atmospheric concentration increases. In other words, very large biota CO_2 emission estimates complicate the problem in that a "missing carbon sink" is required to accommodate the measured record of atmospheric CO_2 concentration increases, whereas lower biota emission estimates are within the range of current consensus on the order of magnitude of the global carbon sink.

The data sources and assumptions underlying the data base of historical and present anthropogenic CO_2 and CH_4 emissions are detailed in Appendix II. The data base includes (where appropriate) emissions of fossil fuel (coal, oil, and gas), other industrial CO_2 (cement manufacture, gas flaring), and biota CO_2 (deforestation and land-use changes) for 13 world regions over the period 1800 to 1988. Anthropogenic methane emissions were estimated for 13 world regions over the period 1950 to 1988 only, because of the short residence time of methane in the atmosphere of about 10 years. Thus, contrary to CO_2, pre-1950 CH_4 emissions do not contribute any longer to current atmospheric concentrations. In addition to GHG emission data, the data base includes historical and projected population data for 13 regions/countries for the period 1800 to 2100. Additional socio-economic data (size of region/country, GDP, and size of adult population) are included for consideration as additional variables in possible GHG allocation/reduction regimes and/or as further background information.

It was *not* the purpose of the present paper to elaborate a new GHG emission inventory. For that the scientific uncertainties in sources and sinks of GHG are still too large. Consequently, the following discussion of emissions by gas, source, and regional disaggregation have to be considered only as indicative and open to revisions with increasing scientific certainty and availability of better data, though this process is likely to take considerable time and research effort. The layout of the data base in the form of an easy to use *Lotus* spreadsheet format and the open architecture of the Parametric Framework used for the calculations presented below, was designed to facilitate the process of a critical discussion and revision of emission data, inclusion of alternative data series, and for performing sensitivity analysis. Critical discussion and permanent reevaluation of GHG emission data are and will continue to be a central issue in any possible climate stabilization regime and are in fact an integral part of the climate convention.

2.1 Carbon dioxide (CO_2)

After water vapor, carbon dioxide is the most abundant and the single most important anthropogenic greenhouse gas. Currently the atmosphere contains some 750 gigatons of carbon (Gt C)[4] corresponding to an atmospheric concentration of 353 ppmv (parts per million by volume). Emissions in the late 1980s are estimated to range between 5.8 to 8.7 Gt C (IPCC, 1990) annually, and the build-up of atmospheric concentration amounts to some 3.4 Gt C or 1.8 ppmv annually. This implies that the global carbon sinks (the oceans and the terrestrial biosphere) take up approximately between 40 to 60 percent of the emitted CO_2. Consequently, between 60 to 40 percent of the emissions remain as "airborne fraction" in the atmosphere resulting in the observed atmospheric CO_2 concentration increases. The most important sources of CO_2 emissions are the burning of fossil fuels and deforestation and land-use changes (the CO_2 releases are from the burning of forest biomass and the carbon releases occur when the soil carbon content is disturbed as a result of changing vegetation cover). Whereas industrial CO_2 emissions (mostly fossil fuels) are known fairly accurately (within perhaps 10 percent) to have amounted to some 5.7 Gt C in 1988, there is considerable uncertainty in the amount of gross and net releases of CO_2 from deforestation and changing land-use patterns (see discussion below).

Industrial Sources of CO_2 Emissions

Industrial sources of CO_2 emissions are dominated by the combustion of fossil fuels, the largest single source of GHG emissions. Worldwide, currently some 5.5 Gt C emissions result from the burning of fossil fuels (*Table 2.2*). Conversely, CO_2 emissions from cement manufacture and gas flaring combined are, with 0.2 Gt C emissions, comparatively small. Industrial CO_2 emissions are the best quantified of all GHG emissions as they can be derived from available detailed energy consumption statistics. Here we have adopted the emission data elaborated by Oak Ridge (Marland *et al.*, 1989) for the period since 1950 based on UN energy statistics. Yearly emission data by country from consumption of coal, oil and natural gas, from gas flaring and cement manufacture have been aggregated for the 13 regions used within the Parametric Framework. For years prior to 1950 earlier IIASA work[5] as

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[4] By convention, CO_2 emissions and concentrations are expressed as the mass of carbon contained in the gas only. To convert to total Gt CO_2 multiply by 3.66.

[5] Marchetti and Nakićenović, 1979; Nakićenović, 1984; Nakićenović, 1988; Grübler and Nakićenović, 1988; Ausubel *et al.*, 1988; Nakićenović *et al.*, 1990; Fujii, 1990.

Table 2.2. Industrial CO_2 emissions in 1988 (Gt carbon).

	"North" (regions 1–6)[a]	"South" (regions 7–13)[a]	World total Gt C	World total %
Fossil fuel combustion:				
Coal	1.61	0.79	2.41	42.3
Oil	1.59	0.56	2.15	38.0
Gas	0.78	0.14	0.91	16.1
Cement manufacture	0.08	0.07	0.14	2.5
Flaring of natural gas	0.01	0.04	0.05	0.9
Total	4.07	1.60	5.66	100.0

[a] See *Table 2.3* for breakdown of regions.
Source: Marland *et al.*, 1989.

well as additional historical statistics on the long-term evolution of energy consumption at the global and national level served as the basis for deriving historical industrial CO_2 emission estimates (cf. discussion in Appendix II). In addition to fossil fuel use, biomass energy like fuelwood, if not harvested on a sustainable basis, is also a net contributor to the CO_2 build-up in the atmosphere, however, its order of magnitude is much smaller than fossil fuels. Estimates indicate (gross) emissions of some 0.4 Gt C from fuelwood burning in the 1980s (Houghton, 1989). Releases from unsustainable fuelwood harvesting are obviously much smaller than the total 0.4 Gt C and are included in the biota sources of CO_2 emissions discussed below.

The largest fossil fuel contributor is coal accounting for some 44 percent of fossil fuel CO_2 emissions. Although coal only accounts for 31 percent of the global fossil energy consumption (and 27 percent in total commercial energy consumption), its share in CO_2 emissions is much larger due to its higher carbon to hydrogen ratio. For delivering 7 million kcal energy (equivalent to one ton coal equivalent, or *tce*)[6], combustion of coal releases 680 kg of carbon, compared to some 560 kg to deliver the same amount of primary energy by crude oil. Natural gas (mostly methane) has the lowest carbon emissions per unit energy (some 410 kg C per tce, or only 60 percent of coal emissions), indicating the significant potential of interfuel substitution in carbon emission reduction strategies (cf. Ausubel *et al.*, 1988).

The structure of the fuel mix (including also zero-carbon energy forms like hydroelectricity and nuclear energy) explains part of the differences in energy related CO_2 emissions. However, even more important are differences

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[6] Higher heating value (HHV).

in population size, the degree of economic development, levels of affluence and consumption, and structure of economic activities. These factors *inter alia* explain the large differences in industrial CO_2 emissions between regions and countries and in their specific emission values and intensities (*Table 2.3*). Disparities in industrial CO_2 emissions are most extreme between North and South. Twenty percent of the world's population emit almost 80 percent of global industrial CO_2 emissions in producing (and consuming) about the same percentage of the global economic output.[7] This disparity becomes even more accentuated when fossil fuel combustion is considered (see below).

Thus, levels, structure, and etiology of emissions vary greatly between countries and regions. An additional complexity is also the extreme heterogeneity within and among regions with a similar degree of economic and industrial development. This is illustrated in *Figure 2.1*, showing energy related carbon emissions (by source) per capita for a number of countries/regions. For comparison, other anthropogenic sources of CO_2 and methane emissions are also shown on a per capita basis. The height of each bar is proportional to the respective per capita emissions, and the width proportional to the size of the respective population. Thus, the area of each bar indicates the relative magnitude of the absolute emissions in each region. *Figure 2.1* also shows the geographical definition of the 13 world regions chosen for this study.

On average, industrial CO_2 emissions per capita range between 3.4 tons C per capita in developed countries and 0.4 tons C per capita in developing countries, i.e., by a factor of eight. At the level of individual countries and regions the differences are even larger: per capita emissions vary by over a factor of 25 between the regions with the highest (North America) and the lowest values (India and Asia outside China). Taking absolute emissions or emissions per GDP as an indicator, significant regional and national differences persist (cf. *Table 2.3*). Even where per capita emissions are similar, they are often so for entirely different reasons: both the USA and the former GDR have per capita emissions in excess of 5 tons carbon per year. In the case of the USA this is due to a large economy with high energy consumption and energy-intensive lifestyles, e.g., a high level of oil consumption for private transportation. In the former GDR it is due to a different level and structure of the economy and its energy supply system, stressing the

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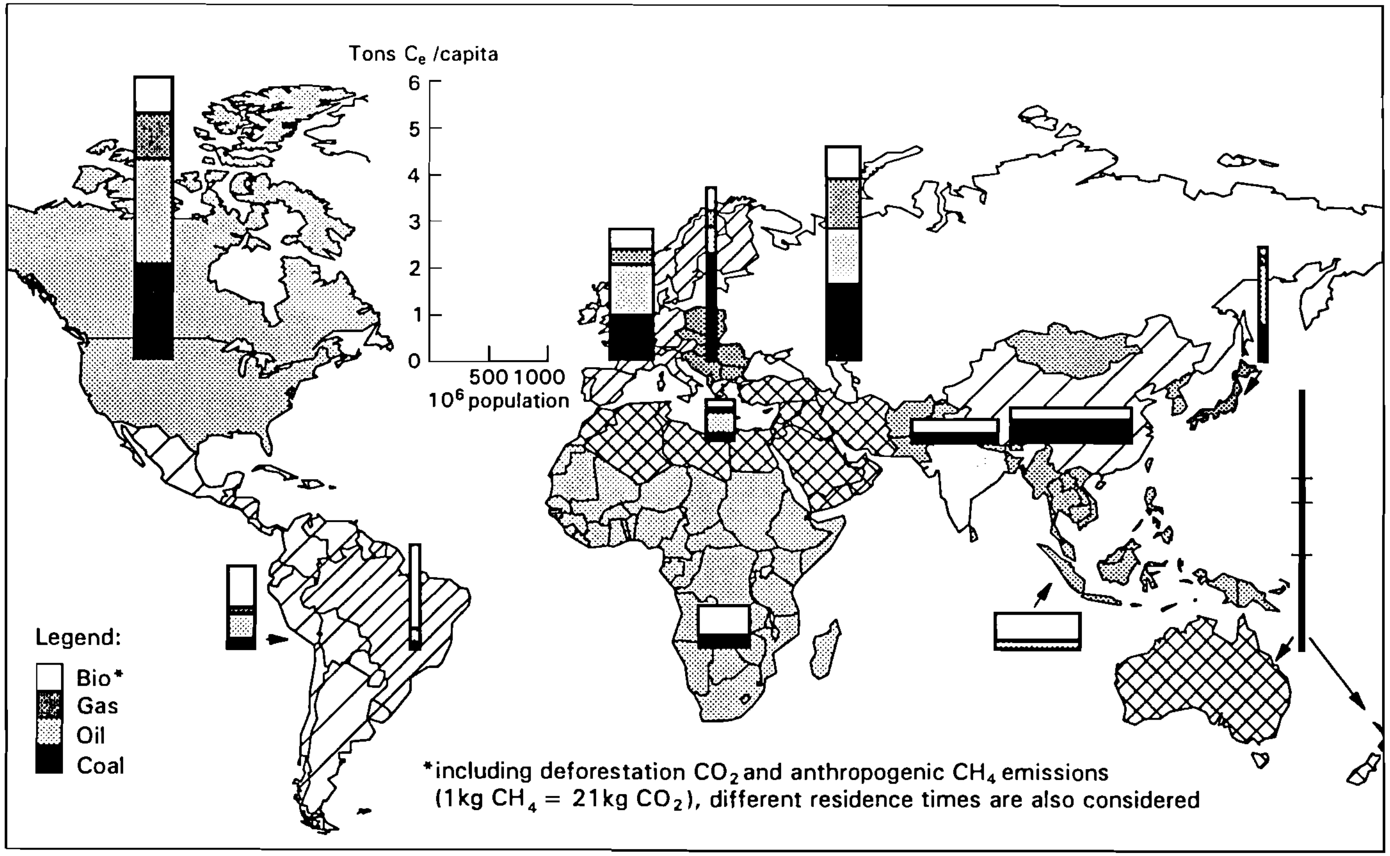
[7] Using GDP based on market exchange rates as an indicator. Based on GDP compared to purchasing power parities (PPP), developed countries still consume about two thirds (64 percent) of economic output globally.

Table 2.3. 1988 industrial CO_2 emissions: comparison of absolute and relative values (gigatons and tons carbon).

		1988 emissions	Per land area	Per capita population		Per unit GDP (1988 $)	
				Total	Adult	mexr[b]	PPP
		Gt C	t C/km^2	t C/cap	t C/cap	t C/1000$	t C/1000$
1	OECD NA	1.43	74	5.28	6.80	0.27	0.30
2	OECD EU	0.85	197	2.22	2.88	0.15	0.18
3	Eastern EU	0.36	396	3.17	3.94	1.48	0.65
4	USSR	1.09	49	3.83	5.21	1.86	0.64
5	Japan	0.27	714	2.20	2.85	0.09	0.17
6	Oceania	0.07	9	3.69	5.03	0.27	0.31
7	China	0.61	64	0.56	0.83	1.83	0.26
8	India	0.17	52	0.21	0.37	0.64	0.20
9	Other Asia	0.16	20	0.21	0.36	0.22	0.10
10	NAME[a]	0.24	19	0.73	1.48	0.45	0.33
11	Other Africa	0.12	5	0.25	0.49	0.51	0.27
12	Brazil	0.06	7	0.41	0.69	0.17	0.10
13	Other LatAm	0.24	20	0.84	1.47	0.44	0.23
	"North" (1–6)	4.07	74	3.41	4.45	0.27	0.30
	"South" (7–13)	1.60	20	0.41	0.70	0.54	0.21
	World	5.66	42	1.11	1.77	0.32	0.27
	Factor difference smallest–highest	23.8	146	25.1	18.9	20.7	6.5

[a] North Africa and Middle East.

[b] Market exchange rates.



*including deforestation CO_2 and anthropogenic CH_4 emissions (1kg CH_4 = 21kg CO_2), different residence times are also considered

Figure 2.1. GHG emissions versus population for 13 world regions (in tons C-equivalent per capita and million population).

energy-intensive basic material production sector and a high share of brown coal in the energy supply mix. Per capita emissions can also differ significantly for similar levels of affluence and degree of economic development. For instance, Switzerland and the USA both have per capita GDP in excess of 20,000 US$(1988), whereas their per capita carbon emissions from fossil fuel use differ by nearly a factor of three (1.8 compared to over 5 tons carbon per capita for Switzerland and the USA respectively).

Since the onset of the Industrial Revolution some 200 Gt C have been emitted by industrial activities. The value adopted here is in good agreement with the estimates of the IPCC of some 195 Gt C over the period 1850 to 1986.[8] This is much larger than the estimated carbon release by deforestation and land-use changes over the same time period of some 117 (±35) Gt C (IPCC, 1990). From all fossil fuels, the contribution of coal to atmospheric concentration increases is the highest at 57 percent. Oil and natural gas follow with 30 and 20 percent respectively, the contribution from cement manufacture and flaring of natural gas are at a modest 3 percent.[9]

The significant "North–South" divide identified above in current industrial carbon emissions becomes even larger when considering their historical dimension: our estimates indicate that about 84 percent of the industrial CO_2 emissions since 1800 still remaining in the atmosphere can be attributed to the emissions of industrialized countries. Conversely, the share of developing countries in energy related atmospheric CO_2 build-up is, with 16 percent, very low, especially in view of the fact that about 70 percent of the people that have lived on Earth since 1800 reside(d) in the South.

The upper part of *Figure 2.2* summarizes the regional breakdown of industrial CO_2 emissions for 1988, and the lower shows the contribution of each region to atmospheric concentration increases over the period 1800–1988. The differences in recent and historical shares of the "global warming pie" between regions illustrate the implications of considering the actions of past generations in addition to the responsibilities to be assumed by present and future generations in climate change mitigation and adaptation efforts.

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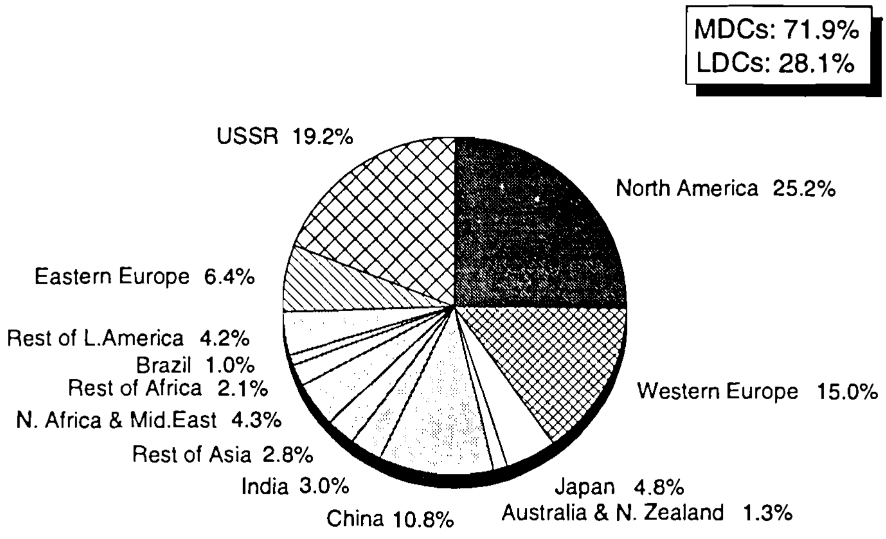
[8] Note that the 200 Gt C of the Parametric Framework refers to the period 1800 to 1988.

[9] At the regional or national level however, natural gas flaring is an historically important source of carbon emissions. For instance, flaring of natural gas in North Africa and the Middle East may have contributed as much as one quarter of the cumulative industrial carbon emissions of that region. Flaring (i.e., wastage) of natural gas may have contributed twice as much carbon emissions than the energy consumption of natural gas in the same region.



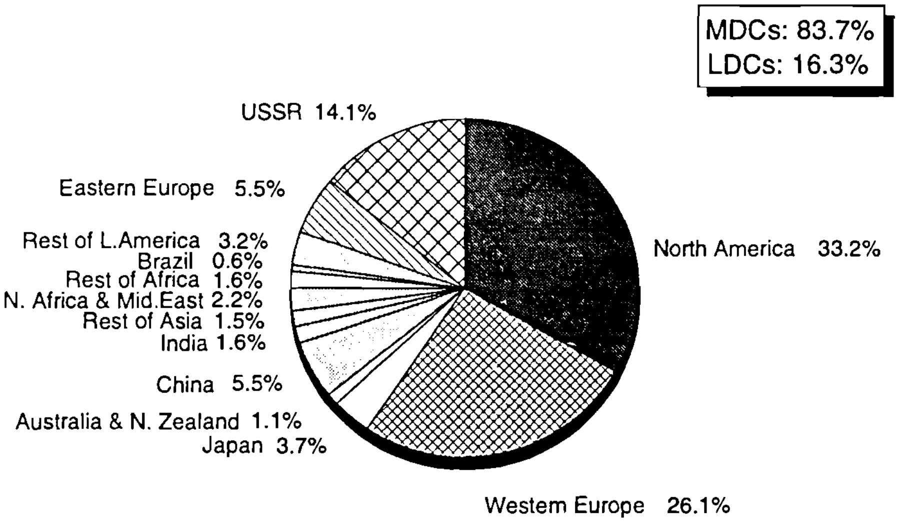


Figure 2.2. Shares (in percent) of different regions in 1988 emissions (top) and in contribution to historical concentration increases over the period 1800 to 1988 (bottom) of industrial sources of CO_2.

Biota Sources of CO_2 Emissions

Changes in the carbon balance of terrestrial vegetation and soils induced by human activities (land-use changes, in particular deforestation) are an additional significant source of CO_2 emissions. Since the pools and natural carbon fluxes in vegetation are large it is difficult to estimate the exact order of magnitude of human impacts. The total amount of carbon stored in vegetation and soil amounts to some 2000 Gt C (600 Gt in vegetative mass and 1400 Gt C in soils), and net annual uptake (gross CO_2 uptake from the atmosphere minus CO_2 respiration by plants) amounts to 50–60 Gt C annually, i.e., 10 times the industrial CO_2 emissions (IPCC, 1990). Changes in land-use patterns and vegetation cover are important because of the large differences in the carbon sequestered by different vegetation systems. The vegetation and soils of undisturbed forests can hold 20 to 100 times more carbon (per ha) than agricultural systems. Consequently, land-use changes can release significant biotic carbon sources to the atmosphere.

Biota carbon emissions stem from the following: 1) burning of biomass associated with land-use changes, e.g., traditional slush and burn agriculture; 2) organic decay of (remaining) biomass, especially after forest clearings; and 3) oxidation of soil carbon in conjunction with changing vegetation cover. Finally, oxidation of wood products (e.g., paper) from forests add additional carbon fluxes, whereas the regrowth of trees removes carbon from the atmosphere. Large uncertainties pertaining to biotic carbon fluxes are a result of: 1) the difficulty in estimating the extent (area) of land-use changes (uncertainty ranges can be larger than ±50 percent), in particular from deforestation where problems arise in satellite monitoring and data interpretation, and uncertainties about the secondary use of deforested areas (forests, grasslands or agriculture); 2) ranges in estimates of the carbon content of biomass and especially for soils of disturbed areas (uncertainty ranges of approximately a factor of two); and 3) uncertainty about the response profile of terrestrial carbon pools to changes in land use. For instance, only 50–60 percent of the annual biotic carbon flux in the early 1980s are calculated to have originated from deforestation taking place in that period, with the remainder consisting of vegetation decay, and soil carbon releases from deforestation of previous years. The combination of all these elements results in an uncertainty range of biotic carbon sources of up to a factor of four. The data uncertainty range becomes even more compounded when one considers that different estimates relying on the same models and the same sources of data for deforestation and carbon stocks yield very different results, and the reasons for such differences are unclear (Houghton, 1991).

For the early 1980s the net carbon flux (deforestation minus afforestation) is estimated by the IPCC to range from 0.6 to 2.6 Gt C, i.e., between 10 to 45 percent of industrial CO_2 sources. Current scientific consensus assumes the same range for the remainder of the 1980s, although preliminary assessments indicate that deforestation rates have accelerated in some regions (FAO, 1991). In this context, one should also note that deforestation rates can vary between individual years even in regions that have been intensively studied like Brazil and have the highest biota carbon fluxes. For instance, estimates on the rate of deforestation in Brazil in 1987 vary from five (Meyers, 1989) to eight (WRI, 1990) million ha. Brazilian studies using satellite data indicate a deforestation rate of three million ha for the same year (IPCC, 1992). More recent results suggest that the rate is likely to have fallen even further to some two million ha in 1989 and 1.4 million ha in 1990 (IPCC, 1992). Therefore it could be quite misleading to infer deforestation rates over extended time periods from point estimates of individual years.

In view of the substantial uncertainties involved, a conservative approach for estimating biota carbon fluxes was adopted for this report. The reason for adopting a lower range of figures for biota CO_2 emissions is primarily related to the fact that until now additional sinks (outside the oceans) could not be identified that would enable a linkage to be made between estimated high emission data with the capacity of known carbon sinks and the observational atmospheric concentration records. Although some estimates indicate additional carbon uptake by vegetation due to nitrogen and CO_2 fertilization effects (perhaps of some 1 Gt C per year), these effects are still subject to scientific debate and are not quantified, especially at a regional level. The existence of large terrestrial carbon sinks would also tremendously complicate the problem of national carbon accounting due to the sheer insurmountable measurement problems. For instance (yet unproven) estimates indicate that, as a result of CO_2 fertilization, tropical forests could sequester a similar amount of CO_2 to tropical deforestation release.

There are many estimates of very high net carbon fluxes resulting from deforestation (e.g., Meyers, 1989; WRI, 1990), some being as high as 3.4 Gt C by the end of the 1980s. However, it has to be emphasized that such high estimates have, to date, not found sufficient scientific consensus to be considered here.[10] Instead, a more conservative approach is adopted, focusing on lower range estimates of carbon release due to land-use changes. The values adopted (cf. *Table 2.4*) should not be interpreted as necessarily "realistic" estimates of deforestation carbon releases, but rather as conservative values used in the absence of broader scientific consensus.[11] The resulting regional estimates systematically tend to be on the lower range of the figures reported in *Table 2.4* (particularly for India and Brazil). Due to the substantial uncertainties related to estimates of net carbon sequestering rates in forests of the northern hemisphere a (conservative) convention was adopted to assume net biotic carbon fluxes to be zero in those cases where no indication of net deforestation rates were supported by national and international surveys. Carbon uptake due to nitrogen and CO_2 fertilization effects is also *not* considered here.

With some 0.8 Gt C annually, the resulting estimated net biota CO_2 flux is at the low end of current scientific consensus within the IPCC process (IPCC, 1992; Houghton, 1991). However, the open architecture adopted for data representation within the Parametric Framework ensures flexibility for incorporation of alternative data sets and for sensitivity analysis. *Table 2.4* gives the regional breakdown of the estimates of current biota carbon emissions adopted here and contrasts these estimates with the upper and lower boundary extremes assembled from various literature sources for the beginning and end of the 1980s.

It is generally agreeed that current biota carbon releases from the northern hemisphere are quite small, if not negative. The range of estimates also indicate that biotic carbon releases or uptakes are small in comparison with industrial CO_2 sources (maximum 10 percent). Therefore, the uncertainty in the underlying data and the fact that we do not take into consideration biotic carbon sinks will not significantly influence the situation of these regions *vis à vis* the remainder of the world due to their high levels of industrial CO_2 emissions in both absolute and per capita terms.

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[10] There is wide consensus however, on the need of more in-depth and detailed studies of deforestation rates and of the carbon characteristics of life vegetation and especially of soils.

[11] Particularly for Africa and Latin America, higher values would have to be adopted (perhaps twice the values given in *Table 2.4*) to fall within the range given by a majority of literature sources. However, consensus among (a limited number of) experts does not necessarily imply more accurate data.

Table 2.4. Estimates of biota carbon fluxes in the early and late 1980s, 10^6 t C per year (rounded figures). Negative values indicate net carbon uptake by terrestrial biota.

		Late 1980s (1985–1987)		Per capita emissions (late 1980s)		
	Late 1970s early 1980s 10^6 t C	Range 10^6 t C	(Values adopted here)	Biota t C/capita	(Values adopted here)	Industrial t C/capita
Temperate zones:						
North America	+25[a] – +38[b]	−139[c] – +6[d]	(0)	−0.51 – +0.02	(0)	5.28
Europe (West and East)	−28[a] – 0[b]	−62[c] – 0[d]	(0)	−0.13 – 0	(0)	2.44
USSR	+35[a] – +100[b]	−140[c] – 0[d]	(0)	−0.49 – 0	(0)	3.83
Oceania	+28[a] – +80[b]	−3[c] – 0[d]	(0)	−0.17 – 0	(0)	3.69
China	+69[a] – +105[b]	−106[c] – 0[d]	(0)	−0.10 – 0	(0)	0.56
Tropical zones:						
India	+9[e] – +80[g]	+5[h] – +150[c]	(5)	+0.01 – +0.18	(+0.01)	0.21
Other Asia	+190[e] – +1058[g]	+300[l] – +730[d]	(320)	+0.39 – +0.95	(+0.41)	0.21
Africa	+200[e] – +753[g]	+170[j] – +390[d]	(170)	+0.35 – +0.82	(+0.35)	0.25
Brazil	+175[e] – +805[g]	+140[k] – +800[d]	(160)	+0.97 – +5.55	(+1.11)	0.41
Other LatAm	+176[e] – +458[g]	+130[m] – +330[d]	(140)	+0.46 – +1.17	(+0.50)	0.84
World	+600[e] – +2600[f]	+800[n] – +2800[d]	(800)	+0.16 – +0.55	(+0.16)	1.11

Emissions in Japan, North Africa, and Middle East are negligible.

[a] Houghton *et al.*, 1987.

[b] Houghton and Skole, 1990.

[c] Subak *et al.*, 1991.

[d] WRI, 1990.

[e] IPCC (Response Strategies), 1991, low estimate.

[f] IPCC (Response Strategies), 1991, high estimate.

[g] OECD, 1991.

[h] Pachauri, 1991.

[i] Meyers, 1989.

[j] US AID, 1990, pp. 3–9.

[k] Alves, 1991.

[l] Houghton, 1991.

[m] Assuming same uncertainty range as in 1980.

[n] IPCC (Response Strategies), 1991, only closed forests.

Deforestation and land-use changes are currently concentrated in tropical latitudes, but the corresponding net carbon release figures are affected by considerable uncertainties and debates in scientific and policy circles. The range of estimates is large and has not narrowed down compared to the figures estimated for the beginning of the 1980s. The uncertainties relate not only to the difficulty of estimating deforestation rates, but also to the paucity in reliable and detailed field measurements for the carbon content of biomass in tropical latitudes and especially for the carbon release of disturbed tropical soils. The uncertainties in the latter are even large enough to accommodate the highest estimates of rates of deforestation with the lower range values given in *Table 2.4*, with low assumptions for biomass and soil carbon content and release rates.

The policy relevance of these data uncertainties are obvious: high biota carbon emission estimates would increase the CO_2 emissions from most developing countries by between a factor of two to four. In the extreme case of Brazil, the highest deforestation estimates would imply an increase of energy and industrial CO_2 emissions by a factor of ten.[12] In such a case the total per capita carbon emissions of Brazil would surpass even the highest per capita emission values of industrialized countries.

The data uncertainties with regard to historical biota carbon emissions are somewhat smaller than for current emissions due to a good knowledge of historical energy- and industry-related CO_2 emissions and measurements of atmospheric concentration increases. The IPCC (1990) estimates for historical biota carbon releases indicate cumulative emissions of some 115 (±35) Gt C over the 1850 to 1985 time horizon. This is in good agreement with the values adopted here for calculations with the Parametric Framework (of 120 Gt C over the same period, and 144 Gt C over the entire period covered by the Parametric Framework, i.e., 1800–1988). Compared to the current regional imbalances in biota carbon emissions, the estimated historical record appears more evenly distributed: perhaps 55 percent of historical biota carbon releases originate from the tropics, and some 45 percent from the temperate latitudes where significant land-use changes and deforestation (particularly in North America, Russia, and Oceania, cf. Richards, 1990) took place in the 19th century.

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[12] *Table 2.4* excludes the preliminary (and subsequently revised) WRI estimate for Brazil of 1200 million tons C in 1987, which would imply biota emissions of 8.3 tons C per capita.

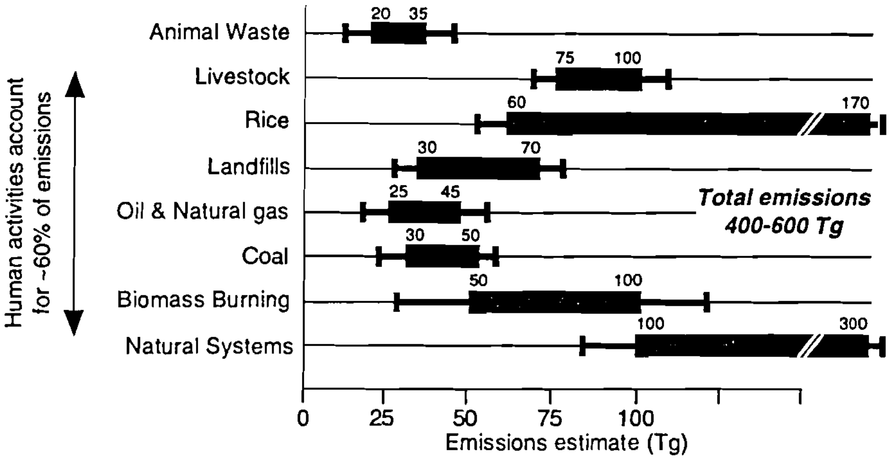

Figure 2.3. Range of estimates of methane sources (in teragrams). Source: Hogan *et al.*, 1991.

2.2 Anthropogenic methane emissions

After water vapor and carbon dioxide, methane is the next important atmospheric gas contributing to the greenhouse effect. Currently the atmosphere contains some 4900 teragrams of methane (Tg of CH_4) corresponding to an atmospheric concentration of 1720 ppbv (parts per billion by volume). Methane concentrations are rising at about one percent per year (equivalent to about 40 to 50 Tg or 14 to 17 ppbv per year). Recent measurements however, indicate that the rate of increase in atmospheric concentrations has slowed down (Steele *et al.*, 1992). It is estimated that a reduction by about 40 to 50 Tg (15 to 20 percent of annual emissions) would halt the rise in atmospheric concentrations, assuming that methane destruction in the atmosphere by OH radicals would remain at present rates, IPCC (1990).

Large uncertainty ranges surround most sources and sinks of methane so that the exact levels of global methane releases are unknown. It is estimated that the natural sources of methane emissions fall within the range of 100 to 300 Tg while anthropogenic sources are estimated to be between 290 to 460 Tg annually. Thus, 60 to 70 percent of all global methane emissions are associated with human activities. *Figure 2.3* illustrates the uncertainty ranges and the relative magnitudes of different anthropogenic (and total natural) sources of methane emissions (Hogan *et al.*, 1991). These ranges are in good agreement with those given by the IPCC (1990 and 1992) and

Table 2.5. Estimated anthropogenic sources of methane. Emissions in 1988, in Tg of CH_4.

	"North" (regions 1–6)	"South" (regions 7–13)	World total	
			Tg	%
Livestock and animal waste	43	62	105	35
Fossil energy use	45	35	80	27
Rice paddies	3	60	63	21
Landfills	24	12	36	12
Biomass burning[a]	1	14	15	5
Total	116	183	299	100

[a] Low end range estimate.

are to be contrasted with the total global methane sink of between 400 to 600 Tg per year, resulting in a net annual atmospheric concentration increase of 40 to 50 Tg.

Numerous anthropogenic activities result in methane emissions, which in addition show wide variations in time and space. Furthermore most sources are dispersed and occur outside the industry sector, which implies difficulties in collecting regular, reliable statistical sources and usually means the absence of direct field measurements. For the purposes of this report it was, however, necessary to choose actual point estimates despite the inherently large uncertainties. In general, we have assumed conservative values given by the ranges in *Figure 2.3* for our data set. *Table 2.5* illustrates our assumptions for five main anthropogenic sources of methane emissions disaggregated into those arising in more developed regions (1 to 6, labeled as "North") and those in developing regions (7 to 13, labeled as "South").

While fossil energy consumption is associated with the largest single category of emissions in the North, livestock and animal waste and rice paddies are the largest two sources of methane emissions in the developing regions. Another difference along the "North–South" divide is that most of the landfill emissions occur in the more developed regions while biomass burning occurs mostly in the developing areas. Based on these point estimates we have subsequently reconstructed the regional historical emissions for the period 1950 to 1988 based on activity variables (like regional rice production, size of livestock or fossil fuel production statistics) since direct observations (emission measurements) are not available. Longer time series were not required due to the limited residence time of methane in the atmosphere of about ten years. The atmospheric residence time can be changed to another value by the use of the Parametric Framework. The time series of methane emissions in the data set of the Parametric Framework give annual releases of anthropogenic sources for the 13 world regions. They were aggregated from individual estimates of five different anthropogenic methane sources (cf. *Table 2.5*) included in the Parametric Framework only as the aggregate sum.

The first and largest source given in *Table 2.5* is associated with agricultural livestock and their wastes. About three-quarters are believed to be caused by enteric fermentation in ruminant animals, including all cattle, sheep, etc., and the rest by the decomposition of animal waste. Our estimate of global emissions from all domestic animals (cf. Appendix II) is about 105 Tg of methane, and thus in the middle of the ranges given in the literature. Emissions depend on the animal populations as well as on the size of the individual animals, the amount, and type of food. Our estimates are based on the domestic animal population sizes in the 13 world regions. According to this method the emissions have increased almost twofold since 1950.

The next largest category of methane emissions is due to the production, transport, and distribution of fossil energy with the main sources being coal mining and oil and gas production. Most of the methane released from coal production is due to underground coal mining (ventilation of methane present in the coal seams and in the surrounding rock strata). Methane leakage from pipelines and distribution grids, and venting and leakage from oil and gas production wells are also important. Our estimates of fossil fuel related methane emissions again fall in the mid-range presented in *Figure 2.3*, and are a result of differing certainty in the underlying time series. While the production of fossil energy sources is known with a high degree of precision, the actual methane emission factors are only indicative. For example, natural gas leakages from pipelines and distribution networks are believed to range from less than half a percent in some industrialized countries to more than six percent for the Soviet Union.[13] Thus, the overall fossil energy methane emissions are not well known. However, they do represent the single fastest growing category of anthropogenic emissions with a more than fourfold increase since 1950.

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[13] However, given the large throughput through the gas pipeline grid of the USSR, such high leakage figures would imply frequent methane explosions. To date however, no such leakage explosions have been reported. The only major recent pipeline accident was due to leakage of liquefied petroleum gas (LPG) and not natural gas (methane).

Rice paddies are another rapidly growing source of methane emissions. They depend on a number of factors that vary regionally and annually including fertilization, water and crop management, growing period, and paddy field characteristics among others. The majority of emissions occur under wet rice cultivations that represent almost 85 percent of the world-wide cultivation area. Our estimates of present and historical emissions are based on rice production data for the 13 world regions. The resulting emissions are in the mid-range given in the literature (e.g., IPCC, 1990; Hogan *et al.*, 1991). However, the uncertainty associated with the range and its span, is the largest of all anthropogenic sources of methane, and extend from less than 50 to 170 Tg. The difficulty is that almost 90 percent of the cultivated area is in Asia and 60 percent of that in China and India where no detailed data are available, so that at best only rough estimates can be made (IPCC, 1990). Estimates indicate that the emissions increased from about 70 Tg in the 1950s to almost 100 Tg by the early 1980s and have decreased by almost 40 percent during the last decade. Another reversal is however likely with further population growth and an increased demand for rice. To some extent this could be offset by better cultivation methods that lead to lower specific emissions. Altogether, rice production has doubled since the 1940s and it can be expected that the methane emissions have increased proportionately.

In contrast to methane emissions from rice cultivation, most of the emissions from landfills originate in the more developed regions which hold a two-thirds share of the global total. These emissions are caused by the anaerobic decay of organic wastes in landfills and are a function of municipal waste generation and disposal practices, landfilling rates, types of waste material and their average hydrocarbon content, and conversion and outgasing rates of methane. Another important determinant is whether the deposition sites are equipped with effective liners and other measures to reduce emissions of methane and other air toxic gases. However, in many industrialized countries methane recovery from landfills is becoming an additional source of energy supply, resulting in reduced CH_4 emissions to the atmosphere. Due to the difficulties in estimating the relative magnitudes of these determining factors, landfill methane sources have the third largest uncertainty range of between 20 to 70 Tg (IPCC, 1990, see also *Figure 2.3*) after rice paddies and biomass burning. Our estimates are exactly in the middle of the range given in the literature.

The extent of land clearing and biomass burning worldwide is not very well understood. Major uncertainties include the amount of biomass burnt each year in different regions by type of vegetation, fraction of wood or biomass removed and used for other purposes from the cleared areas, the kind of burning, etc. Deforestation by itself is an important but probably smaller source of methane compared to other anthropogenic sources such as agricultural activities (e.g., rice production and agricultural wastes). Despite the broad range of estimates given in the literature, one thing is clear, namely, that the emissions from deforestation and biomass burning have increased substantially since the beginning of the Industrial Revolution and probably even since the beginning of land cultivation. The ratio between the largest and lowest estimates in the literature is greater than five and thereby exceeds those of all other anthropogenic methane sources. Currently the largest source of biomass burning that results in methane emissions is believed to be caused by deforestation in tropical and sub-tropical regions of the southern hemisphere. Our estimates reflect this with 90 percent of the emissions originating from the developing regions of the South. The relative magnitude of our estimates is, however, in the lower range with about 30 Tg. This is also consistent with our conservative low estimate of CO_2 emissions from biomass burning because both time series are based on the same estimates of worldwide deforestation.

In summarizing the above discussion on methane emissions, it must again be emphasized how much larger the uncertainties associated with such estimates are, especially when compared to fossil fuel emissions. It is also important to recognize that methane emissions are extremely non-homogeneous, including both industrial, agricultural, and biotic emission sources. Industrial emissions (from fossil fuel production and landfills in industrialized countries) are in principle controllable by appropriate technologies and economic policy instruments. In contrast, agricultural and biotic methane sources are extremely dispersed, frequently occurring outside the formal economy (like subsistence rice farming), and are associated with particularly large uncertainties regarding specific emission factors per unit of anthropogenic activity. Consequently, we suggest that in future studies these two methane emission categories be treated separately.[14]

2.3 CO_2 and CH_4

After discussing individual GHG emissions by gas and category we aggregate all data to estimate the cumulative historical and current annual total emissions of those GHGs which are the largest contributors to potential climate

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[14] This would however require further detailed analysis of sources and ranges of uncertainties in emission estimates published.

change. For this purpose a methane equivalent factor of 21 (on mass basis) compared to CO_2 is used.

Table 2.6 (cf. *Table 2.3* above for industrial CO_2 emissions) presents regionalized total GHG emissions per unit land area, population, and unit of economic output. Compared to the case when only industrial CO_2 sources are considered, the regional disparities are somewhat reduced, especially from a "North–South" perspective. However, regional disparities still remain extremely large. For instance, per capita differences in GHG emissions between regions still differ by a factor of 12, and per unit of GDP (based on purchasing power parities) by a factor of five.

The inclusion of biota carbon and methane emissions significantly affects the relative position of all developing countries with the exception of region 10 (North Africa and Middle East) *vis à vis* the "North". However, the impact is far from uniform among developing, or even among developed countries. Four groups of countries can be distinguished. In the first one, the inclusion of biota and methane emissions increases regional GHG emissions by 20 percent over industrial CO_2 emissions only. This situation applies to all regions of the "North" with the exception of region 6 (Oceania). In the second group of countries/regions, total GHG emissions are about 50 percent higher, i.e. in regions 6 and 7 (Oceania and China), whereas in regions 8 and 13 (India and Rest of Latin America) total GHG emissions are between 150 percent and 250 percent higher due to either extensive deforestation or high agricultural methane emissions. Regions 9 and 11 (Other Asia and Other Africa) have total GHG emissions of around 350 percent over their industrial CO_2 releases. The largest shift occurs in Brazil, where total GHGs are higher by a factor of five than industrial CO_2 emissions alone. Consequently, all specific emission factors deteriorate when one moves from industrial CO_2 to total CO_2 and CH_4 emissions. The required reductions under various allocation scenarios will also generally be higher with increasing GHG equivalent-carbon emissions, if biota and agricultural emission sources are included in addition to energy and industry.

Figure 2.4 (cf. *Figure 2.2* above for energy and industrial CO_2 emissions) summarizes the regional breakdown of greenhouse gas emissions (anthropogenic CO_2 and CH_4). The top of *Figure 2.4* gives 1988 emissions, and the bottom shows the contribution of each region to atmospheric concentration increases. Compared to *Figure 2.2*, the "North–South" divide for current emissions, and especially for contributions to atmospheric concentration increases, is somewhat smaller but still pronounced. Since the onset of the Industrial Revolution industrialized countries account for 58 percent

Table 2.6. 1988 GHG ($CO_2 + CH_4$, all anthropogenic sources): comparison of absolute and relative values (gigatons and tons carbon equivalent).

		1988 emissions	Per land area	Per capita population		Per unit GDP (1988 $)	
				Total	Adult	mexr[b]	PPP
		Gt C_e	t C_e/km^2	t C_e/cap	t C_e/cap	t C_e/1000$	t C_e/1000$
1	OECD NA	1.64	85	6.06	7.81	0.31	0.34
2	OECD EU	1.00	232	2.62	3.39	0.18	0.21
3	Eastern EU	0.42	457	3.65	4.55	1.70	0.75
4	USSR	1.28	56	4.50	6.12	2.19	0.75
5	Japan	0.29	768	2.37	3.07	0.10	0.18
6	Oceania	0.11	13	5.58	7.61	0.41	0.48
7	China	0.92	95	0.85	1.25	2.76	0.39
8	India	0.41	125	0.51	0.89	1.54	0.49
9	Other Asia	0.58	71	0.75	1.33	0.81	0.37
10	NAME[a]	0.30	23	0.90	1.81	0.55	0.40
11	Other Africa	0.42	16	0.87	1.68	1.76	0.94
12	Brazil	0.30	35	2.09	3.50	0.85	0.48
13	Other LatAm	0.47	39	1.69	2.94	0.88	0.45
	"North" (1–6)	4.73	86	3.97	5.18	0.32	0.35
	"South" (7–13)	3.39	43	0.87	1.58	1.14	0.45
	World	8.12	61	1.60	2.54	0.45	0.39
	Factor difference smallest–highest	5.7	59	11.9	8.8	27.6	5.2

[a] North Africa and Middle East.

[b] Market exchange rates.

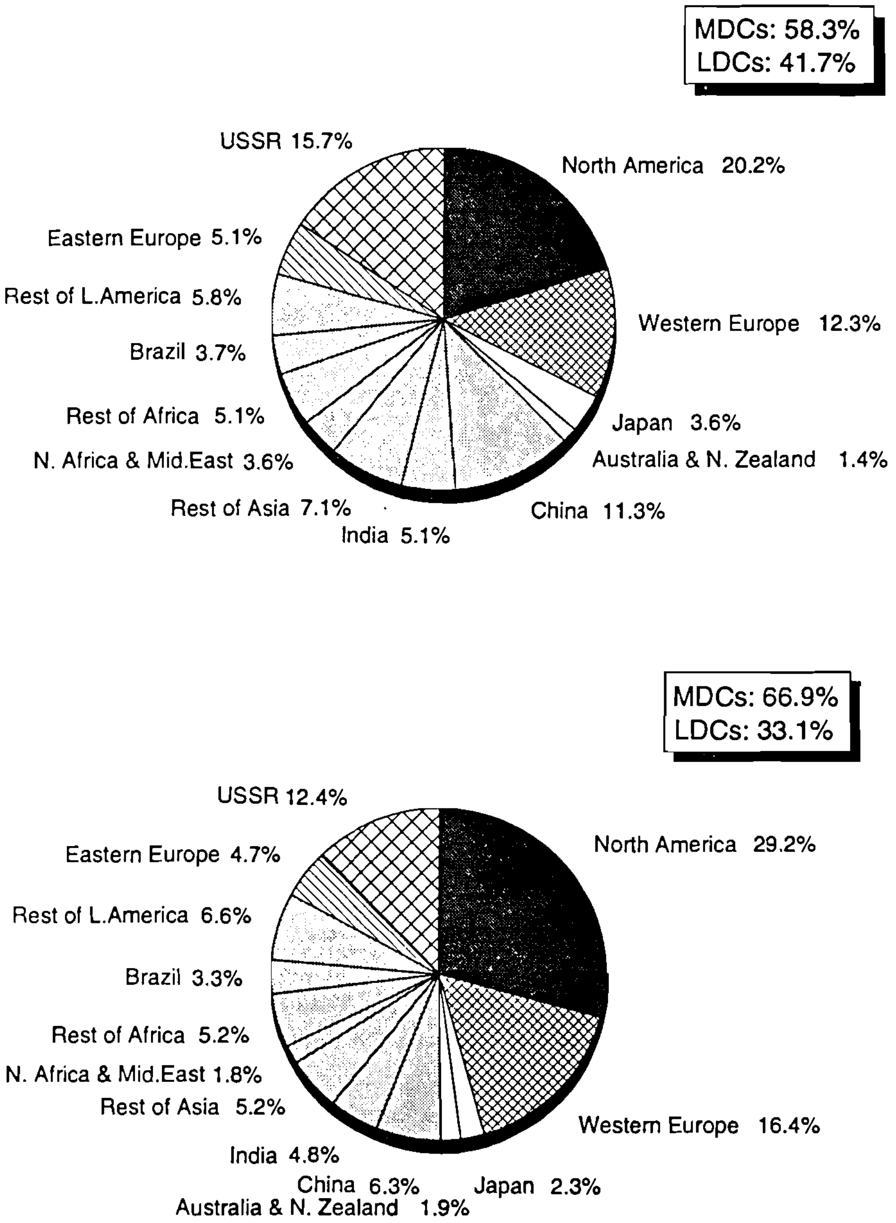

Figure 2.4. Shares (in percent) of different regions in GHG (CO_2 and CH_4) emissions in 1988 (top), and in the contribution to historical (bottom) concentration increases (1800 to 1988 for CO_2, and 1950 to 1988 for CH_4).

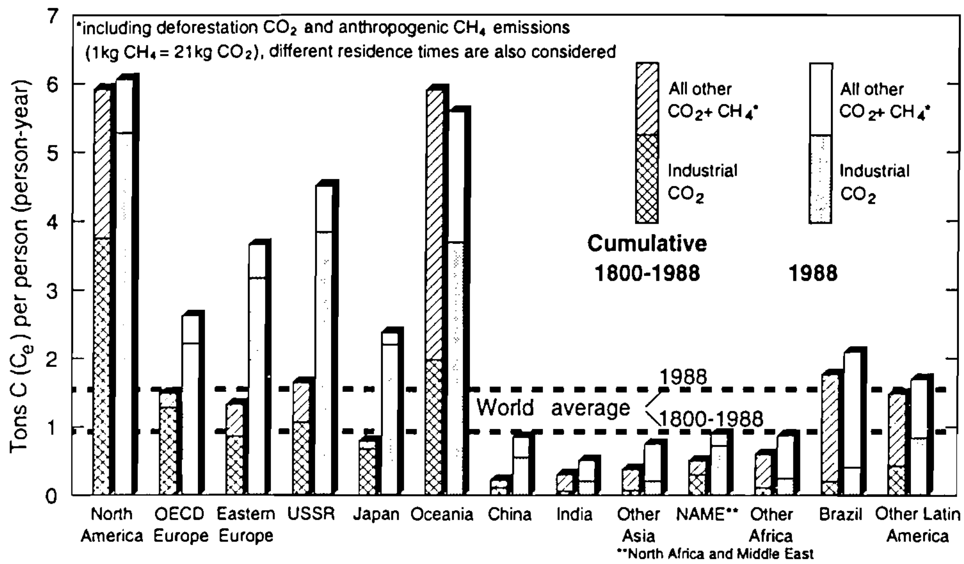

Figure 2.5. 1988 and cumulative (1800–1988) per capita GHG emissions for 13 world regions (in tons C and C-equivalent per capita and per person-year). Range corresponds to industrial CO_2 emissions only, and total CO_2 and CH_4 emissions, respectively.

of current GHG emissions and for 67 percent of the increase in atmospheric concentrations.

Figure 2.5 shows current GHG emissions per capita and historical (1800–1988) cumulative emissions per person-year lived over this time period. Again industrial CO_2 and total CO_2 and CH_4 emissions are separated. Compared to *Figure 2.4*, "North–South" disparities are more pronounced when expressed on a per capita basis. However, it is also interesting to note that generally the patterns of differences between current and historical contributions on a per capita basis among countries resemble each other. Thus, countries with current higher per capita emissions have also emitted more[15] per person in the past. Regions with low current emissions seem also to have low historical emissions both on an absolute and on a per capita basis. The

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[15] Differences between current and historical per capita emissions are more pronounced in Eastern Europe, the former USSR, and Japan. There increases in anthropogenic GHG emissions are a much more recent phenomenon compared to early industrializing Western Europe or North America.

implications of such disparities for different GHG reduction and allocation scenarios will be discussed in the following section.

3. Greenhouse Gases Reduction Criteria

The Framework Convention on Climate Change (resolution INC/1992/1) states in Article 2 as an objective of the Convention:

> "...to achieve ...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

This objective clearly implies that a reduction in the growth of global greenhouse gas emissions is required because stabilization of concentrations is the overall goal. In conjunction with the findings of the IPCC, such an objective furthermore implies that also absolute emission levels have to be reduced since they exceed the known terrestrial sinks.

> "... the parties should protect the climate for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof." [Article 3.1 INC, 1992]

Furthermore the Annex I to the Framework Convention notes:

> "... that the largest share of historical and current global emissions of greenhouse gases has originated in developed countries, that per capita emissions in developing countries are still relatively low and that the share of global emissions originating in developing countries will grow to meet their social and development needs,..."

These passages from the Convention clearly indicate the dilemmas involved in simultaneously stabilizing GHG concentrations while allowing for economic development. Perhaps for that reason the Convention abstains from giving a single criterion which could reconcile such diverging objectives. In this report we consider four different reduction criteria and investigate their implications for the 13 different world regions. All four are incorporated in the Parametric Framework and thus enable the user to investigate the consequences of changing assumptions such as altering the underlying data, changes in the reference year or period for assessment of the reduction criteria, changes in the target year by which the reduction is to be achieved, and alterations in other accompanying parameters used in the Parametric Framework.

The four criteria are: equal per capita emission rights, across-the-board percentage cuts, cutbacks proportional to past contributions to atmospheric concentration increase, and equal per capita emission rights equivalent to natural GHG sinks.

The first criterion is conceptually simplest and in fact was explicitly suggested in earlier drafts of the Framework Convention stating that emissions should converge at a common per capita level (INC, 1991). In the case of the calculations here each of the 13 regions is allowed to emit a fixed amount of greenhouse gases per capita. Under global emission stabilization or reduction, this criterion requires that the more industrialized regions (1–6) make severe emission cuts, while populous developing regions are in most cases permitted to increase their absolute emissions considerably. This criterion has the additional advantage that it is invariant for both global emissions increase and decrease: some of the industrialized regions need to reduce their per capita emissions even if global emissions are allowed to increase. The other three criteria are asymmetrical in the sense that they would allow large emitters to increase their emissions more than the developing regions in the case of global increase. Inclusion of methane emissions and carbon dioxide emissions from deforestation in general favors the more developed regions of the northern hemisphere.

Across-the-board percentage cuts or the "grandfathering" criterion is more similar to the Montreal and London Protocols on CFCs phase-out and the European Convention on Transboundary Air Pollution in that it specifies percentage decrease with respect to some representative reference year or period. A particular instance of such a criterion was given in an earlier text of the Framework Convention given as "Alternative A (ii)" specifying a stabilization of "[Net] emissions of [energy related]/[anthropogenic] greenhouse gases [other than those controlled by the Montreal Protocol] at [in general] 1990 levels by the year 2000" (INC, 1991). In general, the criterion would require a certain percentage cut in the future, say in the year 2000, with respect to a given historical level. Choice of an earlier reference year favors regions with slowly growing emissions or those regions that achieved higher emission levels earlier. The inclusion of methane and carbon dioxide emissions from deforestation in general favors the more developed regions of the northern hemisphere. Under the global emission increase variant, this criterion would favor high emitters by allowing proportional increases with respect to the reference levels.

The criterion of cutbacks proportional to past contributions to anthropogenic concentration increase reflects the common but differentiated responsibility considerations specified in the principles of the Framework Convention (INC, 1992). Another way of understanding this criterion is to consider emissions and the resulting anthropogenic increase of greenhouse gases concentration as a natural resource available to humanity to be shared throughout the world by both current, past, and future generations. Those regions and countries that have emitted overproportionally have accumulated a "natural debt" (Smith, 1990). Thus, the criterion could represent possible compensation for "natural debt" since the largest part of current anthropogenic concentration increase originates from more developed regions. It clearly favors rapidly developing regions that have not made much of an historical contribution relative to current emission rates. The inclusion of methane and carbon dioxide emissions from deforestation in general favors the more developed regions of the northern hemisphere. It should also be mentioned that the criterion prescribes reduction for all regions though greater ones for those that bear larger historical responsibility. Thus, it does not allow for emission increase in the developing regions as does the equal-per-capita criterion (as long as global GHG reductions are not too drastic). Under the global emission increase variant, this criterion would overproportionally favor high emitters and is in our opinion inappropriate in those cases. This criterion is also the most complex of the four since it involves cumulative historical greenhouse emissions to be analyzed by accounting for the different residence times of carbon dioxide and methane in the atmosphere and the different global warming potentials of these two gases. For the other three criteria, the historical contribution to concentration increases is not explicitly considered. Instead, annual emissions in the reference period serve as the sole determining factor for future emissions in the target year.

The last of the four criteria is perhaps the most complex at least at the conceptual level. A fraction of anthropogenic greenhouse gases is "removed" from the atmosphere annually by natural sinks. The basic idea (e.g., Argawal and Narain, 1991) is to first allocate these natural sinks in some manner and reduce emissions beyond those levels. In theory, this could be done by accounting for regional emissions and subtracting endogenous sinks such as absorptions of carbon dioxide by biota and coastal waters. In addition, each region would receive some fair share of other common sinks such as oceanic uptake of carbon dioxide or atmospheric destruction of methane. The resulting net emissions balance could then be reduced by equal percentage or according to historical contribution or by some other method. The real problem is that the exact nature and distribution of natural sinks is even less well known than the structure of anthropogenic emissions. In any case, roughly one half of the carbon dioxide emissions are removed from the atmosphere annually. Total current carbon dioxide emissions are about 6.4 Gt of carbon so that the magnitude of the global natural sink would be about 3 Gt of carbon annually (between 40 to 60 percent of the emissions). According to the criterion this number is allocated on an equal per capita basis among the 13 world regions. In the Parametric Framework the magnitude of the sink can be changed by the user. Emissions in the reference year are reduced to the allocated levels that correspond to the sink specified for the reference year. If the future emissions are assumed not to exceed the specified current sink, of say 3 Gt of carbon, then this criterion converges with the equal per capita emissions. The difference is that in the equal per capita emissions case the sum total global emissions are not specified explicitly but are the result, while in the case of the allocation of the sink, the global sum total is specified and the required level of per capita emissions is the result. Thus, the two criteria can be used in conjunction. Strictly speaking the hypothetical allocation of a "natural sink" is a misnomer and also technically incorrect since sinks are a function of the emission levels. Lower emissions are associated with lower sinks, while it is believed (or at least hoped) that higher emission levels would also lead to proportionally higher natural sinks.

3.1 Reduction scenarios based on four criteria

In the following sections we analyze the quantitative implications of different GHG allocation criteria for an illustrative common global reduction target. For reasons of comparability between different scenarios (criteria and type of GHG considered), all calculations are based on the same target value of emissions to be reached. We have adopted a target value of 4 Gt C (or C-equivalent) to be reached by the year 2050. This drastic reduction target value was chosen for illustrative purposes in order to elucidate more clearly the distributional consequences of different allocation criteria. The target value of 4 Gt C by 2050 represents a 50 percent cut of current anthropogenic GHG emissions and is somewhere between the Accelerated Policies and the Alternative Accelerated Policies Scenarios of the 1990 report of the IPCC.

The only exception is the scenario based on the natural sink allocation criterion, where we have assumed a target value of 3 Gt C plus an additional sink of 1.5 Gt C-equivalent for methane emissions. We have only used one target year throughout the analysis, as the criteria examined are static (between two reference years only) and do not contain any element of determining different dynamic paths for the achievement of a given emission reduction target. Reference and target year as well as target values can be chosen freely with the Parametric Framework.

3.2 Equal emission rights per head

This scenario assumes that per capita GHG emissions converge to a common value of 420 kg C (or C-equivalent) per capita, i.e., 4 Gt C divided by a world population of 9.5 billion in 2050 (based on a World Bank Projection by Zachariah and Vu, 1988). The results of the scenario are given in *Table 3.1*.

The most important characteristic of this scenario is that it is the only one in which the developing regions of the "South" are in fact allowed to increase their absolute emission levels. In a few cases even per capita increases can occur, i.e., where present per capita emissions are lower than the target value such as in regions 8, 9, 10, and 11. A surprising finding of the analysis is that if CO_2 and CH_4 emissions from all sources are considered together, then even the region with the lowest current per capita emissions is still above the level consistent with a target value of 420 kg C-equivalent per capita by 2050. This implies reductions in *per capita emissions* for all regions if CO_2 and CH_4 are considered together, though *absolute emission* levels could rise in regions 8 to 11.

The other extreme in such a scenario is represented by the more developed regions of the North that have to achieve drastic reductions in both per capita and absolute levels of emissions. They are higher than in any of the other three scenarios considered here.[16] The magnitude of the drastic reductions required is best illustrated by region 1 (North America) which would have to reduce current GHG (CO_2 and CH_4) emissions to a meager one fifteenth (7 percent) of current levels, implying a reduction rate of four percent annually until the year 2050. For other developed regions the reductions required are smaller, but by no means less dramatic: absolute

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[16] With the exception of a case in which natural GHG sinks are allocated on a per capita basis and the target value equals the natural GHG sinks, in which case the two scenarios are identical.

Table 3.1. Overview of emission reduction scenario (to 4 Gt C or C-equivalent) by 2050. Criterion: Equal per capita emissions in target year. Comparison of base year and target emissions and required reductions.

		Base year value (1988)			Target year	Reduction rates, %/yr for controlling		
		Industrial CO_2 Gt C	Total CO_2 Gt C	$CO_2 + CH_4$ Gt C_e	value Gt C (C_e)	Industrial CO_2 only	CO_2 only	$CO_2 +$ CH_4
1	OECD NA	1.43	1.43	1.64	0.13	−3.8	−3.8	−4.0
2	OECD EU	0.85	0.85	1.00	0.16	−2.7	−2.7	−2.9
3	Eastern EU	0.36	0.36	0.42	0.06	−2.9	−2.9	−3.1
4	USSR	1.09	1.09	1.28	0.15	−3.2	−3.2	−3.4
5	Japan	0.27	0.27	0.29	0.05	−2.7	−2.7	−2.8
6	Oceania	0.07	0.07	0.11	0.01	−3.1	−3.1	−3.8
7	China	0.61	0.61	0.92	0.69	+0.2	+0.2	−0.5
8	India	0.17	0.17	0.41	0.64	+2.2	+2.2	+0.7
9	Other Asia	0.16	0.47	0.58	0.70	+2.4	+0.6	+0.3
10	NAME[a]	0.24	0.24	0.30	0.37	+0.7	+0.7	+0.3
11	Other Africa	0.12	0.27	0.42	0.70	+2.9	+1.5	+0.8
12	Brazil	0.06	0.22	0.30	0.11	+1.0	−1.1	−1.6
13	Other LatAm	0.24	0.36	0.47	0.24	±0.0	−0.7	−1.1
	"North" (1–6)	4.07	4.07	4.73	0.56	−3.2	−3.2	−3.4
	"South" (7–13)	1.60	2.35	3.39	3.44	+1.2	+0.6	±0.0
	World	5.66	6.41	8.12	4.00	−0.6	−0.8	−1.1

[a] North Africa and Middle East.

emissions have to be reduced to 14 percent of current levels by the year 2050, implying reduction rates of about three percent annually (between 2.8 to 3.8 percent/year). Such high reduction rates (to be sustained over 70 years) are without precedent in history. Only over very limited periods of time were similar carbon reduction rates achieved. For instance, France has reduced its energy related carbon emissions by some 2.3 percent/year since 1973 due to both energy efficiency improvements and the vigorous introduction of nuclear energy.

If the scenario is based only on fossil fuel and industry sources of CO_2 then all of the developing regions (7 to 13) can increase their absolute emission levels, while the reduction levels of the industrialized regions are slightly lower than is the case when considering all GHGs from all sources. If CO_2 from biota sources are added then Latin America (regions 12 and 13) has to reduce its absolute CO_2 emissions. When methane emissions are also considered, all of the developing regions are allowed smaller increases, with Latin America (regions 12 and 13) requiring larger reductions (compared to the "CO_2 only" scenario), and region 7 (China) shifts from a position of absolute emission increase to decrease.

In another sensitivity analysis the equivalence factor between the radiative forcing of CO_2 and CH_4 was changed from 21 to 58 on a mass basis (*Table 3.2*). This implies that methane emissions are weighted more heavily against CO_2 in contributing to global warming. This sensitivity analysis results in net absolute emission reductions for all regions except region 11 (other Africa), indicating how important this factor is in this case. In this context it should be noted that changing the global warming potential of methane might turn out to be the most important variation due to the large uncertainty concerning, in particular, the indirect radiative forcing of CH_4 compared to CO_2 (see, e.g., the IPCC 1992 supplement).

3.3 Across the board percentage cuts ("grandfathering")

This scenario assumes that all regions have to cut their current absolute emission levels by a certain percentage in the target year with respect to the reference year. Here we illustrate the results by applying this scenario to our data set again using the standard set of assumptions (target year 2050, reference year 1988, and target total global emissions of 4 Gt C or C-equivalent). Depending on which greenhouse gases are considered, this results in a homogeneous reduction of 1988 absolute emission levels throughout the world

Table 3.2. Sensitivity analysis for criterion: Equal per capita ($CO_2 + CH_4$) emissions in target year (0.42 t C-equivalent/capita in 2050). Sensitivity: Methane equivalence factor of 58 vs 21.

		1988 $CO_2 + CH_4$ emissions Methane GWP=21		1988 $CO_2 + CH_4$ emissions Methane GWP=58		%/year reduction required to reach 420 kg C_e/capita by 2050			
						Absolute emissions		Per capita emissions	
		Gt C_e	t C_e/capita	Gt C_e	t C_e/capita	CH_4 GWP=21	CH_4 GWP=58	CH_4 GWP=21	CH_4 GWP=58
1	OECD NA	1.64	6.06	2.01	7.42	−4.0	−4.3	−4.2	−4.5
2	OECD EU	1.00	2.62	1.26	3.31	−2.9	−3.3	−2.9	−3.3
3	Eastern EU	0.42	3.65	0.51	4.51	−3.1	−3.4	−3.4	−3.8
4	USSR	1.28	4.50	1.61	5.68	−3.4	−3.8	−3.8	−4.1
5	Japan	0.29	2.37	0.33	2.66	−2.8	−3.0	−2.8	−2.9
6	Oceania	0.11	5.58	0.18	8.92	−3.8	−4.6	−4.1	−4.8
7	China	0.92	0.85	1.64	1.35	−0.5	−1.4	−1.1	−1.9
8	India	0.41	0.51	0.83	1.02	+0.7	−0.4	−0.3	−1.4
9	Other Asia	0.58	0.75	0.76	0.99	+0.3	−0.1	−0.9	−1.4
10	NAME[a]	0.30	0.90	0.39	1.19	+0.3	−0.1	−1.2	−1.7
11	Other Africa	0.42	0.87	0.66	1.39	+0.8	+0.1	−1.2	−1.9
12	Brazil	0.30	2.09	0.44	3.07	−1.6	−2.2	−2.6	−3.2
13	Other LatAm	0.47	1.69	0.68	2.42	−1.1	−1.7	−2.2	−2.8
	"North" (1−6)	4.73	3.97	5.90	4.95	−3.4	−3.7	−3.6	−3.9
	"South" (7−13)	3.39	0.87	5.24	1.34	±0.0	−0.7	−1.2	−1.9
	World	8.12	1.60	11.14	2.19	−1.1	−1.6	−2.1	−2.6

[a] North Africa and Middle East.

by 51 percent (CO_2 + CH_4), 38 percent (all CO_2), and 29 percent (energy and industrial CO_2) respectively.

Table 3.3 summarizes the results of this scenario on a per capita basis. The reason for showing a per capita representation is that while in absolute emissions terms the rank order between regions is preserved, regional per capita disparities become larger due to differentiated rates of future population growth. For example, when all GHGs are considered, reaching a target value of 4 Gt C-equivalent implies a reduction of absolute emissions by 51 percent or at a rate of 2.1 percent per year (1988–2050 average). However per capita emissions have to be reduced much more drastically in the "South" (regions 7–13) than in the "North". Modest population growth in the "North" results in average per capita emission reduction rates of 1.3 percent per year (range of between 1.1 to 1.5 percent/year) only. Thus, whereas per capita emission reduction in the regions of the "North" are all below 1.5 percent per year, the average reduction in the "South" is 2.3 percent per year with a range between 1.8 to 3.1 percent/year. As a result, present per capita emission disparities widen. Currently the "North" emits 5.6 times as much GHG per capita than the "South", and by the year 2050 this ratio increases in this scenario to 8.9. Clearly "grandfathering" implies placing a larger burden on the future generations of the "South" for global emission reductions. However, *absolute* per capita emission reductions in the "North" are larger: -3.55 tons/capita compared to -0.45 tons per capita in the "South" (cf. *Tables A1.3* and *A1.4* in Appendix I).

A counterintuitive situation arises when considering which GHGs should be included under a "grandfathering" criterion. Developing countries would have an interest in accounting for biotic carbon and methane emissions, in addition to industrial CO_2 because their respective current emissions would be higher, leading to a higher "emission allowance" in the target year. For instance, when only industrial CO_2 emissions are considered then the "North" would have to reduce to 2.87 Gt C, whereas the "South" would have to reduce by the same percentage from its currently low emission levels to 1.13 Gt C by 2050. When all CO_2 and CH_4 emissions are considered, the resulting regional allocation (again for a global target of 4 Gt C-equivalent) would be 2.33 Gt (down 19 percent from the industrial CO_2 case) versus 1.67 Gt C-equivalent (48 percent higher than in the industrial CO_2 case) in the "North" and "South" respectively.

This scenario is also the most sensitive to the choice of the reference year from which equal percentage cuts are being calculated. Consequently the reference year varies between 1988 and 1970. The results of the calculation

Table 3.3. Overview of emission reduction scenario (to 4 Gt C or C-equivalent) by 2050. Criterion: Across-the-board percentage cuts from 1988 absolute emissions. Comparison of per capita emission levels and required reductions.

		Base year value (1988)			Target year value (2050)			%/yr reduction rates		
		Ind. CO_2 t C/cap	Total CO_2 t C/cap	CO_2+CH_4 t C_e/cap	Ind. CO_2 t C/cap	Total CO_2 t C/cap	CO_2+CH_4 t C_e/cap	Ind. CO_2	Total CO_2	CO_2 + CH_4
1	OECD NA	5.28	5.28	6.06	3.26	2.88	2.61	−0.8	−1.0	−1.4
2	OECD EU	2.22	2.22	2.62	1.61	1.42	1.32	−0.5	−0.7	−1.1
3	Eastern EU	3.17	3.17	3.65	1.91	1.69	1.54	−0.8	−1.0	−1.4
4	USSR	3.83	3.83	4.50	2.11	1.86	1.73	−1.0	−1.2	−1.5
5	Japan	2.20	2.20	2.37	1.51	1.33	1.13	−0.6	−0.8	−1.2
6	Oceania	3.69	3.69	5.58	2.10	1.86	2.22	−0.9	−1.1	−1.5
7	China	0.56	0.56	0.85	0.26	0.23	0.28	−1.2	−1.4	−1.8
8	India	0.21	0.22	0.51	0.08	0.07	0.13	−1.6	−1.8	−2.1
9	Other Asia	0.21	0.61	0.75	0.07	0.18	0.17	−1.8	−2.0	−2.4
10	NAME[a]	0.73	0.73	0.90	0.19	0.17	0.17	−2.1	−2.3	−2.7
11	Other Africa	0.25	0.57	0.87	0.05	0.10	0.12	−2.6	−2.7	−3.1
12	Brazil	0.41	1.53	2.09	0.16	0.51	0.55	−1.6	−1.8	−2.1
13	Other LatAm	0.84	1.27	1.68	0.30	0.40	0.42	−1.7	−1.9	−2.2
	"North" (1–6)	3.41	3.41	3.97	2.16	1.91	1.75	−0.7	−0.9	−1.3
	"South" (7–13)	0.41	0.60	0.87	0.14	0.18	0.20	−1.8	−1.9	−2.3
	World	1.11	1.26	1.60	0.42	0.42	0.42	−1.6	−1.8	−2.1

[a] North Africa and Middle East.

for energy and industrial CO_2 emissions only will be discussed here (*Table 3.4*) since it is the most sensitive to changes in the reference year. *Table 3.5*, however, gives equivalent results when all GHG emissions are considered. A general conclusion of this sensitivity analysis confirms the fact that those regions and countries whose emissions increased most rapidly during the last decades have to bear ever higher reductions the earlier the reference year. Conversely, those regions and countries that experienced stable emissions or even emission reductions benefit the most and are in some cases even allowed marginal increases in absolute emissions (see region 2 in *Table 3.4*). The other troublesome result of this sensitivity analysis is that if the reference year is as early as 1970, those developing countries that are in the middle of economic and industrial development will be forced to try to achieve double the reductions than if 1988 is chosen as the reference year (cf. regions 7 and 8 in *Table 3.4*). However, a reassuring result of the analysis is that the relative position and reduction requirements of different regions are *invariant* to small changes in the reference year, e.g., between 1985 and 1988, and are also robust when other GHGs are considered.

3.4 Cutbacks proportional to past contributions

According to the logic of differentiated responsibility, the scenario defines future cutbacks in direct proportion to the respective share of each region in the anthropogenic increase of atmospheric concentrations of GHGs. For example if a particular region is responsible for ten percent of the increase in atmospheric concentration of CO_2 from the pre-industrial levels of 280 to the current level of 353 ppmv, then it has to bear a ten percent share in the total global reduction of absolute emission levels. Here again we assume a reduction to 4 Gt C or C-equivalent emissions level by the year 2050.

Table 3.6 gives the historical contributions to the concentration increase in percentage of the world total (of 100 percent) by region for (energy and) industrial CO_2, all CO_2 emissions and for combined CO_2 and CH_4 emissions. The assessment is based on an analysis using the Parametric Framework[17]

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[17] Past CO_2 emissions are accounted for with a hybrid model of an airborne fraction approach combined with a long-term ocean uptake component (cf. Grübler and Fujii, 1991). For the purpose of accounting for past contributions to atmospheric concentration increase only the ocean uptake part of the model is relevant. We have adopted an ocean uptake constant of 0.3%/yr which implies that historical carbon emissions remaining in the atmosphere are discounted by this annual rate. For methane emissions we use an atmospheric removal rate of 25%/yr to calculate emissions remaining in the atmosphere. All these parameters for accounting historical emissions can be modified in the Parametric Framework.

Table 3.4. Sensitivity analysis for criterion: Across-the-board percentage cuts (to 4 Gt C by 2050) from absolute values of base year. Sensitivity: Variation of base year (fossil fuel and industrial CO_2 emissions), Gt C.

		1988 emissions	Equal % cuts from base year levels to 4 Gt C by 2050				
		Gt C	1988 base	1985 base	1980 base	1975 base	1970 base
1	OECD NA	1.43	1.01	1.00	1.09	1.16	1.29
2	OECD EU	0.85	0.60	0.66	0.76	0.80	0.89
3	Eastern EU	0.36	0.25	0.27	0.27	0.26	0.24
4	USSR	1.09	0.77	0.75	0.71	0.72	0.65
5	Japan	0.27	0.19	0.19	0.20	0.21	0.21
6	Oceania	0.07	0.05	0.05	0.04	0.05	0.04
7	China	0.61	0.43	0.41	0.32	0.28	0.22
8	India	0.17	0.12	0.11	0.08	0.06	0.06
9	Other Asia	0.16	0.11	0.11	0.09	0.08	0.07
10	NAME[a]	0.24	0.17	0.17	0.14	0.12	0.10
11	Other Africa	0.12	0.09	0.09	0.08	0.07	0.06
12	Brazil	0.06	0.04	0.04	0.04	0.04	0.03
13	Other LatAm	0.24	0.17	0.16	0.17	0.15	0.15
	"North" (1–6)	4.07	2.87	2.92	3.07	3.19	3.33
	"South" (7–13)	1.60	1.13	1.08	0.93	0.81	0.67
	World	5.66	4.00	4.00	4.00	4.00	4.00
	2050 emission as % of base year	–	(70.6%)	(76.0%)	(79.1%)	(90.3%)	(102.6%)

[a] North Africa and Middle East.

Table 3.5. Sensitivity analysis for criterion: Across-the-board percentage cuts (to 4 Gt C-equivalent by 2050) from absolute emissions of base year (1988). Sensitivity: Variation of base year, all GHGs ($CO_2 + CH_4$), Gt C-equivalent.

	1988 emissions Gt C_e	Equal % cuts from base year levels to 4 Gt C_e by 2050				
		1988 base	1985 base	1980 base	1975 base	1970 base
1 OECD NA	1.64	0.81	0.76	0.76	0.78	0.83
2 OECD EU	1.00	0.49	0.51	0.53	0.52	0.55
3 Eastern EU	0.42	0.21	0.20	0.19	0.18	0.17
4 USSR	1.28	0.63	0.58	0.52	0.50	0.47
5 Japan	0.29	0.14	0.14	0.13	0.12	0.12
6 Oceania	0.11	0.05	0.05	0.06	0.09	0.10
7 China	0.92	0.45	0.41	0.36	0.34	0.31
8 India	0.41	0.20	0.19	0.17	0.19	0.23
9 Other Asia	0.58	0.28	0.39	0.39	0.35	0.30
10 NAME[a]	0.30	0.15	0.14	0.11	0.10	0.09
11 Other Africa	0.42	0.20	0.24	0.30	0.23	0.22
12 Brazil	0.30	0.15	0.14	0.13	0.20	0.20
13 Other LatAm	0.47	0.23	0.26	0.33	0.40	0.40
"North" (1–6)	4.73	2.33	2.24	2.20	2.20	2.24
"South" (7–13)	3.39	1.67	1.76	1.80	1.80	1.76
World	8.12	4.00	4.00	4.00	4.00	4.00

[a] North Africa and Middle East.

and includes anthropogenic emissions since 1800. This period basically covers the whole history of industrialization and therefore also reflects differentiated benefits incurred through carbon deposition in the atmosphere by different countries. Industrialized countries have generated an overproportional share of CO_2 increase and have presumably thereby also benefited in achieving their current high standards of living and affluence. Together they account for 84 percent of industrial (and energy) atmospheric CO_2 concentration increase. Some regions apparently bear almost no historical responsibility in the concentrations increase, with shares ranging between one and two percent. This includes five of the seven developing regions. Their grand total share is a mere 16 percent. This should also be compared with the uneven distribution of the world's inhabitants with more than 80 percent of the current population living in regions with less than 20 percent historical share in concentrations increase. There are slight shifts in this unequal distribution between the "North" and the "South" if other anthropogenic sources of greenhouse gases are added. For all sources of CO_2, the share of developing countries increases to 32 percent and when methane emissions are included, to 33 percent.

It is interesting to note that the historical contributions to current concentrations are closely related to the pattern of current emissions in the regions. Low shares in historical contributions are highly correlated with low current emissions, and the relative change in position of various regions when other sources of greenhouse gases are added are also very similar. Thus, the current distribution of emissions is also a good "proxy" for differentiated historical responsibility. Highly industrialized countries are responsible for most of the past and present contributions, while populous developing countries bear only a small responsibility. However, their relative positions are rather sensitive to the inclusion of biota sources of CO_2 and CH_4.

Table 3.6 also shows the distribution of 4 Gt C (and C-equivalent) emissions in 2050 according to the criterion of reductions proportional to past contributions. Clearly, all regions need to reduce, but the reductions are much more substantial in the "North". It is apparently not in the interest of any region to include biota sources of CO_2 and CH_4 into the accounting process since all regions are worse off. However, should the total emissions to be allocated by 2050 also increase with the addition of other greenhouse gases then it would indeed be in the interest of the "North" that they are considered. In any case, this scenario improves the relative position of the

Table 3.6. Overview of emission reduction scenario (to 4 Gt C or C-equivalent) by 2050. Criterion: Reduction proportional to past contribution to concentration increase. Comparison of past contribution, base year, and target emissions.

	Past contribution 1800–1988 in %			Emission in 1988 Gt C (C_e)			Emission in 2050 Gt C (C_e)		
	Ind. CO_2	Total CO_2	CO_2 + CH_4	Ind. CO_2	Total CO_2	CO_2 + CH_4	Ind. CO_2	Total CO_2	CO_2 + CH_4
1 OECD NA	33.2	29.7	29.2	1.43	1.43	1.64	0.88	0.71	0.44
2 OECD EU	26.1	16.6	16.4	0.85	0.85	1.00	0.41	0.45	0.32
3 Eastern EU	5.5	4.8	4.7	0.36	0.36	0.42	0.27	0.25	0.22
4 USSR	14.1	12.5	12.4	1.09	1.09	1.28	0.85	0.78	0.76
5 Japan	3.7	2.3	2.3	0.27	0.27	0.29	0.21	0.21	0.20
6 Oceania	1.1	1.9	1.9	0.07	0.07	0.11	0.05	0.03	0.03
7 China	5.5	6.0	6.3	0.61	0.61	0.92	0.52	0.46	0.66
8 India	1.6	4.5	4.8	0.17	0.17	0.41	0.14	0.07	0.21
9 Other Asia	1.5	5.0	5.2	0.16	0.47	0.58	0.13	0.35	0.36
10 NAME[a]	2.2	1.7	1.8	0.24	0.24	0.30	0.21	0.20	0.22
11 Other Africa	1.6	5.2	5.2	0.12	0.27	0.42	0.10	0.15	0.20
12 Brazil	0.7	3.3	3.3	0.06	0.22	0.30	0.05	0.14	0.17
13 Other LatAm	3.2	6.5	6.5	0.24	0.35	0.47	0.18	0.20	0.20
"North" (1–6)	83.8	67.8	66.9	4.07	4.07	4.73	2.67	2.43	2.03
"South" (7–13)	16.2	32.2	33.1	1.60	2.34	3.39	1.33	1.57	1.97
World	100.0	100.0	100.0	5.66	6.41	8.12	4.00	4.00	4.00

[a] North Africa and Middle East.

"South" compared to the current distribution of the emissions, but its disadvantage is that it does not allow for any emission increases even in those regions with extremely low current levels.

Carbon dioxide gas has a particularly long life in the atmosphere. This is the main reason why emissions data going back to the beginning of the Industrial Revolution have to be invoked to assess the past contribution to current atmospheric concentration. Furthermore, the addition of methane to the total global warming potential of CO_2 and CH_4 is also based on a number of critical assumptions as explained above. These include the global warming potential of CH_4 relative to CO_2, assumed to be 21 for the purposes of this assessment, and the lifetime of CH_4 in the atmosphere, assumed here to be reduced by 25 percent of the remaining amount each year. *Table 3.7* reports the results of varying some of the model assumptions in order to test the sensitivity of our analysis for past contributions to current concentrations by various regions. It is interesting to note that the overall result is rather invariant to these assumption changes. For example, the share of the "North" varies only from 63 to 70 percent for a combination of changes in these two parameters and a reduction in the historical observation period by almost 20 years. Thus, the differentiated historical responsibility is a robust concept if defined as the relative contribution of different regions to current (or recent) anthropogenic concentrations of GHGs.

3.5 Sink adjusted emissions

Global GHG sinks differ in magnitude and especially in relation to anthropogenic emissions. That the absorptive capacity of the global GHG sinks is overstretched is reflected in the increasing concentrations of all GHGs in the atmosphere. Sinks for carbon dioxide are estimated to be up to 3 Gt C, with the distribution between oceanic and terrestrial carbon sinks subject to considerable scientific uncertainty. The most important methane sink is the atmosphere (CH_4 destruction by OH radicals). If natural emissions of some 240 Tg methane (from e.g., natural wetlands, wild animals, termites, etc.) are subtracted from the natural methane sinks (in the IPCC 1990 report assumed to be 500 Tg), the residual sink available to absorb anthropogenic emissions is obtained. In our case the methane sink is assumed to be around 260 (500–240) Tg CH_4 (about 1.5 Gt C-equivalent), or about 80 percent of estimated current anthropogenic methane emissions.

The sink adjusted scenario for carbon emissions is, with 3 Gt C, lower than the 4 Gt C assumed for the other scenarios. The total GHG emission

Table 3.7. Sensitivity analysis for criterion: Reduction proportional to past contribution. Sensitivity: Regional shares in terms of past concentration increase for all GHGs with varying atmospheric residence time (ART) and GWP of CH_4, and with a change in the reference year, in percent.

	GWP:	21	21	21	58	21	58
	ART:	25	25	25	10	10	25
	Reference year	1988	1980	1970	1988	1988	1988
1	OECD NA	29.2	30.7	33.4	27.0	28.7	28.3
2	OECD EU	16.4	16.8	17.5	15.4	16.1	16.0
3	Eastern EU	4.7	4.5	4.5	4.6	4.7	4.6
4	USSR	12.4	11.7	11.1	12.0	12.3	12.3
5	Japan	2.3	1.9	1.3	2.1	2.2	2.2
6	Oceania	1.9	2.1	2.1	1.9	1.9	1.9
7	China	6.3	5.9	5.5	7.4	6.6	6.8
8	India	4.8	5.2	6.0	5.7	5.1	5.2
9	Other Asia	5.2	4.8	4.2	6.4	5.5	5.6
10	NAME[a]	1.8	1.5	1.1	1.9	1.8	1.8
11	Other Africa	5.2	5.1	4.9	5.6	5.3	5.4
12	Brazil	3.3	3.2	2.8	3.3	3.3	3.3
13	Other LatAm	6.5	6.6	5.6	6.7	6.5	6.6
	"North" (1–6)	66.9	67.8	70.0	63.0	65.9	65.4
	"South" (7–13)	33.1	32.2	30.0	37.0	34.1	34.6
	World	100.0	100.0	100.0	100.0	100.0	100.0

[a] North Africa and Middle East.

level in the scenario is actually higher because of the additional methane sinks (of about 1.5 Gt C-equivalent). However, the two sinks, although additive, are not substitutable in terms of allocating emissions between the total global or regional GHG emission targets. Consequently allocations of carbon and methane sinks had to be considered separately in the Parametric Framework calculations.

There are of course a number of alternative ways of allocating sink adjusted emission levels among the 13 world regions. Here we first analyze the consequences of a per capita allocation of global GHG sinks and a reduction of the emissions exceeding these levels. In a sensitivity analysis this scenario is compared to cases where the global GHG sinks are allocated on a per unit land area, and a combination of land and per capita allocation criteria.

Table 3.8 shows a comparison of the sink adjusted emission allocation for 2050 with actual levels in 1988. Access to natural GHG sinks is distributed among the regions on an equal per capita basis. Therefore, the allocation is the same as in the case of the first criterion (per capita emission levels) analyzed above, except that here only the total sink is specified and the emission levels are the result of the calculation in the Parametric Framework. The allocations for 2050 are very low compared with other cases and would indeed represent targets that are almost impossible to achieve. In fact, the regional allocations for 2050 of about 314 kg of carbon per capita are lower than current per capita CO_2 emissions in all regions except India (220 kg C per capita in 1988). If biota sources of CO_2 are excluded, then in addition to India (region 8), regions 9 and 11 are today also below the target per capita level for 2050. The fact that present per capita emissions in most developing countries exceed the per capita sink allocation by 2050 (with a doubled world population) illustrates that GHG sink allocations on a per capita basis would disallow most developing countries from increasing their absolute GHG emissions over present levels (cf. *Table 3.8*). The achievement of such drastic reductions in global emissions, as implied by a sink adjusted emission criterion without the possibility for higher future emissions in the developing countries, thus appears rather unrealistic and definitely undesirable from the perspective of further economic growth in the "South".

The combined CO_2 and CH_4 sinks are assumed to be somewhat more generous with about 4.5 Gt of C-equivalent per year. On a per capita basis this increases the emission allowances to about 470 kg of C-equivalent per person and year. However, the current combined emissions of CO_2 and CH_4 are also higher so that this limit represents per capita reductions from current

Table 3.8. Overview of emission reduction scenario. Criterion: Reduction to natural sink adjusted emissions (3 Gt C for CO_2 and 1.5 Gt C-equivalent for CH_4) by 2050. Comparison of 1988 and target year absolute emission levels, in Gt C or C-equivalent.

	Industrial CO_2 in Gt C	All CO_2 in Gt C		CH_4 in Gt C-equivalent		CO_2+CH_4 in Gt C-equivalent	
	1988	1988	2050	1988	2050	1988	2050
1 OECD NA	1.43	1.43	0.10	0.21	0.05	1.64	0.15
2 OECD EU	0.85	0.85	0.12	0.15	0.06	1.00	0.18
3 Eastern EU	0.36	0.36	0.04	0.06	0.02	0.42	0.06
4 USSR	1.09	1.09	0.11	0.19	0.06	1.28	0.17
5 Japan	0.27	0.27	0.04	0.02	0.02	0.29	0.06
6 Oceania	0.07	0.07	0.01	0.04	0.00	0.11	0.01
7 China	0.61	0.61	0.52	0.31	0.26	0.92	0.78
8 India	0.17	0.17	0.48	0.24	0.24	0.41	0.72
9 Other Asia	0.16	0.47	0.52	0.11	0.26	0.58	0.78
10 NAME[a]	0.24	0.24	0.28	0.06	0.14	0.30	0.42
11 Other Africa	0.12	0.27	0.53	0.15	0.26	0.42	0.79
12 Brazil	0.06	0.22	0.08	0.08	0.04	0.30	0.12
13 Other LatAm	0.24	0.36	0.18	0.11	0.09	0.47	0.27
"North" (1–6)	4.07	4.07	0.42	0.66	0.21	4.73	0.63
"South" (7–13)	1.60	2.35	2.58	1.04	1.29	3.39	3.87
World	5.66	6.41	3.00	1.71	1.50	8.12	4.50

[a] North Africa and Middle East.

levels in *all* regions. The required reductions are impressive in absolute terms as well. Many of the developing regions are required to make substantial reductions, while some more developed regions would be required to sustain reductions to the tune of more than five percent per year. For example, region 1 would need to reduce its emissions by over a factor of 14 between now and 2050. On balance this kind of scenario is too extreme and is less preferable than explicit equal per capita emission allocation according to criterion one.

As a sensitivity analysis to a per capita sink allocation we have examined the allocation of the 3 Gt natural carbon sinks on the basis of land area, and also the separate allocation of terrestrial and oceanic carbon sinks. The results are summarized in *Table 3.9* which shows current regional absolute emissions and the two different carbon sink allocation criteria – total carbon sinks by land area of each region and by allocating terrestrial sinks (half of the emissions) on the basis of land area and oceanic carbon sinks (also about 1.5 Gt C) as a global commons on a per capita basis. The sink allocation per unit of land area gives higher emission allocations to large regions, which often results in lower emissions for the more developed regions. However, many of the developing regions would also incur reductions including regions 7, 8, 9, 12, and 13. This allocation scheme of natural sinks does not lead to any obvious redistribution of emission levels along the "North-South" divide, but it does result in differential effects within the two groups of regions by favoring less populous regions whether they are in the "North" or "South". The fact that the per unit land allocation criterion penalizes regions with high population densities and high population growth, probably makes it inappropriate for the allocation of emissions under a global reduction scenario. Allocating terrestrial and oceanic carbon sinks separately on the other hand somewhat improves the situation for more populous countries but does not significantly change the overall "North-South" emission divide that emerged from a simple per capita allocation criterion (*Table 3.8* above). Hence, this subvariant of the sink allocation criteria introduces additional complexity into the debate without yielding widely different results from a simple per capita criterion.

4. Comparison of Criteria

Tables A1.1 to *A1.8* in Appendix I summarize the differences in regional GHG emissions for a common illustrative reduction scenario to 4 Gt C

Table 3.9. Sensitivity analysis for criterion: Reduction to natural sink adjusted emissions by 2050 (carbon sink assumed = 3 Gt C). Total CO_2 emissions per region, 1988 and 2050, Gt C. Sensitivity: Variation of carbon sink allocation criteria: Per unit land area, terrestrial sinks allocated per unit land area, ocean sinks on per capita basis.

		1988 CO_2 emissions Gt C	3 Gt carbon sinks allocation			
			Total sinks per land area	1.5 Gt terrestrial and 1.5 Gt oceanic sink		
				Terrestrial per land area	Oceanic per capita	Total
1	OECD NA	1.43	0.43	0.22	0.05	0.27
2	OECD EU	0.85	0.10	0.05	0.06	0.11
3	Eastern EU	0.36	0.02	0.01	0.02	0.03
4	USSR	1.09	0.50	0.25	0.06	0.31
5	Japan	0.27	0.01	0.00	0.02	0.02
6	Oceania	0.07	0.18	0.09	0.00	0.09
7	China	0.61	0.21	0.11	0.26	0.37
8	India	0.17	0.07	0.04	0.24	0.28
9	Other Asia	0.47	0.18	0.09	0.26	0.35
10	NAME[a]	0.24	0.28	0.14	0.14	0.28
11	Other Africa	0.27	0.55	0.28	0.26	0.54
12	Brazil	0.22	0.19	0.10	0.04	0.14
13	Other LatAm	0.36	0.30	0.13	0.09	0.22
	"North" (1–6)	4.07	1.24	0.62	0.21	0.83
	"South" (7–13)	2.35	1.76	0.88	1.29	2.17
	World	6.41	3.00	1.50	1.50	3.00

[a] North Africa and Middle East.

by the year 2050. They compare the results of three reduction criteria of the four analyzed with the Parametric Framework: equal percentage cuts (with two different base years), cutbacks proportional to past contribution, and equal emission rights per capita. Comparisons are made for fossil fuel and industrial CO_2, and all anthropogenic GHG (CO_2 and CH_4) emissions, respectively. Absolute and per capita emissions, as well as absolute and per capita emission reductions (or increases) between the base (1988) and target (2050) years are also given for the two categories of GHG emissions. In the following we briefly review the different allocation scenarios analyzed with respect to their consequences on absolute emission levels, required absolute emission reductions, and finally, their distributive effect as reflected in differences in per capita emission levels.

Table 4.1 shows absolute levels of industrial CO_2 emissions for the 13 world regions in 1988 and for the three alternative allocation scenarios in the year 2050 assuming global emission reductions to be at a target value of 4 Gt C. *Table 4.2* gives the same comparison for all anthropogenic CO_2 and CH_4 emissions combined. The salient feature of the comparison of different allocation scenarios is that it reveals both general tendencies. This was to be expected for the major considerations (such as that per capita criteria tend to favor developing countries in GHG reduction scenarios) with surprising results emerging only after the quantitative implications and differences between various criteria have been calculated.

The main difference among the criteria analyzed is whether they imply emission reductions by all regions/countries (though at different rates), i.e., are they proper *reductive criteria,* or are they *distributive criteria* (i.e., allocate emission rights), from which the required reductions are then inferred. Reductive criteria result in emission reductions in *all* regions, whereas distributive criteria – depending on current emissions levels – can imply both reductions or increases in GHG emissions.

From the four criteria investigated, only the criterion of converging per capita emissions (or the equivalent per capita sink allocation) is a distributive criterion. Consequently it is also the only one where both increases and decreases in regional emissions result with respect to the target year. From the perspective of developing countries it is also the only criterion that would allow future emission increases for raising per capita energy consumption levels. Even under the rather stringent global emission reduction assumptions adopted here (4 Gt C) all developing countries could increase their absolute emissions, provided only industrial CO_2 emissions are considered. Emissions from the "South" would double in such a scenario to some 3.4 Gt C, whereas

Table 4.1. Different allocation criteria for CO_2 reduction strategies (to 4 Gt C by 2050), fossil fuel and industrial CO_2, Gt C.

	1988 emissions	Equal percent cuts		Cutbacks proportional to past contribution	Equal emission rights per capita (by 2050)
		1988 base	1980 base		
1 OECD NA	1.43	1.01	1.09	0.88	0.13
2 OECD EU	0.85	0.60	0.76	0.41	0.16
3 Eastern EU	0.36	0.25	0.27	0.27	0.06
4 USSR	1.09	0.77	0.71	0.85	0.15
5 Japan	0.27	0.19	0.20	0.21	0.05
6 Oceania	0.07	0.05	0.05	0.05	0.01
7 China	0.61	0.43	0.32	0.52	0.69
8 India	0.17	0.12	0.08	0.14	0.64
9 Other Asia	0.16	0.11	0.09	0.13	0.70
10 NAME[a]	0.24	0.17	0.14	0.21	0.37
11 Other Africa	0.12	0.09	0.08	0.10	0.70
12 Brazil	0.06	0.04	0.04	0.05	0.11
13 Other LatAm	0.24	0.17	0.17	0.18	0.24
"North" (1–6)	4.07	2.87	3.08	2.67	0.56
"South" (7–13)	1.60	1.13	0.92	1.33	3.44
World	5.66	4.00	4.00	4.00	4.00

[a] North Africa and Middle East.

Table 4.2. Different allocation criteria for GHG reduction strategies (to 4 Gt C-equivalent by 2050), CO_2 and CH_4 (all sources), Gt C-equivalent.

	1988 emissions	Equal percent cuts		Cutbacks proportional to past contribution	Equal emission rights per capita (by 2050)
		1988 base	1980 base		
1 OECD NA	1.64	0.81	0.76	0.44	0.13
2 OECD EU	1.00	0.49	0.53	0.32	0.16
3 Eastern EU	0.42	0.21	0.19	0.22	0.06
4 USSR	1.28	0.63	0.52	0.76	0.15
5 Japan	0.29	0.14	0.13	0.20	0.05
6 Oceania	0.11	0.05	0.06	0.03	0.01
7 China	0.92	0.45	0.36	0.66	0.69
8 India	0.41	0.20	0.17	0.21	0.64
9 Other Asia	0.58	0.28	0.39	0.36	0.70
10 NAME[a]	0.30	0.15	0.11	0.22	0.37
11 Other Africa	0.42	0.20	0.30	0.20	0.70
12 Brazil	0.30	0.15	0.13	0.17	0.11
13 Other LatAm	0.47	0.23	0.33	0.20	0.24
"North" (1–6)	4.73	2.33	2.20	1.97	0.56
"South" (7–13)	3.39	1.67	1.80	2.03	3.44
World	8.12	4.00	4.00	4.00	4.00

[a] North Africa and Middle East.

emissions from the "North" would have to be decreased drastically from the current 4.1 to 0.6 Gt C. The situation is somewhat different when biotic carbon and methane emissions are also considered for the same emission reduction scenario to 4 Gt C-equivalent. Here, all developing countries taken together would only be allowed a stabilization of their current absolute emissions, despite a per capita allocation criterion, simply because the required global reduction (to less than 50 percent of current emissions) is so large. Only four developing regions (8 to 11) would be allowed relatively modest absolute emission increases: about 20 percent above 1988 levels for regions 9 and 10, and some 60 percent (from comparatively low levels) for regions 8 and 11. The developing regions 7, 12, and 13 (China and all of Latin America) would even have to bear a decrease.

Thus, the major conclusion of the comparison between *distributive* and *reductive* criteria is that from the perspective of the developing countries distributive criteria, especially when based on a per capita basis, are clearly preferable because they are the only ones that allow absolute emission increases in the "South". Conversely the difference between the various *reductive* criteria investigated is comparatively minor. Offering a compromise in differentiated GHG reduction targets (e.g., by considering different historical responsibilities) may thus not be sufficient to bridge the significant "North–South" divide emerging from per capita emission allowance scenarios *vis à vis* other reduction scenarios.

It is important to reiterate here the observation made in previous sections when analyzing the implications of different allocation criteria under the emission reduction schemes. We discovered a surprising degree of invariance with respect to some of the basic assumptions of the analysis. This is mirrored for instance in *Table 4.2* where the emissions in 2050 under equal percent cuts are compared with two different reference years, 1988 and 1980 respectively. We also analyzed the resulting changes from larger variations in the reference year going back to 1970. The resulting redistribution of emissions is minimal in most cases. For example, in *Tables 4.1* and *4.2* the emissions in the "North" change by seven percentage points if the base year is varied between 1988 and 1980.

Another similarity can be observed among what we have called *reductive* criteria (equal percent cuts, and cutbacks proportional to past contribution). They all result in basically the same distribution of emissions in the target year 2050. The main exception here is region 2 (OECD Europe) that shows larger variance between the equal percent cuts and cutbacks proportional to past contributions. That the similarity in other cases is so close is indeed a counter-intuitive result upon first reflection. However, a closer analysis indicates that there is a fundamental reason for this similarity that is inherent in the nature of global GHG emissions. Namely, the emissions of most GHGs have increased at almost exponential rates since the beginning of the Industrial Revolution and in particular since World War II. Exponential growth portrays an interesting property: its integral is proportional to the function itself. In our case this means that emissions in any particular reference year should have a similar distribution among different regions as do the respective cumulative emissions up to that reference year. Thus, the resemblance of emission distribution between the equal percent cuts and cutbacks proportional to past contributions indicates that historical increases of anthropogenic sources of GHGs has been rather close to an exponential growth path in most of the worlds regions. For all practical purposes it would be easier and more prudent to use an equal percent cuts criterion instead of the much-more-difficult-to-determine allocation according to differentiated historical responsibility, although at the surface level the latter appears to many observers to be inherently more "equitable".

Figure 4.1 summarizes the results obtained by contrasting 1988 emissions for selected regions and countries with the resulting regional emission allowances in a global reduction scenario to 4 Gt (C or C-equivalent) based on the three allocation criteria. The figure also illustrates the effect of the comprehensiveness of GHGs considered. In the case of *reductive* criteria it is in the interest of the "North" to consider only industrial CO_2 emissions. Conversely, it is in the interest of the "South" to consider all sources of CO_2 and methane as a calculation base for emission reduction. In the case of a *distributive* criterion the regional interests are similar: It is in everybody's interest to include as few GHGs as possible.

The similarity between the *reductive* criteria is preserved if the comparison is made on a per capita basis, as shown in *Tables 4.3* and *4.4*. On the other hand, the contrast between the *reductive* criteria versus the *distributive* criterion (i.e., allocation on the basis of equal emission rights per capita) is even more transparent (cf. *Figure 4.2*). In the reductive criteria scenarios global inequalities are aggravated: the difference between the per capita emission levels of the "North" and the "South" increases from about a factor eight today to between 15 and 20 in the year 2050 (see *Table 4.3*). The global disparities also increase when all GHGs are considered albeit by somewhat lower factors: from about a factor of 4.5 today to between 6 and 9 in the year 2050 (see *Table 4.4)*. By definition, the per capita allocation criterion leads to equalization of the emissions throughout the world. In fact,

Table 4.3. Different allocation criteria for CO_2 reduction strategies (to 4 Gt C by 2050), per capita fossil fuel and industrial CO_2, tons C/capita.

	1988 emissions	Equal percent cuts		Cutbacks proportional to past contribution	Equal emission rights per capita (by 2050)
		1988 base	1980 base		
1 OECD NA	5.28	3.26	3.37	2.83	0.42
2 OECD EU	2.22	1.61	1.96	1.11	0.42
3 Eastern EU	3.17	1.91	1.97	2.02	0.42
4 USSR	3.83	2.11	1.87	2.34	0.42
5 Japan	2.20	1.51	1.53	1.64	0.42
6 Oceania	3.69	2.10	1.88	2.23	0.42
7 China	0.56	0.26	0.19	0.32	0.42
8 India	0.21	0.08	0.05	0.09	0.42
9 Other Asia	0.21	0.07	0.05	0.08	0.42
10 NAME[a]	0.73	0.19	0.16	0.23	0.42
11 Other Africa	0.25	0.05	0.05	0.06	0.42
12 Brazil	0.41	0.16	0.15	0.18	0.42
13 Other LatAm	0.84	0.30	0.29	0.32	0.42
"North" (1–6)	3.41	2.16	2.22	2.01	0.42
"South" (7–13)	0.41	0.14	0.11	0.16	0.42
World	1.11	0.42	0.40	0.42	0.42

[a] North Africa and Middle East.

Table 4.4. Different allocation criteria for GHG reduction strategies (to 4 Gt C-equivalent by 2050), per capita CO_2 and CH_4 (all sources), tons C-equivalent/capita.

		1988 emissions	Equal percent cuts		Cutbacks proportional to past contribution	Equal emission rights per capita (by 2050)
			1988 base	1980 base		
1	OECD NA	6.06	2.61	2.46	1.41	0.42
2	OECD EU	2.62	1.32	1.43	0.87	0.42
3	Eastern EU	3.65	1.54	1.43	1.67	0.42
4	USSR	4.50	1.73	1.44	2.10	0.42
5	Japan	2.37	1.13	1.04	1.55	0.42
6	Oceania	5.58	2.22	2.60	1.29	0.42
7	China	0.85	0.28	0.22	0.40	0.42
8	India	0.51	0.13	0.11	0.14	0.42
9	Other Asia	0.75	0.17	0.23	0.22	0.42
10	NAME[a]	0.90	0.17	0.13	0.25	0.42
11	Other Africa	0.87	0.12	0.18	0.12	0.42
12	Brazil	2.09	0.55	0.48	0.61	0.42
13	Other LatAm	1.69	0.42	0.59	0.36	0.42
	"North" (1–6)	3.97	1.75	1.66	1.49	0.42
	"South" (7–13)	0.87	0.20	0.22	0.25	0.42
	World	1.60	0.42	0.42	0.42	0.42

[a] North Africa and Middle East.

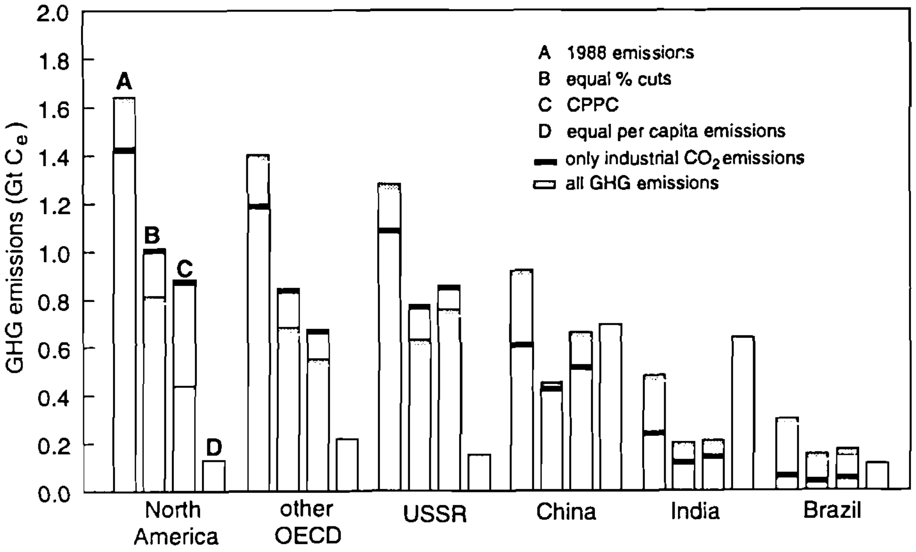


Figure 4.1. A comparison of three allocation criteria for GHG reduction strategies (to 4 Gt C or C-equivalent by 2050) for selected regions/countries, comparison to 1988 emissions, and impact of considering only industrial CO_2 emissions or all CO_2 and CH_4 emissions, in Gt C or C-equivalent per region/country.

the average per capita emissions in the "Southern" regions stay the same as in the base year: a bit over 400 kg of C per inhabitant.

The above results are also mirrored in the absolute changes in emission levels between the reference and target years for the 13 world regions (see Appendix I). It clearly shows that only the last allocation criterion of equal emission rights per capita actually leads to an emission increase in all developing regions (7 to 13) while in all other cases emissions decrease throughout the world. As concluded above, the extent of decrease is quite similar between the *reductive* scenarios analyzed. The principal difference resides in whether a reductive or distributive emission allocation regime will emerge from the international negotiations.

Figure 4.3 illustrates the magnitude of the "North-South" divide in demographics, economics, and historical and current GHG emissions. As such its serves as a "barometer" quantifying various pressures on distributional issues inherent in any climate stabilization strategy. Disparities extend beyond those illustrated in *Figure 4.3*. They entail disparities between GHG

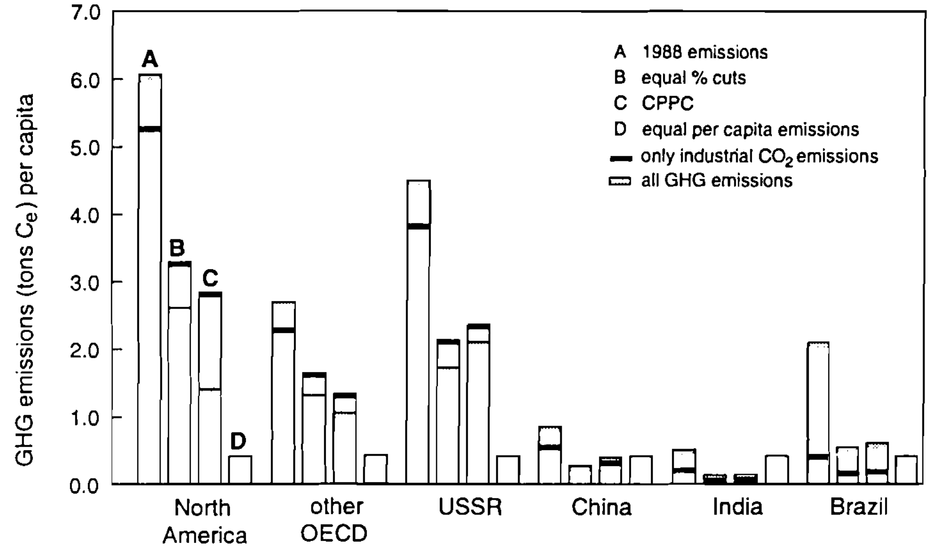
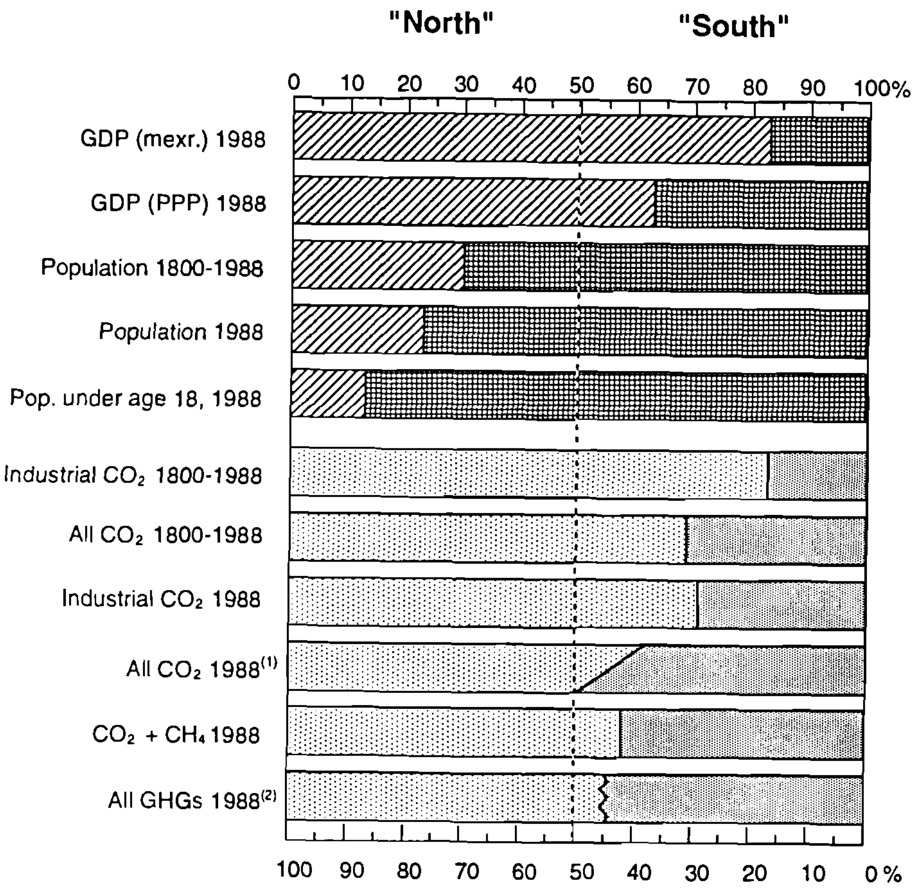


Figure 4.2. A comparison of three allocation criteria for GHG reduction strategies (to 4 Gt C or C-equivalent by 2050) for selected regions/countries. Comparison on *per capita* basis (cf. *Figure 4.1*), in tons C or C-equivalent per capita.

sources and sinks, between benefits accruing from GHG emissions and possible damage of climate change, between different generations of the past, present and future, and more generally between any "winners" and "losers" of GHG control policies.

The different criteria investigated in the present study are mere illustrations of possible outcomes from different GHG allocation and control regimes. The corresponding political process is likely to take considerable time and its results should be judged on its success in reaching an agreement at all – despite all disparities – rather than whether it satisfies "pure" theoretical equity and fairness principles from a philosophical perspective. The criteria studied here and the Parametric Framework developed could assist the process by identifying possible areas of convergence in differences in interests, as well as by quantifying the implications of the different regimes proposed so that possible areas of conflict and priority for negotiation can be identified in an early phase. The approach can also be useful for identifying and comparing regional programs for GHG emission mitigation.



(1) Uncertainty range of 0.8 to 2.6 Gt C biota emissions in the "South"
(2) Approximation

Figure 4.3. The greenhouse "barometer". Regional shares ("North" versus "South") in economic activity, population, and GHG emissions.

5. Conclusions

The quantitative implications of four GHG emission allocation criteria were analyzed for 13 world regions assuming a reduction of global emissions to 4 Gt C (C-equivalent) by the year 2050. For each of the criteria analyzed additional sensitivity analysis were performed. Four major results were obtained, and are detailed below.

1. The most important finding is that there are two different generic types of allocation criteria – we have called them *distributive* and *reductive.* Distributive criteria allocate limited future emissions (e.g., on a per capita basis) while reductive criteria allocate only required emission *reductions.* Across the board percentage cuts (ABPC) and cutbacks proportional to past contributions (CPPC) are examples of reductive criteria. Their advantage is that they are effective in lowering GHG emissions, but they are insensitive to development needs and lead also to widening per capita gaps. Equal emission rights per person (EERP) and natural sink adjusted emissions (NCSC) are examples of distributive criteria. They place a large burden on the "North" by giving more generous emission allocations to the "South" thereby helping the process of economic growth, but do not provide for incentives to curb population growth. The largest differences in emission allocations are obtained between these two criteria compared to any other changes in the analysis.
2. The differences in the emission allocations obtained were smaller within each of the two classes. They were sufficiently small so that the simpler criterion is clearly preferable. For example, one counter-intuitive finding is that across the board percentage cuts (grandfathering) achieve quite similar future emission allocations as cutbacks proportional to past contribution. Historical responsibilities and current emissions have a very similar structure across the world regions and between the "North" and "South". In many ways this is fortunate because it is in practice very difficult to assess the historical responsibilities for individual countries whereas current emissions are much easier to estimate. Similarly, equal per capita emission rights are preferable over allocation of natural sink adjusted emissions, due to the complexity and immense uncertainty surrounding the latter.
3. A consistent finding in the analysis was that the inclusion of different GHGs (comprehensiveness) had a smaller effect on emission allocation than the difference between the two generic classes of allocation criteria. Furthermore, the regional interests with respect to comprehensiveness vary systematically with the type of allocation criterion considered. Therefore, the basic principle of the allocation is more important than the comprehensiveness of the allocation scheme.
4. The smallest of all variations in emission distribution resulted from altering the reference year. Variations in the reference year from 1988 to 1980 made comparatively little difference on the results obtained. Thus, the choice of the base year is less important than the comprehensiveness

of GHGs considered, and the latter in turn is less important than the choice of the generic class of allocation criteria.

A number of priorities for future research can be derived from this analysis. First, analysis should concentrate on the two generic classes of allocation criteria identified rather than on a detailed study within a given class. In addition, any design of new (or multiple) allocation criteria should preferably also include *incentives*, such as efficiency improvements, conservation, or sustainable population development.

Second, required improvements in data should focus on better quality and disaggregation of non-industrial and subsistence level GHG emissions, and refinement of the regional breakdown of the analysis. This would allow for a better distinction to be made between different GHGs as a function of the possibility for policy intervention (e.g., industrial CO_2 emissions versus subsistence rice paddy farming CH_4 emissions), and better capture differences in the socio-economic development status among regions (e.g., between oil exporting and importing countries or between developing and "newly industrializing" countries within a particular region). Better regional differentiation might also facilitate the application of different allocation principles to different groups of countries.

Third, and perhaps most importantly, work should focus on the *dynamic transition paths* implied by different allocation criteria. All of our comparisons were based on two snapshots, the reference and the target year. For further work in this area it will be important to also analyze the shape and type of transition paths from today's to possible future distributions of global GHG emissions. Only a careful analysis of transition paths can give insights into the extent of mitigation required over time, resulting costs, and timing of measures, and thus of the feasibility of compliance with international accords. Making the analysis dynamic could also facilitate contrasting politically negotiated emission targets and estimates of the costs and benefits of GHG mitigation measures and their regional variation. Thus, a feedback between normative allocation regimes, such as the ones analyzed here, and alternative approaches, such as least-cost considerations, could be achieved.

Appendix I

Table A1.1. Different allocation criteria for CO_2 reduction strategies (to 4 Gt C by 2050), fossil fuel and industrial CO_2, Gt C.

		1988 emissions	Equal percent cuts		Cutbacks proportional to past contribution	Equal emission rights per capita (by 2050)
			1988 base	1980 base		
1	OECD NA	1.43	1.01	1.09	0.88	0.13
2	OECD EU	0.85	0.60	0.76	0.41	0.16
3	Eastern EU	0.36	0.25	0.27	0.27	0.06
4	USSR	1.09	0.77	0.71	0.85	0.15
5	Japan	0.27	0.19	0.20	0.21	0.05
6	Oceania	0.07	0.05	0.05	0.05	0.01
7	China	0.61	0.43	0.32	0.52	0.69
8	India	0.17	0.12	0.08	0.14	0.64
9	Other Asia	0.16	0.11	0.09	0.13	0.70
10	NAME[a]	0.24	0.17	0.14	0.21	0.37
11	Other Africa	0.12	0.09	0.08	0.10	0.70
12	Brazil	0.06	0.04	0.04	0.05	0.11
13	Other LatAm	0.24	0.17	0.17	0.18	0.24
	"North" (1–6)	4.07	2.87	3.08	2.67	0.56
	"South" (7–13)	1.60	1.13	0.92	1.33	3.44
	World	5.66	4.00	4.00	4.00	4.00

[a] North Africa and Middle East.

Table A1.2. Different allocation criteria for GHG reduction strategies (to 4 Gt C-equivalent by 2050), CO_2 and CH_4 (all sources), Gt C-equivalent.

		1988 emissions	Equal percent cuts		Cutbacks proportional to past contribution	Equal emission rights per capita (by 2050)
			1988 base	1980 base		
1	OECD NA	1.64	0.81	0.76	0.44	0.13
2	OECD EU	1.00	0.49	0.53	0.32	0.16
3	Eastern EU	0.42	0.21	0.19	0.22	0.06
4	USSR	1.28	0.63	0.52	0.76	0.15
5	Japan	0.29	0.14	0.13	0.20	0.05
6	Oceania	0.11	0.05	0.06	0.03	0.01
7	China	0.92	0.45	0.36	0.66	0.69
8	India	0.41	0.20	0.17	0.21	0.64
9	Other Asia	0.58	0.28	0.39	0.36	0.70
10	NAME[a]	0.30	0.15	0.11	0.22	0.37
11	Other Africa	0.42	0.20	0.30	0.20	0.70
12	Brazil	0.30	0.15	0.13	0.17	0.11
13	Other LatAm	0.47	0.23	0.33	0.20	0.24
	"North" (1–6)	4.73	2.33	2.20	1.97	0.56
	"South" (7–13)	3.39	1.67	1.80	2.03	3.44
	World	8.12	4.00	4.00	4.00	4.00

[a] North Africa and Middle East.

Table A1.3. Different allocation criteria for CO_2 reduction strategies (to 4 Gt C by 2050), fossil fuel and industrial CO_2, absolute changes from 1988 levels, Gt C.

		1988 emissions	Equal percent cuts		Cutbacks proportional to past contribution	Equal emission rights per capita (by 2050)
			1988 base	1980 base		
1	OECD NA	1.43	−0.42	−0.34	−0.55	−1.30
2	OECD EU	0.85	−0.25	−0.09	−0.44	−0.69
3	Eastern EU	0.36	−0.11	−0.09	−0.09	−0.30
4	USSR	1.09	−0.32	−0.38	−0.24	−0.94
5	Japan	0.27	−0.08	−0.07	−0.06	−0.22
6	Oceania	0.07	−0.02	−0.02	−0.02	−0.06
7	China	0.61	−0.18	−0.29	−0.09	+0.08
8	India	0.17	−0.05	−0.09	−0.03	+0.47
9	Other Asia	0.16	−0.05	−0.07	−0.03	+0.54
10	NAME[a]	0.24	−0.07	−0.10	−0.03	+0.13
11	Other Africa	0.12	−0.03	−0.04	−0.02	+0.58
12	Brazil	0.06	−0.02	−0.02	−0.01	+0.05
13	Other LatAm	0.24	−0.07	−0.07	−0.06	±0.00
	"North" (1–6)	4.07	−1.20	−0.99	−1.40	−3.51
	"South" (7–13)	1.60	−0.47	−0.68	−0.27	+1.84
	World	5.66	−1.66	−1.66	−1.66	−1.66

[a] North Africa and Middle East.

Table A1.4. Different allocation criteria for GHG reduction strategies (to 4 Gt C-equivalent by 2050), CO_2 and CH_4 (all sources), absolute changes from 1988 levels, Gt C-equivalent.

		1988 emissions	Equal percent cuts		Cutbacks proportional to past contribution	Equal emission rights per capita (by 2050)
			1988 base	1980 base		
1	OECD NA	1.64	−0.83	−0.88	−1.20	−1.51
2	OECD EU	1.00	−0.51	−0.47	−0.68	−0.84
3	Eastern EU	0.42	−0.21	−0.23	−0.20	−0.36
4	USSR	1.28	−0.65	−0.76	−0.52	−1.13
5	Japan	0.29	−0.15	−0.16	−0.09	−0.24
6	Oceania	0.11	−0.06	−0.05	−0.08	−0.10
7	China	0.92	−0.47	−0.56	−0.26	−0.23
8	India	0.41	−0.21	−0.24	−0.20	+0.23
9	Other Asia	0.58	−0.30	−0.19	−0.22	+0.12
10	NAME[a]	0.30	−0.15	−0.19	−0.08	+0.07
11	Other Africa	0.42	−0.22	−0.12	−0.22	+0.28
12	Brazil	0.30	−0.15	−0.17	−0.13	−0.19
13	Other LatAm	0.47	−0.24	−0.14	−0.27	−0.23
	"North" (1–6)	4.73	−2.40	−2.53	−2.76	−4.17
	"South" (7–13)	3.39	−1.72	−1.59	−1.36	+0.05
	World	8.12	−4.12	−4.12	−4.12	−4.12

[a] North Africa and Middle East.

Table A1.5. Different allocation criteria for CO_2 reduction strategies (to 4 Gt C by 2050), per capita fossil fuel and industrial CO_2, tons C/capita.

	1988 emissions	Equal percent cuts		Cutbacks proportional to past contribution	Equal emission rights per capita (by 2050)
		1988 base	1980 base		
1 OECD NA	5.28	3.26	3.37	2.83	0.42
2 OECD EU	2.22	1.61	1.96	1.11	0.42
3 Eastern EU	3.17	1.91	1.97	2.02	0.42
4 USSR	3.83	2.11	1.87	2.34	0.42
5 Japan	2.20	1.51	1.53	1.64	0.42
6 Oceania	3.69	2.10	1.88	2.23	0.42
7 China	0.56	0.26	0.19	0.32	0.42
8 India	0.21	0.08	0.05	0.09	0.42
9 Other Asia	0.21	0.07	0.05	0.08	0.42
10 NAME[a]	0.73	0.19	0.16	0.23	0.42
11 Other Africa	0.25	0.05	0.05	0.06	0.42
12 Brazil	0.41	0.16	0.15	0.18	0.42
13 Other LatAm	0.84	0.30	0.29	0.32	0.42
"North" (1–6)	3.41	2.16	2.22	2.01	0.42
"South" (7–13)	0.41	0.14	0.11	0.16	0.42
World	1.11	0.42	0.40	0.42	0.42

[a] North Africa and Middle East.

Table A1.6. Different allocation criteria for GHG reduction strategies (to 4 Gt C-equivalent by 2050), per capita CO_2 and CH_4 (all sources), tons C-equivalent/capita.

		1988 emissions	Equal percent cuts		Cutbacks proportional to past contribution	Equal emission rights per capita (by 2050)
			1988 base	1980 base		
1	OECD NA	6.06	2.61	2.46	1.41	0.42
2	OECD EU	2.62	1.32	1.43	0.87	0.42
3	Eastern EU	3.65	1.54	1.43	1.67	0.42
4	USSR	4.50	1.73	1.44	2.10	0.42
5	Japan	2.37	1.13	1.04	1.55	0.42
6	Oceania	5.58	2.22	2.60	1.29	0.42
7	China	0.85	0.28	0.22	0.40	0.42
8	India	0.51	0.13	0.11	0.14	0.42
9	Other Asia	0.75	0.17	0.23	0.22	0.42
10	NAME[a]	0.90	0.17	0.13	0.25	0.42
11	Other Africa	0.87	0.12	0.18	0.12	0.42
12	Brazil	2.09	0.55	0.48	0.61	0.42
13	Other LatAm	1.69	0.42	0.59	0.36	0.42
	"North" (1–6)	3.97	1.75	1.66	1.49	0.42
	"South" (7–13)	0.87	0.20	0.22	0.25	0.42
	World	1.60	0.42	0.42	0.42	0.42

[a] North Africa and Middle East.

Table A1.7. Different allocation criteria for CO_2 reduction strategies (to 4 Gt C by 2050), fossil fuel and industrial CO_2, per capita changes from 1988 levels, tons C/capita.

		1988 emissions	Equal percent cuts		Cutbacks proportional to past contribution	Equal emission rights per capita (by 2050)
			1988 base	1980 base		
1	OECD NA	5.28	−2.02	−1.91	−2.45	−4.86
2	OECD WEU	2.22	−0.61	−0.26	−1.11	−1.80
3	Eastern EU	3.17	−1.26	−1.20	−1.15	−2.75
4	USSR	3.83	−1.72	−1.96	−1.49	−3.41
5	Japan	2.20	−0.69	−0.67	−0.56	−1.78
6	Oceania	3.69	−1.59	−1.81	−1.46	−3.27
7	China	0.56	−0.30	−0.37	−0.24	−0.14
8	India	0.21	−0.13	−0.16	−0.12	+0.21
9	Other Asia	0.21	−0.14	−0.16	−0.13	+0.21
10	NAME[a]	0.73	−0.54	−0.57	−0.50	−0.31
11	Other Africa	0.25	−0.20	−0.20	−0.19	+0.17
12	Brazil	0.41	−0.25	−0.26	−0.23	−0.01
13	Other LatAm	0.84	−0.54	−0.55	−0.52	−0.42
	"North" (1–6)	3.41	−1.25	−1.19	−1.40	−2.99
	"South" (7–13)	0.41	−0.27	−0.30	−0.25	+0.01
	World	1.11	−0.69	−0.71	−0.69	−0.69

[a] North Africa and Middle East.

Table A1.8. Different allocation criteria for GHG reduction strategies (to 4 Gt C-equivalent by 2050), CO_2 and CH_4 (all sources), per capita changes from 1988 levels, tons C-equivalent/capita.

		1988 emissions	Equal percent cuts		Cutbacks proportional to past contribution	Equal emission rights per capita (by 2050)
			1988 base	1980 base		
1	OECD NA	6.06	−3.45	−3.60	−4.65	−5.64
2	OECD EU	2.62	−1.30	−1.19	−1.75	−2.20
3	Eastern EU	3.65	−2.11	−2.22	−1.98	−3.23
4	USSR	4.50	−2.77	−3.06	−2.40	−4.08
5	Japan	2.37	−1.24	−1.33	−0.82	−1.95
6	Oceania	5.58	−3.36	−2.98	−4.29	−5.16
7	China	0.85	−0.57	−0.63	−0.45	−0.43
8	India	0.51	−0.38	−0.40	−0.37	−0.09
9	Other Asia	0.75	−0.58	−0.52	−0.53	−0.33
10	NAME[a]	0.90	−0.73	−0.77	−0.65	−0.48
11	Other Africa	0.87	−0.75	−0.69	−0.75	−0.45
12	Brazil	2.09	−1.54	−1.61	−1.48	−1.67
13	Other LatAm	1.69	−1.27	−1.10	−1.33	−1.27
	(“North(” (1–6)	3.97	−2.22	−2.31	−2.48	−3.55
	(“South(” (7–13)	0.87	−0.67	−0.65	−0.62	−0.45
	World	1.60	−1.18	−1.18	−1.18	−1.18

[a] North Africa and Middle East.

Appendix II

Data Sources for the GHG emission inventory of the Parametric Framework.

Industrial CO_2 Emissions

These include CO_2 emissions from the burning of fossil fuels coal, oil, and natural gas as well as emissions from flaring of natural gas and the manufacture of cement.

1950-1988. Source: Marland *et al.* , 1989. Estimates based on UN energy balances and cement manufacturing data of the US Bureau of Mines and using the methodology developed by Marland and Rotty (1983). An updated data base covering the period 1950 to 1988 was used. Emissions by source and per country were aggregated to the 13 world regions/countries of the Parametric Framework.

1800-1949. Fossil Fuels: Estimates adapted from Fujii (1990) and modified to the 13 regional breakdown of the Parametric Framework. Data based on energy balances from Darmstadter *et al.* (1971) for the period 1925 to 1950. For earlier years, apparent consumption (production – exports + imports) based on physical output statistics from Mitchell (1980, 1982, 1983) and aggregations of time series of national energy balances were used. Data sources include: Canada: Urquhart and Buckley (1965); Germany: Schilling and Hildebrandt (1977); UK and USA: Nakićenović (1984); USSR and Tsarist Russia: Fetisov (1991); all other countries: Woytinsky (1926). Energy consumption data were calibrated with emission factors to yield 1950 carbon emissions consistent with the UN data set estimates of Marland *et al.* (1989).

Pre-1950. Gas flaring and cement manufacture: Activity data from Valais *et al.* (1982) and Schurr and Netschert (1960) for gas flaring, and Zimmermann (1951) and Woytinsky and Woytinsky (1953) for cement manufacture. Regional carbon emission factors of gas flaring calibrated with 1950 gas flaring CO_2 emissions (Marland *et al.*, 1989), for cement manufacture an emission factor of 0.134 tons carbon per ton cement was used.

Biota Carbon Emissions

This includes carbon emissions due to land-use changes, i.e., carbon emissions from burning and organic decay of vegetation and carbon releases from soil in conjunction with changing land-use patterns.

1988· Conservative, low-range estimates, as discussed in Section 2.1.2 and *Table 2.4*. Estimates assume zero carbon balance for temperate latitude vegetation systems, and global net emissions of 800 Mt C (lower bound of IPCC range) from tropical latitudes.

1800-1980: Adapted from estimates for 8 world regions made by Houghton and Skole (1990) based on a detailed "bookkeeping" model of land-use changes and related carbon release profiles of different ecosystems. Original data were retained for North America, USSR, Oceania, China, and Latin America. National estimates and regional breakdown derived from original data (Houghton and Skole, 1990) for Western and Eastern Europe, Japan, India, and Brazil assume that subregional and national emissions are in the same proportion as the national/regional carbon releases due to agricultural land-use conversions over the periods 1860–1920 and 1920–1978 estimated by Richards *et al.* (1983). The latter estimate covers approximately half of the total biotic carbon releases (62.4 Gt C between 1860 and 1978) compared to 120 Gt C of the Parametric Framework over the period 1850–1985, which includes also deforestation and land-use changes not related to the expansion of regular cropping areas.

Data between 1980 and 1988 were interpolated exponentially with the exception of Brazil where an average biotic carbon release of 160 Mt C/year over the 1980s was assumed. Releases in individual years have been irregular and can be substantially higher than the 10-year average value assumed here. It should be noted that historical and current biotic carbon release estimates may not be comparable directly as based on different data sources using different methodologies. In particular historical carbon releases estimated by Houghton and Skole (1990) assume higher carbon content of vegetation and soil systems than suggested by the authors in later publications (cf. Houghton, 1991) and adopted as conservative estimates for the 1988 values of the Parametric Framework.

Anthropogenic Methane Emissions

The Parametric Framework includes estimates of five major sources of anthropogenic methane emissions for the 13 world regions from 1950 to 1988. Longer time series were not required due to the limited residence time of methane in the atmosphere of about 10 years. These time series were estimated as a function of anthropogenic activity levels directly associated with the five emission categories. First, the five activity levels were derived from the appropriate data sources for the 13 regions for the period from 1950 to 1988 and then multiplied by regional emission factors by source. Thus, we have implicitly assumed that the methane emission factors have not changed substantially during this period within each of the five emission categories in the respective regions. This is a strong assumption that had to be made due to the lack of explicit emission estimates for the period. The factors are based on emission estimates and activity levels for the years 1984 to 1988 from the following data sources: Crutzen *et al.* (1986); Matthews *et al.* (1991); Lerner *et al.* (1988); Cicerone and Oremland (1988); IPCC (1990, 1992);

Crutzen (1991); Hogan *et al.* (1991); and Subak *et al.* (1991). The relevant data sources used in deriving the anthropogenic activity levels for the estimation of the five anthropogenic methane emission categories are given below.

1. Methane emissions are caused by enteric fermentation in ruminant animals, including all cattle, sheep, other livestock, wild animals, and the rest by the decomposition of animal waste. Our estimate of global emissions from all domestic cattle and sheep is about 105 Tg of methane which is in the middle of the ranges given by Crutzen *et al.* (1986); Lerner *et al.* (1988); IPCC (1990); Hogan *et al.* (1991); and Subak *et al.* (1991). The specific emissions depend on the animal populations as well as on the size of the individual animals, the amount and type of food. Our estimates are based on the size of the animal population in the 13 world regions. The livestock numbers are from selected agricultural production statistics published by FAO (1963, 1971, 1975, 1976, 1986, 1989).
2. The main sources of energy-related methane emissions are underground coal mining, oil and gas production, and natural gas transport and distribution. Most of the methane released from coal production is due to underground coal mining. Methane leakage from pipelines and venting from oil and gas wells is the other important source. While the production of fossil energy sources is known with a rather high degree of precision the actual methane emission factors are only indicative. Thus, the overall fossil energy methane emissions are not well known. Our estimates are based on the coal and natural gas primary energy consumption (including associated gas from oil production) and stem from the same sources as the estimates of carbon dioxide emissions from coal and natural gas given above.
3. Methane emissions from rice paddies depend on a number of factors that vary regionally and annually including fertilization, water and crop management, growing period, and paddy characteristics. The majority of emissions arise under wet rice cultivation which represents almost 85 percent of the worldwide cultivation area. Our estimates of the historical emissions are based on rice production in the 13 world regions. The implicit (and probably unrealistic) assumption is that the ratio of wet rice production to total regional production has not changed drastically since 1950. The rice production data are from selected agricultural production statistics published by FAO (1963, 1971, 1975, 1976, 1986, 1989).
4. Methane emissions from landfills are caused by the anaerobic decay or organic wastes and are a function of municipal waste generation and disposal practices, landfilling rates, types of waste material such as their average hydrocarbon content and conversion and outgasing rates of methane. Our estimates of the historical emissions are based on population size in the 13 world regions between 1950 and 1988. In fact where actually measured, the methane emissions from landfills are closely correlated with levels of population and economic activities. Sources of historical population data for the 13 world regions are given below.

5. Methane emissions associated with land clearing, biomass burning and deforestation in general depend on many factors including the amount of biomass burnt each year in different regions by type of vegetation, fraction of wood or biomass removed and used for other purposes from the cleared areas, the kind of burning (e.g., flaming, charcoal, smouldering, fires, etc.). The relative magnitude of our estimates is, however, in the lower range with about 30 Tg. This is consistent with our relatively low estimates of CO_2 emissions from biomass burning. Historical estimates were derived by assuming that they are proportional to carbon dioxide emissions from biotic sources such as deforestation and unsustainable biomass burning. The factor of proportionality was fixed for the period 1984 to 1988 and applied to the time series on biota carbon dioxide emissions given above.

Additional Socio-economic Background Data

Population

1800–1988: Time series adapted from Fuji (1990) and complemented by estimates from Durand (1967), Demeny (1990), and Mitchell (1980, 1982, 1983) to yield the 13 geographical regions of the Parametric Framework. The 1988 adult population (over 18 years of age) is from the UN (1990).

1989–2100: Based on World Bank population projections (Zachariah and Vu, 1988).

Gross Domestic Product (GDP)

1988 data in US\$1988 are from *The Economist* (1990). For non-convertible currencies *The Economist* (1990) uses "compromise" exchange rates, yielding, for instance, for the former USSR a per capita GDP level of US\$2,055. This is a more realistic estimate than traditional (e.g., CIA) estimates yielding up to US\$8,819 per capita (US DOC, 1991). In the report (but not yet included in the Parametric Framework) purchasing power parity (PPP) GDP estimates were also used in the comparisons. Data are derived from UNDP (1990). National per capita PPP GDP estimates were recalculated with 1988 population figures (*The Economist*, 1990) to yield total PPP GDP, and then aggregated to the 13 regions used in the study.

Land Area

Total land area data are derived from FAO (1989) Production Statistics. National and regional estimates were adjusted to the 13 regions of the Parametric Framework.

Appendix III
The Parametric Framework

General Information

The Parametric Framework is programmed in Lotus 1-2-3 release 2.3. The software package contains data for 13 world regions (see *Figure 2.1* above and the section on Regional Land Area below) on: land area, population, carbon dioxide, and methane emissions by source. The Parametric Framework consists of seven data files, a work file, and a library. Numerical data are contained in the files LAND.WK1, PAST.WK1, and WB_POP.WK1. The files CON_FOSS.WK1, CON_CARB.WK1, CON_GHG.WK1, and METHANE.WK1, are used for GHG accounting and for calculating regional contributions to historical concentration increase. Finally, the major tool for calculating various GHG allocation scenarios is the spreadsheet WORKFILE.WK1 and its associated library WORKFILE.MLB.

Before invoking the Parametric Framework, all of these files are to be copied to the directory from which Lotus 1-2-3 can be called and which is recognized as default setup.[1] All communication with the Parametric Framework is menu driven and done by scrolling and entering the appropriate commands and/or required information.

Calling the Parametric Framework

Lotus 1-2-3 is called from the default directory where the Parametric Framework files are stored. After calling Lotus 1-2-3, load the file WORKFILE.WK1, choose the Lotus "Add-in" menu option, load the file MACROMGR.ADN and invoke the library WORKFILE.MLB. Thereafter, all communications with the Parametric Framework are done in the WORKFILE.WK1 and are menu-driven. WORKFILE.WK1 performs all of the calculations and data manipulations for the four allocation criteria. To move over the screen (worksheet) just scroll up, down, left, and right (note that results are also displayed beyond column "F" on the screen). The screen is updated automatically after the prompted information is changed or new parameter values (to unprotected cell ranged) are assigned. To move from one allocation criterion to another, press "ALT-F3" and type a MACRO name and press ENTER. The MACRO names refer to the four allocation criteria: ABPC for across the board percentage cuts; EERP for equal emission rights per person; CPPC for cutbacks proportional to past contributions; and NCSC for natural carbon sink per capita. Use MENU to return to the main menu. The results from

---

[1] Proper setup specification is required for the Parametric Framework to work (otherwise, error (ERR) messages will appear throughout the spreadsheets). To check and modify setup, use the worksheet-global-default-directory Lotus menu sequence.

any Parametric Framework run can be printed and/or plotted using the standard Lotus 1-2-3 menu options. As all calculations for different criteria are performed within WORKFILE.WK1, a comparison of different scenarios is also possible using standard Lotus print and graphic features (see the section on comparing model runs below). A sample run of the Parametric Framework is given below.

Changing the Data Files

The Parametric Framework includes a complete data set contained in the seven Lotus 1-2-3 spreadsheets. Data are disaggregated for 13 world regions. The aggregation level cannot be changed, but the data themselves can be changed and/or modified (if required, protected ranges have first to be "unprotected" by the respective Lotus option). Data include regional land area, historical population levels and future population projections, historical carbon dioxide emissions by major source, and historical methane emissions. Next, a short description is given of each of the seven data files and instructions are given on how the files are to be updated and stored so that they can be used by the Parametric Framework.

Regional Land Area

Spreadsheet LAND.WK1 contains the data on the land area for the 13 regions of the world defined as follows:

1. North America (USA and Canada).
2. Western Europe (including Greece and the former GDR; excluding Yugoslavia and Turkey).
3. Eastern Europe (excluding the former USSR and the former GDR; including Yugoslavia).
4. USSR (ex-USSR, and Russia prior to 1917).
5. Japan.
6. Oceania (Australia and New Zealand).
7. China (mainland only).
8. India.
9. Rest of Asia (excluding the Middle East countries, China, India; including Mongolia, Afghanistan, Pakistan, Korea (North and South), and remaining Indian Ocean and Pacific Asian countries.
10. North Africa and Middle East ("NAME", including Turkey and Iran).
11. Rest of Africa (Africa outside North Africa).
12. Brazil.
13. Rest of Latin America (Latin America excluding Brazil).

DEVELOPED COUNTRIES (regions 1 to 6)
LESS DEVELOPED COUNTRIES (regions 7 to 13)
WORLD

The regional disaggregation cannot be changed within the Parametric Framework, however, data can be changed and/or modified by invoking Lotus 1-2-3 and loading LAND.WK1. The file has to be saved under the same name so that it can be used by the Parametric Framework.

Future Population Projections

WB_POP.WK1 contains population projections (Zachariah and Vu, 1988) in millions for the 13 regions of the Parametric Framework for the period 1989 to 2100. For changing values, load, modify, and save WB_POP.WK1 for subsequent use of alternative future population data by the program.

Historical Data

PAST.WK1 contains historical time series for population in millions from 1800 to 1988; carbon dioxide emissions in gigatons of carbon from 1800 to 1988 disaggregated into industrial and biota sources; methane emissions in teragrams of methane from 1950 to 1988. The data can be changed and/or modified by invoking Lotus 1-2-3 and loading PAST.WK1. In order to be used by the Parametric Framework, the file has to be saved under the same name and then the following files have to be retrieved and saved in consecutive order: CON_CARB.WK1, CON_FOSS.WK1, METHANE.WK1, CON_GHG.WK1. Additional socio-economic background data (adult population and GDP) are stored directly in WORKFILE.WK1 and can be changed there.[2]

GHG Equivalences

PAST.WK1 also calculates aggregated historical time series required by the Parametric Framework – total carbon dioxide emissions and total carbon dioxide and methane emissions (i.e., total greenhouse gases emissions) by summing the relevant subcategories for each year. The latter are calculated using a methane to carbon dioxide equivalence factor on a mass basis. The assumed default value is 21. Following the convention of the Parametric Framework, aggregated GHG emissions are expressed as tons carbon-equivalent (to convert to tons CO_2-equivalent multiply by 3.66). The methane equivalence factor can be changed into any other appropriate value, but it must be loaded into the Parametric Framework by first saving PAST.WK1 under the same name and then loading and saving CON_GHG.WK1.

---

[2] For changes first clear "window" "title" via the respective Lotus menu. Data are stored in the ranges EE9.. (adult population) and EF9.. (GDP). After changing, go (F5) back to field a131 and restore "horizontal" "title" and save WORKFILE.WK1.

Atmospheric concentrations

The spreadsheet CON_FOSS.WK1 calculates regional contributions to atmospheric carbon concentrations due to industrial sources of carbon dioxide (including fossil energy, cement production, and gas flaring) and CON_CARB.WK1 calculates regional contributions to atmospheric carbon concentrations due to total carbon dioxide emissions (including also biota sources of CO_2). In both cases the contributions to atmospheric concentrations are calculated using an ocean uptake constant for the following time intervals: 1800–1970, 1800–1971, ... , 1800–1988. The default value for the ocean uptake constant is assumed to be 300 years (i.e., discounting emissions at a rate of 0.3 percent per year). To change the value, load spreadsheet CON_CARB.WK1, make changes and save under the same name, then retrieve spreadsheet CON_FOSS.WK1 (the new value will appear on the screen) and save under the same name.

The spreadsheet METHANE.WK1 calculates regional contributions to the methane concentrations from emissions over the period 1950 to 1988 which remain currently in the atmosphere. This spreadsheet calculates intermediate numbers, using a methane decay constant. Its default value is assumed to be 25 percent per a year of the (remaining) emitted quantity, corresponding to an average atmospheric residence time of methane of about 10 years. To change the value, load spreadsheet METHANE.WK1, change the value and save the file under the same name and then retrieve CON_GHG.WK1 (saving it under the same name).

CON-GHG.WK1 calculates regional contributions to atmospheric carbon equivalent concentrations due to both carbon dioxide and methane emissions. Regional contributions are calculated for the following time intervals: 1800–1970, 1800–1971, ... , 1800–1988. Carbon dioxide and methane concentrations are calculated individually as explained in the two preceding paragraphs and are then added using the methane to carbon dioxide equivalence factor on a mass basis. To change the equivalence factor see the section on GHG equivalences above. To change the long-term ocean uptake constant for CO_2 see section on atmospheric concentrations above.

Comparing Model Runs

Different model runs can be compared from the data, all stored in WORKFILE.WK1. After running individual scenarios with consistent definitions of reference and target year, type of GHGs considered, and global emission target values, results can be further processed using standard Lotus print and graphics options. Prespecified graphics help the visualization of the results of individual model runs and to compare different allocation criteria. To this end WORKFILE.WK1 contains the following graphics, to be invoked by the "name" and "use" options of the Lotus graphics menu. Resulting regionalized emission allocation between the chosen base year and target year can be compared on absolute (_ABS) and on a per capita (_PCP) basis. Graphic CR_1_ABS and CR_1_PCP show absolute and per capita regional allocations for criterion 1 (across the board percentage cuts). Graphics for the other criteria are set up identically: CR_2_ABS and CR_2_PCP for equal emission rights per person, CR_3_ABS and CR_3_PCP for cutbacks proportional to past contributions, and CR_4_ABS and CR_4_PCP for natural sink adjusted emissions. Comparison of 1988 emissions and target year allocations *between* different criteria (ABPC, CPPC, EERP) are shown on the graphics ABS_CRIT and PCP_CRIT on absolute and per capita basis respectively.

A Sample Run of the Parametric Framework

```
                                 A                                  EZ
1   CARBON EMISSION MODEL: Model uses following parameters:
2       Ocean Uptake Constant (T, years)..........................:   300
3       Methane Removal from the Atmosphere (%decay per year).....:  25.00%
4       Carbon Equivalent Factor of Methane.......................:    21
5     If you want to change parameters, load, make changes and then
6       save again following spreadsheets (in consecutive order):
7       past.wk1, con_carb.wk1, con_foss.wk1, methane.wk1, con_ghg.wk1.
                 A                B         C         D         E         F
120
121 -------------------------------------------------------------------
122 Define current model by using MACRO: press "ALT-F3", then type:
123   Across the Board Percentage Cuts............................:  ABPC
124   Equal Emission Rights per Head of Population................:  EERP
125   Cutbacks Proportional to Past Contribution..................:  CPPC
126   Natural Carbon Sink per Capita..............................:  NCSC
127 If MACRO does not work, you have to load and add-in (see options of the
128 Lotus 123 menu) to the memory program MACROMGR.ADN (provided with Lotus
129 123 software), then activate program and load library WORKFILE.MLB.
130 ===================================================================
```

```
131
132 Welcome to the environment of scenario #1:
133 ACROSS THE BOARD PERCENTAGE CUTS, WITH SENSITIVITY ANALYSIS FOR CHOICE
134   OF BASE YEAR (to return to the menu press "ALT-F3", then type "MENU")
135 Define base and target years: BASE   PRESENT   TARGET % DECAY IS DEFINED
136 Define in columss B and D:     1985     1988     2050   FOR THE PERIOD
137 a base year from the range ---------------------------  PRESENT..TARGET
138 1970..1988; a target year from the range 1989..2100. Please also specify
139 ---------------------------  what kind of data you want to see in the
140 The workspace is below.----  column F (INFO) just for information: type
141 Use arrow keys to move.----  "1" in the column F for the data of your
142 You can also look at the---  choice and "0" for all other ones:
143 the same scenario #1 in----  Regional Land Size, TKm2.........:      0
144 per capita terms in the----  1988 Regional Population, mlns...:      0
145 colums G..J.---------------  1988 Regional Adult Popul., mlns.:      1
146 Please do not forget that--  Regional 1988 GDP, mlns $........:      0
147 you can put "1" only in----  1988 Fossil Fuel Emissions, Gt C.:      0
148 one cell in the column F,--  1988 Total CO2 Emissions, Gt C...:      0
149 otherwise you may receive--  1988 GHG Emissions, Gt C equiv...:      0
150 a wrong number in the cell-  1988 Population Density, 000/Km2.:      0
151 F160: workspace is below.--  1988 GHG/Land, Mt/Km2............:      0
152 Please do not forget that--  1988 Fossil Fuel per Capita, t C.:      0
153 you can put "1" only in----  1988 Total CO2 per Capita, t C...:      0
154 one cell in the column F,--  1988 GHG per Capita, t C equiv...:      0
155 otherwise you may receive--  1988 Fossil/Adult Capita, t C....:      0
156 a wrong number in the cell-  1988 Total CO2/Adult Capita, t C.:      0
157 F160.----------------------  1988 GHG/Adult Capita, t C equiv.:      0
158 You can put "1" only in----  1988 Fossil/GDP, Kg C/1988 $.....:      0
159 one cell in the column F.--  1988 Total CO2/GDP, Kg C/1988 $..:      0
160 The workspace is below.----  1988 GHG/GDP, Kg C equiv./1988 $.:      0
161
162 -----------------------------------------------------------------------
163 Define the type of Greenhouse Gas: type "1" in the column F for
164   the Greenhouse Gas you currently work with, and type "0" for
165   all other ones. WARNING! You can put "1" only in one cell.
166     Fossil Fuels and Industry Carbon Dioxide Emissions........:      0
167     Total CO2 Emission (Fossil Fuels, Industry and Biota).....:      0
168     Total GHG Emissions (Carbon Dioxide and Methane)..........:      1
169 -----------------------------------------------------------------------
170 Define emissions in target year as % of emissions in ref. year:   49.24%
171 -----------------------------------------------------------------------
172 REGIONS                             EMISSION, Gt C       ANNUAL
173                                1985      1988      2050  % DECAY   INFO
174 -----------------------------------------------------------------------
175   North America...........:1.523194 1.640520 0.750020    -1.25% 210.109
176   Western Europe..........:1.027420 0.998494 0.505901    -1.09% 294.138
177   Eastern Europe..........:0.409183 0.416638 0.201481    -1.16%  91.608
178   USSR....................:1.169931 1.276643 0.576074    -1.28% 208.529
179   Japan...................:0.275273 0.290202 0.135544    -1.22%  94.516
180   Oceania.................:0.102588 0.109683 0.050514    -1.24%  14.405
181   China...................:0.828379 0.918007 0.407893    -1.30% 732.602
182   India...................:0.382911 0.411972 0.188545    -1.25% 465.486
183   Rest of Asia............:0.789934 0.575672 0.388963    -0.63% 434.401
184   North Africa & Mid. East:0.272597 0.295806 0.134226    -1.27% 163.282
185   Rest of Africa..........:0.478317 0.416193 0.235523    -0.91% 248.332
186   Brazil..................:0.287963 0.300735 0.141793    -1.21%  85.813
187   Rest of Latin America...:0.516694 0.473722 0.254420    -1.00%  161.29
188   DEVELOPED COUNTRIES.....:4.507590 4.732181 2.219537    -1.21%
189   LESS DEVELOPED COUNTRIES:3.556798 3.392109 1.751367    -1.06%
190   WORLD...................:8.064389 8.124291 3.970905    -1.15%
191 -----------------------------------------------------------------------
192 The end of the workspace. To return to the menu press "ALT-F3", then typ
193
```

```
                  A                        B        C        D        E        F
205 Welcome to the environment of scenario #2:
206 EQUAL EMISSION RIGHTS PER HEAD OF PRESENT (OR FUTURE) POPULATION
207   (to return to the menu press "ALT-F3", then type "MENU")
208 Define base and target years: BASE   PRESENT   TARGET % DECAY IS DEFINED
209 Define in columss B and D:     1985     1988     2050   FOR THE PERIOD
210 a base year from the range -------------------------- PRESENT..TARGET
211 1970..1988; a target year from the range 1989..2100. Please also specify
212 -------------------------  what kind of data you want to see in the
213 The workspace is below.----  column F (INFO) just for information: type
214 Use arrow keys to move.----  "1" in the column F for the data of your
215 You can also look at the---  choice and "0" for all other ones:
216 the same scenario #1 in----  Regional Land Size, TKm2.........:        0
217 per capita terms in the----  1988 Regional Population, mlns...:        0
218 colums G..J.---------------  1988 Regional Adult Popul., mlns.:        1
219 Please do not forget that--  Regional 1988 GDP, mlns $........:        0
220 you can put "1" only in----  1988 Fossil Fuel Emissions, Gt C.:        0
221 one cell in the column F,--  1988 Total CO2 Emissions, Gt C...:        0
222 otherwise you may receive--  1988 GHG Emissions, Gt C equiv...:        0
223 a wrong number in the cell-  1988 Population Density, 000/Km2.:        0
224 F160: workspace is below.--  1988 GHG/Land, Mt/Km2............:        0
225 Please do not forget that--  1988 Fossil Fuel per Capita, t C.:        0
226 you can put "1" only in----  1988 Total CO2 per Capita, t C...:        0
227 one cell in the column F,--  1988 GHG per Capita, t C equiv...:        0
228 otherwise you may receive--  1988 Fossil/Adult Capita, t C....:        0
229 a wrong number in the cell-  1988 Total CO2/Adult Capita, t C.:        0
230 F160.----------------------  1988 GHG/Adult Capita, t C equiv.:        0
231 You can put "1" only in----  1988 Fossil/GDP, Kg C/1988 $.....:        0
232 one cell in the column F.--  1988 Total CO2/GDP, Kg C/1988 $..:        0
233 The workspace is below.----  1988 GHG/GDP, Kg C equiv./1988 $.:        0
234
235 ------------------------------------------------------------------------
236 Define the type of Greenhouse Gas: type "1" in the column F for
237   the Greenhouse Gas you currently work with, and type "0" for
238   all other ones. WARNING! You can put "1" only in one cell.
239     Fossil Fuels and Industry Carbon Dioxide Emissions........:        0
240     Total CO2 Emission (Fossil Fuels, Industry and Biota).....:        0
241     Total GHG Emissions (Carbon Dioxide and Methane)..........:        1
242 ------------------------------------------------------------------------
243 REGIONS                      EMISSION PER CAPITA, t C   ANNUAL
244 Define: D246 only              1985      1988     2050  % DECAY   INFO
245 ------------------------------------------------------------------------
246   North America...........:5.783297 6.063112   0.4192    -4.22%5.292564
247   Western Europe..........:2.699014 2.616741   0.4192    -2.91%2.221669
248   Eastern Europe..........:3.653422 3.653897   0.4192    -3.43%3.166278
249   USSR....................:4.226410 4.498331   0.4192    -3.76%3.826584
250   Japan...................:2.290983 2.366815   0.4192    -2.75%2.200141
251   Oceania.................:5.399402 5.581462   0.4192    -4.09%3.685588
252   China...................:0.796250 0.846105   0.4192    -1.13%0.562138
253   India...................:0.500442 0.507815   0.4192    -0.31%0.215273
254   Rest of Asia............:1.095232 0.747279   0.4192    -0.93%0.608834
255   North Africa & Mid. East:0.899957 0.899723   0.4192    -1.22%0.734442
256   Rest of Africa..........:1.099075 0.869844   0.4192    -1.17%0.571842
257   Brazil..................:2.124191 2.086149   0.4192    -2.56%1.528038
258   Rest of Latin America...:1.942974 1.685072   0.4192    -2.22%1.267336
259   DEVELOPED COUNTRIES.....:3.846025 3.969128   0.4192    -3.56%
260   LESS DEVELOPED COUNTRIES:0.970122 0.869965   0.4192    -1.17%
261   WORLD...................:1.666763 1.595695   0.4192    -2.13%
262 ------------------------------------------------------------------------
263 The end of the workspace. To return to the menu press "ALT-F3", then typ
264
```

```
             A                     B        C        D        E         F
276 Welcome to the environment of scenario #3:   CUTBACKS PROPORTIONAL TO
277   PAST CONTRIBUTIONS TO CONCENTRATION INCREASE ON A REGION BASIS
278     (to return to the menu press "ALT-F3", then type "MENU")
279 Define base and target years: BASE    PRESENT   TARGET % DECAY IS DEFINED
280 Define in colums B and D:       1985     1988     2050   FOR THE PERIOD
281 a base year from the range -------------------------- PRESENT..TARGET
282 1970..1988; a target year from range 1989..2100. To run this scenario,
283 ---------------------------  you have to specify also absolute emission
284 The workspace is below.----  level in target year for the World total
285 Use arrow keys to move.----  (define in the bottom cell of the column D
286 You can also look at the---  of the workspace below). In the column F
287 the same scenario #3 in----  you can always see regional contributions
288 per capita terms in the----  to atmospheric carbon concentration due to
289 colums G..J.---------------  the emissions of the Greenhouse gas you
290                              currently work with.
291 ----------------------------------------------------------------------
292 Define the type of Greenhouse Gas: type "1" in the column F for
293   the Greenhouse Gas you currently work with, and type "0" for
294   all other ones. WARNING! You can put "1" only in one cell.
295     Fossil Fuels and Industry Carbon Dioxide Emissions........:       0
296     Carbon Dioxide Emission (Fossil Fuels, Industry and Biota):       0
297     Total GHG Emissions (Carbon Dioxide and Methane)..........:       1
298 ----------------------------------------------------------------------
299 Caution: negative emissions in column D mean that reduction below 0
300   emissions is required, i.e. the region has a net emission deficit in a
301   target year. Error message in the column E indicates that exponential
302   % decay is not defined for negative emissions.
303 ----------------------------------------------------------------------
304 REGIONS                             EMISSION, Gt C    ANNUAL
305 Define: D322 only.              1985     1988     2050  % DECAY   INFO
306 ----------------------------------------------------------------------
307   North America...........:1.523194 1.640520 0.418436    -2.18%  29.63%
308   Western Europe..........:1.027420 0.998494 0.315335    -1.84%  16.56%
309   Eastern Europe..........:0.409183 0.416638 0.225145    -0.99%   4.64%
310   USSR....................:1.169931 1.276643 0.775978    -0.80%  12.14%
311   Japan...................:0.275273 0.290202 0.201213    -0.59%   2.16%
312   Oceania.................:0.102588 0.109683 0.029260    -2.11%   1.95%
313   China...................:0.828379 0.918007 0.667581    -0.51%   6.07%
314   India...................:0.382911 0.411972 0.209712    -1.08%   4.90%
315   Rest of Asia............:0.789934 0.575672 0.363141    -0.74%   5.15%
316   North Africa & Mid. East:0.272597 0.295806 0.228552    -0.42%   1.63%
317   Rest of Africa..........:0.478317 0.416193 0.198866    -1.18%   5.27%
318   Brazil..................:0.287963 0.300735 0.166071    -0.95%   3.27%
319   Rest of Latin America...:0.516694 0.473722 0.200703    -1.38%   6.62%
320   DEVELOPED COUNTRIES.....:4.507590 4.732181 1.965370    -1.41%  67.09%
321   LESS DEVELOPED COUNTRIES:3.556798 3.392109 2.034629    -0.82%  32.91%
322   WORLD...................:8.064389 8.124291        4    -1.14% 100.00%
323 ----------------------------------------------------------------------
324 The end of the workspace. To return to the menu press "ALT-F3", then typ
325
```

```
                     A                B      C      D      E      F
337 Welcome to the environment of scenario #4:  EQUAL EMISSION RIGHTS PER
338   CAPITA FOR EMISSIONS EQUIVALENT TO NATURAL CARBON SINKS, UNIFORM
339   CUTBACKS OF EMISSIONS CURRENTLY EXCEEDING THESE LEVELS.
340     (to return to the menu press "ALT-F3", then type "MENU")
341 Define base and target years: BASE   PRESENT   TARGET % DECAY IS DEFINED
342 Define in colums B and D:       1985      1988      2050   FOR THE PERIOD
343 a base year from the range -------------------------- PRESENT..TARGET
344 1970..1988; a target year from range 1989..2100. In the column D natural
345 -------------------------- carbon sink in the reference year is given
346 The workspace is below.---- on per capita basis for the target year.
347 Use arrow keys to move.---- In the column F you can always see regional
348 You can also look at the--- population for the target year of your
349 the same scenario #4 in---- choice.
350 absolute terms in the------
351 colums G..J.---------------
352
353 ------------------------------------------------------------------------
354 Define the type of Greenhouse Gas: type "1" in the column F for
355   Greenhouse Gas you currently work with, and type "0" for all
356   other ones. WARNING! You can put "1" only in one cell.
357     Fossil Fuels and Industry Carbon Dioxide Emissions........:        0
358     Carbon Dioxide Emission (Fossil Fuels, Industry and Biota):        0
359     Total GHG Emissions (Carbon Dioxide and Methane)..........:        1
360 ------------------------------------------------------------------------
361 Total level of emissions, you currently work with, in the reference
362   year.....................     1985 is, Gt C...................:8.064389
363 Define natural carbon sink in the reference year, Gt C........:        4
364   (usually sink is assumed to be approximately about 50% of emissions;
365     the rest is the airborn fraction).
366 ------------------------------------------------------------------------
367 REGIONS                         EMISSION PER CAPITA, t C   ANNUAL
368 Define: F363 only                  1985      1988     2050 % DECAY  INFO
369 ------------------------------------------------------------------------
370   North America...........:5.783297 6.063112 0.419173    -4.22%309.9531
371   Western Europe..........:2.699014 2.616741 0.419173    -2.91%371.3646
372   Eastern Europe..........:3.653422 3.653897 0.419173    -3.43%133.2022
373   USSR....................:4.226410 4.498331 0.419173    -3.76%363.2212
374   Japan...................:2.290983 2.366815 0.419173    -2.75%126.2901
375   Oceania.................:5.399402 5.581462 0.419173    -4.09%24.33513
376   China...................:0.796250 0.846105 0.419173    -1.13%1638.934
377   India...................:0.500442 0.507815 0.419173    -0.31%1527.840
378   Rest of Asia............:1.095232 0.747279 0.419173    -0.93%1666.280
379   North Africa & Mid. East:0.899957 0.899723 0.419173    -1.22%875.9147
380   Rest of Africa..........:1.099075 0.869844 0.419173    -1.17%1674.618
381   Brazil..................:2.124191 2.086149 0.419173    -2.56%269.7288
382   Rest of Latin America...:1.942974 1.685072 0.419173    -2.22%560.9025
383   DEVELOPED COUNTRIES.....:3.846025 3.969128 0.419173    -3.56%1328.366
384   LESS DEVELOPED COUNTRIES:0.970122 0.869965 0.419173    -1.17%8214.220
385   WORLD...................:1.666763 1.595695 0.419173    -2.13%9542.586
386 ------------------------------------------------------------------------
387 The end of the workspace. To return to the menu press "ALT-F3", then typ
388
```

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