On strategies for reducing greenhouse gas emissions

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Equity is of fundamental concern in the quest for international cooperation to stabilize greenhouse gas concentrations by the reduction of emissions. By modeling the carbon cycle, we estimate the global CO_2 emissions that would be required to stabilize the atmospheric concentration of CO_2 at levels ranging from 450 to 1,000 ppm. These are compared, on both an absolute and a per-capita basis, to scenarios for emissions from the developed and developing worlds generated by socio-economic models under the assumption that actions to mitigate greenhouse gas emissions are not taken. Need and equity have provided strong arguments for developing countries to request that the developed world takes the lead in controlling its emissions, while permitting the developing countries in the meantime to use primarily fossil fuels for their development. Even with major and early control of CO_2 emissions by the developed world, limiting concentration to 450 ppm implies that the developing world also would need to control its emissions within decades, given that we expect developing world emissions would otherwise double over this time. Scenarios leading to CO_2 concentrations of 550 ppm exhibit a reduction of the developed world's per-capita emission by about 50% over the next 50 years. Even for the higher stabilization levels considered, the developing world would not be able to use fossil fuels for their development in the manner that the developed world has used them.

The Kyoto Protocol and the Next 10 Years

By ratification of the United Nations Framework Convention on Climate Change (1), a large majority of countries acknowledge that change in the Earth's climate and its adverse effects are a common concern for humankind, and that the ultimate objective of the convention is the stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. The measures agreed at the third conference of the parties to the convention in Kyoto (2) in 1997 would, however, only represent a first step toward reaching this goal, even if the agreed commitments were fully implemented (3). In this agreement, developed countries (including countries in economic transition) would reduce their emissions so that during the period 2008–2012 their average emission rate would be 5% lower than that in 1990, while no specific targets were prescribed for developing countries.

Changes in regional emissions since 1990 give an indication of the likelihood that these targets will be reached. Estimated annual emissions of carbon dioxide from fossil fuels and cement production§ are shown in Table 1 [*cf.* Bolin (3)] for 1990 and 1999, as well as for a scenario for 2010 in which it has been assumed that:

- Annex 1 countries (developed countries including those in economic transition) decrease their emissions by 5% between 1990 and 2010 to meet the Kyoto protocol target.
- Countries in economic transition increase their emissions by 1.5% per year from 1999 to 2010, which is well within the quota allotted to them as an outcome of the Kyoto negotiations.
- Remaining Annex 1 countries (Organization for Economic Cooperation and Development countries in 1990) decrease their emissions sufficient to meet the overall Annex 1 target.

Table 1. Human-induced emissions of carbon dioxide (in Gt C yr^{-1}) as a result of fossil fuel combustion and cement production in 1990 and 1999, and a scenario for 2010, based on the commitments for developed countries as prescribed by the Kyoto protocol

	1990	1999	2010 (scenario)
Developed countries (Annex 1)	3.9	3.85	3.7
Countries in economic transition	1.25	0.85	1.0
Remaining developed countries	2.65	3.0	2.7
Developing countries (non-Annex 1)	2.2	2.7	3.9
Total	6.1	6.55	7.6

The Kyoto protocol (2) specifies a list of countries in Annex B that differ slightly from Annex 1 listed in the Framework Convention on Climate Change (FCCC) (1). In terms of aggregate population and emissions the primary difference is the inclusion of Turkey in Annex 1 but not Annex B. Throughout this study we use Annex 1. Countries in economic transition are listed in the FCCC and include Eastern Europe and most countries of the former Soviet Union.

- Non-Annex I countries (i.e., developing countries) increase their emissions from 1999 until 2010, at the average rate (3.4% per year) observed since 1980.

Note that in this scenario, the remaining Annex I countries would meet their obligations partially by acquiring allowances for emissions from countries in economic transition.

Of course, the targets in the Kyoto protocol are not as simple as depicted in Table 1. They also include other greenhouse gases (methane, nitrous oxide, perfluorocarbons, hydrofluorocarbons, and SF_6) broadening the scope of emission reductions. These may account for more than their share of emission reductions and thereby reduce the extent of carbon dioxide emission control and the overall cost (7, 8). Furthermore, carbon dioxide sinks from land use, land-use change, and forestry are included. The so-called flexible mechanisms, e.g., emissions trading and emission reduction projects in developing countries, might spread emission reductions to improve cost effectiveness. Cost effectiveness and effects on trade have become important for the ratification of the Kyoto protocol by sufficient Annex 1 countries for the protocol to come into force. The extent to which cost effectiveness and trade issues can be alleviated by sinks and flexible mechanisms in the Kyoto protocol depends on implementation and compliance issues; these issues were addressed at

Abbreviations: IPCC, Intergovernmental Panel on Climate Change; SRES, Special Report on Emission Scenarios.

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§Detailed estimates of annual emissions from fossil fuel burning and cement production (http://cdiac.esd.ornl.gov/trends/trends.htm) span the period from 1751 through 1997. Emissions for 1998 and 1999 are estimated by applying emissions factors (5) to regional energy consumption statistics (6) to calculate emissions over the period from 1996 through 1999. Emissions are then scaled to match detailed regional estimates (http://cdiac.esd.ornl.gov/trends/trends.htm) for emissions from fossil fuel burning and cement production over the overlap period from 1996 to 1997 including bunker fuels. Scaled regional emission estimates, therefore, implicitly include emissions from cement production. Emissions are reported in gigatons carbon: 1 Gt C = 10^9 t C = 10^{15} g C = 3.67×10^{15} g CO_2.

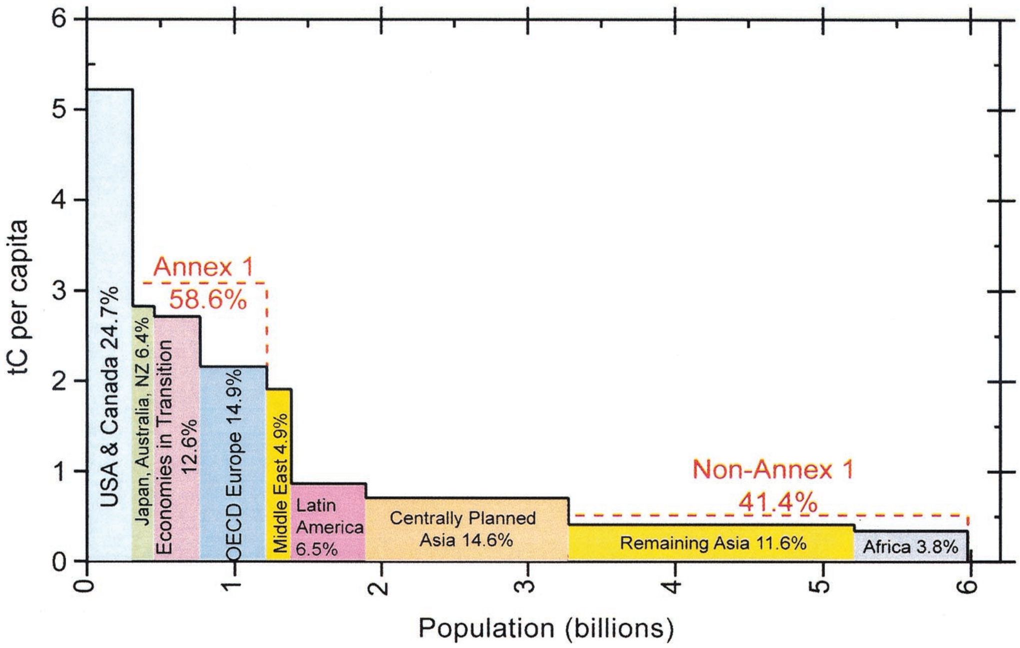

Fig. 1. Per-capita fossil CO_2 emissions in 1999 averaged for nine geographical regions and grouped into Annex 1 and non-Annex 1 countries. Height of bars gives the average per-capita annual emissions of each region. Width of bars gives the population. Area of bars is proportional to the 1999 CO_2 emissions from fossil fuels and cement production; the percentages given indicate the fraction of 1999 global emissions attributed to each region.

the sixth session of the Conference of the Parties in November 2000 but were not resolved.

Equity and Per-Capita Emissions

Non-Annex 1 countries will probably still emit only about as much fossil carbon as Annex 1 countries in 2010 (see Table 1) even though their total population probably will have increased to about 5.6 billion, i.e., more than four times the projected population in Annex 1 countries.

The difference between developed and developing countries of the world in their use of fossil fuels is obvious and even more so if the emission data for 1999 are further disaggregated and considered in relation to their populations (see Fig. 1). The average per-capita emission from non-Annex 1 countries is 0.57 ton C yr^{-1}, nearly twice 0.32 ton C yr^{-1} from Africa, whereas the value for the United States and Canada is 5.2 ton C yr^{-1}. There are, of course, major differences between countries within each region as well as between rich and poor people within countries. The average global per-capita emission is 1.09 ton C yr^{-1}. Few non-Annex 1 countries are above that level of average emissions and those are primarily oil-producing countries. Per-capita emissions (9) from no single Annex 1 country is less than 1 ton C yr^{-1}. They emit today on average 5.5 times more fossil carbon dioxide per capita than do the non-Annex 1 countries. In light of current economics, infrastructure, and technology for supply and end use of energy, fossil fuels will be an increasing main source for primary energy for the needed development of non-Annex 1 countries for quite some time to come. Need and equity have provided strong arguments for developing countries to request that the developed world takes the lead in controlling its emissions, while permitting the developing countries in the meantime to use primarily fossil fuels for their development.

The gap in carbon dioxide emissions between Annex 1 and non-Annex 1 countries is narrowed somewhat if emissions from changing land use are included. Over the last 20 years, deforestation and changing land use have resulted in emissions of about 1.7 ± 0.8 Gt C yr^{-1}. These primarily stem from deforestation in tropical non-Annex 1 countries (10). On a per-capita basis, they are largest in Latin America, which if aggregated with fossil emissions bring the average per-capita emissions of Latin America to about the level of those for the Middle East from fossil fuel burning, but still well below the average for the Annex 1 countries.

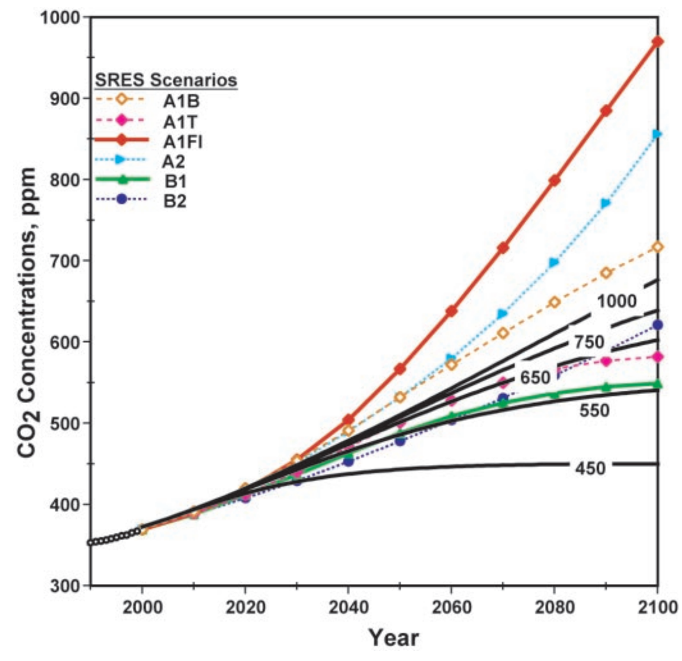

Fig. 2. Atmospheric CO_2 concentration. The average of annual average concentrations of atmospheric concentration of CO_2, as measured at the Mauna Loa (Hawaii) and the South Pole observatories from 1990 to 1999 are shown by circles (http://cdiac.esd.ornl.gov/trends/trends.htm). Specified concentration pathways leading to stable concentrations ranging from 450 to 1,000 ppm are shown by the labeled solid lines. Curves with symbols show concentrations from 2000 through 2100 resulting from the six specified SRES emission scenarios shown in Fig. 3.

The enhanced carbon dioxide concentration in the atmosphere contributes most of the enhanced greenhouse gas radiative forcing from human activities and it will disappear only slowly. The atmospheric carbon dioxide concentration has increased by about 31%, from a preindustrial concentration of about 280 to 367 ppm in 1999. The total radiative forcing of climate as a result of enhanced concentrations of all greenhouse gases is at present equivalent to a carbon dioxide concentration of about 440 ppm. It is, of course, important not to ignore possible measures to reduce concentrations of these other gases by control of their emissions and the emissions of other gases that affect their concentration (11).

Long-Term Scenarios of Greenhouse Gas Emissions and the Stabilization of Greenhouse Gas Concentrations

In the long term, the net carbon dioxide emissions from human activities would have to be reduced to well below current emission levels to stabilize greenhouse gas radiative forcing and thereby to limit the extent of climate change. Although the relation between an enhanced concentration level and climate change is not firmly established, it is of interest to examine the required reductions of future net emissions to arrive at alternative stable concentration levels. Such analyses were presented in the early 1990s (12). In the present analysis, the required emission reductions have been calculated¶ with improved global carbon cycle models and are compared with revised scenarios of how emissions might otherwise evolve.

Carbon dioxide concentrations and the associated fossil emissions are shown in Figs. 2 and 3 over the period from 1990 to 2100. From 1990 to 1999, estimates based on observations are given. From 2000 to 2100 two families of curves are shown:

(*i*) Stabilization of carbon dioxide concentrations at alternative levels between 450 and 1,000 ppm (12, 17). Carbon dioxide concentration pathways that arrive at these levels were constructed by maximizing cost effectiveness under the assumptions of global participation in the control of emissions that would otherwise increase monotonically to about 20 Gt C yr^{-1} by 2100 (cf. ref. 18).

(*ii*) Intergovernmental Panel on Climate Change (IPCC) Special Report Emission Scenarios (SRES) (19). These are scenarios intended not to include emission controls to limit climate change and have been based on different story lines about population change, economic development, energy supply systems, etc.‖ What will happen is, of course, not known but will fall within this total range.

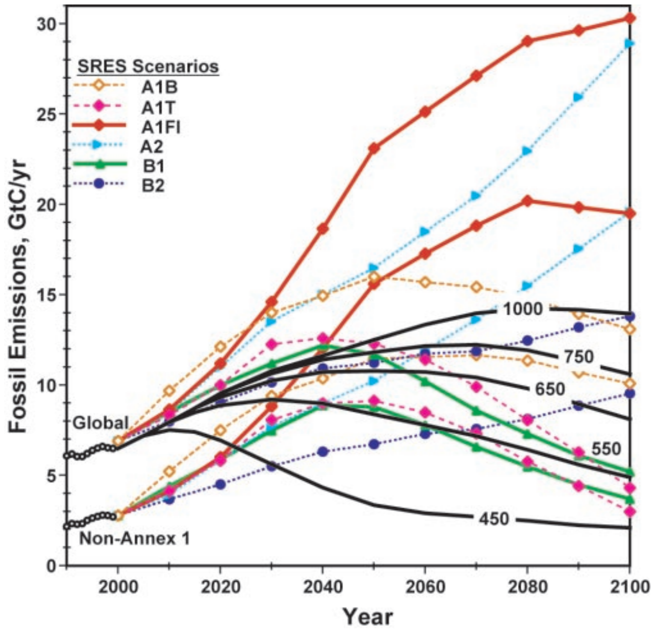

Fig. 3. Annual global fossil emissions of CO_2. Emissions from 1990 to 1999 as a result of fossil fuel burning and cement production are shown by circles. Deduced global fossil CO_2 emissions that lead to the concentration pathways toward stable CO_2 concentrations ranging from 450 to 1,000 ppm given in Fig. 2 are shown by the labeled solid curves. Six SRES emission scenarios are shown by the curves with symbols. In addition to global SRES emissions, the emissions from non-Annex 1 countries are similarly shown, starting from the 1999 annual emissions of 2.7 Gt C.

Some key conclusions can be drawn from Figs. 2 and 3:

• The SRES scenarios for future carbon dioxide emissions vary widely associated with story lines for the future development of society (19). All yield carbon dioxide concentrations at the end of the century above about 550 ppm. The B1 and A1 scenarios are based on a low projection of future global population with 7 billion people in 2100 after having reached a maximum of 9 billion earlier during the century, whereas the B2 and A2 scenarios follow medium and high projections, respectively. The two lowest—the B1 scenario characterized by a story line emphasizing environmental and societal sustainability, and the A1T scenario characterized by a story line emphasizing rapid economic growth along with rapid development of nonfossil energy sources—are close to a stabilization pathway leading to a carbon dioxide level between 550 and 650 ppm with emissions in 2100 well below the present and declining. The scenario with most rapidly increasing emissions, A1FI, on the other hand, is characterized by a story line emphasizing rapid economic growth and carbon-intensive energy supply systems, reaching carbon dioxide concentrations above 900 ppm by 2100.

• In all cases the carbon dioxide concentrations continue to rise at about the present rate during the next few decades and diverge only slowly as a consequence of the gradual accumulation in the atmosphere of the rapidly widening range of SRES emissions, between 7 and 12 Gt C yr^{-1} by 2020.

The contribution of other greenhouse gases, some with long residence times in the atmosphere, may raise the level of equivalent carbon dioxide concentration by about 100 ppm or more above that of carbon dioxide alone. To achieve stabilization of greenhouse gas concentrations at, e.g., 650 ppm carbon dioxide equivalent, carbon dioxide concentration would be limited to 550 ppm unless, e.g., a major decrease in projected methane were achieved (11).

The futures as projected in these scenarios are very different for Annex 1 and non-Annex 1 countries primarily because of

¶The integrated science assessment model (ISAM) is the earth system model used to calculate concentrations from emission scenarios and emissions from CO_2 stabilization pathways including feedbacks from projected climate change (13). The ISAM terrestrial plant and soil model is parameterized to reproduce the responses (central, high, and low uptake) found in six dynamic global vegetation models that were intercompared for one common scenario (14). The ISAM ocean model is parameterized to reproduce the responses (average, high, and low uptake) found in the intercomparison of 10 detailed ocean carbon cycle models (15). All results shown are for the reference (central) values of model parameters. Fossil emissions are deduced from CO_2 stabilization pathways by first calculating the fossil plus land-use emissions needed to match the pathway, and then subtracting a land-use emission scenario scaled so that the resulting fossil emissions match the 1999 emission estimate. The land-use emission scenario (IS92a) decreases to zero by 2100 (16). Scaled in this way, the land-use emission in 2000 is 2.2 Gt C yr^{-1}, higher than 1.07 Gt C yr^{-1} specified in the SRES scenarios.

‖The six SRES marker/illustrative scenarios analyzed are representatives from six groups of scenarios with alternative development/technology story lines described in detail in the SRES (19). Their approximate breakdown into Annex 1 includes all countries of the former Soviet Union, giving slightly higher emissions and lower per-capita emissions for the SRES Annex 1 than if the actual list of Annex 1 countries was included. The CO_2 stabilization pathways analyzed were constructed (12) assuming the baseline scenario (i.e., emissions without intervention to mitigate climate change) IPCC IS92a (16) that has similar population growth as the SRES B2 scenario (19). The B2 population scenario follows a midrange population projection (20), and per-capita emissions for stabilization are calculated by using this projection.

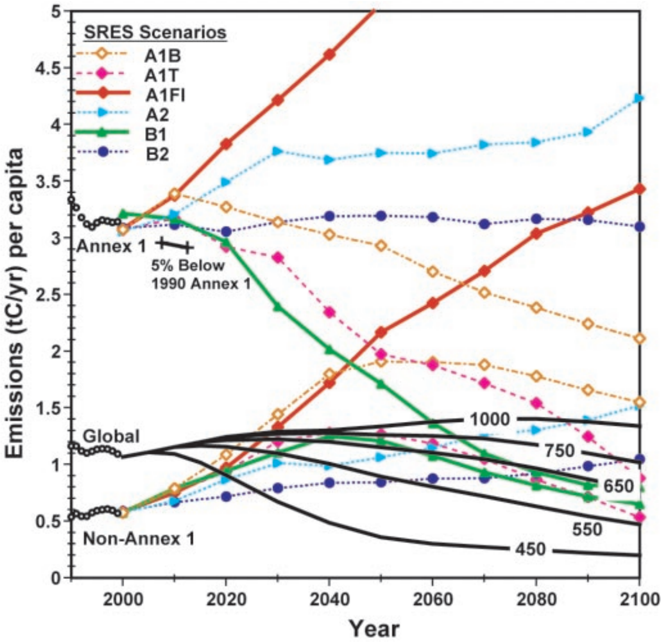

Fig. 4. Per-capita fossil emissions of CO_2. Emissions per capita from 1990 to 1999 are shown by the circles. Emissions 5% below the 1990 Annex 1 rate over the period from 2008 to 2012 are shown by a line segment. Deduced global fossil emissions leading to the specified CO_2 concentration pathways (Fig. 2) that asymptote to constant concentrations at labeled values from 450 to 1,000 ppm are shown by the solid curves. Per-capita fossil emissions for Annex 1 and non-Annex 1 regions for the six SRES scenarios are shown separately by the curves with symbols.

their very different situations, now and for some considerable time into the future. In Fig. 3, the portion of emissions in the SRES scenarios from non-Annex 1 countries is shown for comparison. For all scenarios their emissions rise from their current rate, gradually accounting for a greater fraction of global emissions in the scenarios. Some combinations of stabilization level and emission scenario are very informative: For example, in the A1B scenario, non-Annex 1 emissions surpass global emissions estimated to arrive at a stable concentration of 450 ppm in just about 18 yr. Whereas, in the A1T and B1 scenarios, non-Annex 1 emissions do not surpass global emissions estimated to arrive at stabilization at 650 ppm or above before 2100 (the time extent of the scenarios).

The carbon emissions per capita presented in Fig. 4 give a view of how the present difference between developed and developing countries with regard to fossil emissions might change in the future. The same two families of cases are shown as in Fig. 3. The solid curves show the global per-capita emissions of carbon dioxide required to stabilize concentrations at 1,000, 750, 650, 550, and 450 ppm following the concentration pathways shown in Fig. 2. The SRES emission scenarios shown in Fig. 3 have similarly been converted into emissions per capita, but are displayed separately for Annex 1 and non-Annex 1 countries.

From this analysis, we conclude the following:

• For stabilization at 450 ppm, the global per-capita emissions would have to decrease from the present value of 1.1 ton C yr^{-1} to below about 0.5 ton C yr^{-1} by the middle of the century, i.e., the present level of per-capita emissions in non-Annex 1 countries (see Fig. 4). Scenarios for per-capita emissions from non-Annex 1 countries surpass the global per-capita emission rate leading to 450 ppm stabilization within 16–30 yr, while the most rapidly declining average emission scenario for Annex 1 countries will not by that time have reached 2 ton C yr^{-1}. Even with major and early control of CO_2 emissions by Annex 1 countries, limiting concentration to 450 ppm implies that the average per-capita emissions from non-Annex 1 countries would have to decline from a maximum of about 0.8 ton C yr^{-1} within a decade or two.

• Stabilization at 550 ppm also would imply a rapid decrease of emissions by Annex 1 countries. Emission scenario B1 leads to a global emission in 2100 somewhat above that deduced for stabilization at 550 ppm (Fig. 3), with per-capita emissions in both Annex 1 and non-Annex 1 countries declining at about the same rate in 2100. In this scenario non-Annex 1 countries never emit more than 1.3 ton C yr^{-1} per capita and Annex 1 countries reach that level during the latter half of the century. This lowest Annex 1 scenario in Fig. 4 implies a reduction of present average per-capita emissions by Annex 1 countries by about 25% during the next three decades and by about 50% by 2050. Emission controls of some kind in both developed and developing countries would be required for all other scenarios.

• An Annex 1 emission decrease of 5% below the 1990 rate over the period 2008–2010 would result in a somewhat lower average per-capita emission in Annex 1 countries than for any of the SRES scenarios for that time.

• Global emissions that approach stable concentrations up to 1,000 ppm never exceed 1.4 ton C yr^{-1} per capita compared with current Annex 1 fossil emissions of 3.2 ton C yr^{-1} per capita. Therefore, non-Annex 1 countries will never on average have the opportunity to base their energy supply for economic development on fossil fuels in the manner that has been the case for the Annex 1 countries.

Uncertainties in carbon cycle and carbon dioxide emissions from land use translate into uncertainty in the deduced global fossil emissions for stabilization in Figs. 3 and 4. A central estimate of the modeled relation between carbon dioxide emissions and atmospheric concentration was used to deduce the global emissions required for stabilization of carbon dioxide concentration. The range of results for different carbon cycle models gives rise to a fossil emission range of about 4.9 ± 1.9 Gt C yr^{-1} (for 550 ppm) by the end of the century, corresponding to a global per-capita emission range of about 0.47 ± 0.18 ton C yr^{-1}, a measure of this source of uncertainty¶. To deduce the global fossil emissions for stabilization requires the specification of future land-use emissions. In the stabilization results in Figs. 3 and 4, specified rate of land-use emissions start in the year 2000 near the high end of the recent estimate of 1.6 ± 0.8 Gt C yr^{-1} (10) and are assumed to decline for the remainder of the century¶. If a low estimate of land-use emissions was specified, this would allow for greater fossil emissions— 1.4 Gt C yr^{-1} and 0.23 ton C yr^{-1} per capita greater at the start of the century. Atmospheric concentration depends on the net emissions from both land use and fossil fuels; therefore, the future reduction of land-use emissions from deforestation is also important for stabilization of carbon dioxide concentration.

Despite the uncertainties of our present knowledge, the conclusions reached above are rather robust. They need serious consideration in the search for a prudent strategy to reach the goals agreed by the parties to the climate convention. The magnitude, timing, and societal costs of emission controls in developed and developing countries needed to reach the various stabilization levels depend on the future evolution and implementation of technologies, as well as the future development of society. These cannot be predicted a century into the future. Therefore, as was expressed by the IPCC (4), "The challenge is not to find the best policy today for the next hundred years, but to select a prudent strategy and to adjust it over time in the light of new information." This also applies for the interpretation of the present analysis.

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