INTER-GENERATIONAL AND SPATIAL EQUITY ISSUES OF CARBON ACCOUNTS

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RR–92–6
May 1992

Reprinted from *Energy* (1991) **16**(11/12):1397–1416.

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Laxenburg, Austria

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Printed by Novographic, Vienna, Austria.

Foreword

The central objective for a framework convention on climate change is to achieve a stabilization, and perhaps even a reduction, of greenhouse gas emissions. Carbon dioxide emissions from fossil energy are an important part of these considerations since they are the major contributor to the anthropogenic greenhouse effect. Most of the proposed reduction measures, such as carbon taxes, tradable permits, and national or per capita emission quotas, are all associated with important equity issues for three reasons: (1) they have different effects on individual countries and world regions; (2) they should take into account differentiated responsibility; and (3) they should consider different potentials and capabilities for mitigation. However, no single criterion for global emissions reduction is sufficient to satisfy different (and perhaps conflicting) equity principles.

This paper by Arnulf Grübler and Yasumasa Fujii develops a quantitative assessment of one possible, but very stringent, equity criterion for global greenhouse gas reductions. By examining past and current carbon dioxide emissions from fossil energy consumption, the authors adopt the hypothesis that every human being is allowed the same maximum emission quota irrespective of the time and place in which they lived. This inter-generational and inter-personal equity criterion is particularly interesting because it considers historical emissions (and therefore differentiated responsibility) explicitly as an integral part of the allocation scheme. Much of the emissions from the last century are still in the atmosphere due to the long residence time of carbon dioxide. Therefore, future generations, especially in the developing countries, will have to bear the potential burden of our current and inherited emissions.

Regardless of the equity and/or differentiated responsibility criteria adopted in a convention to slow global warming, the analysis suggests the need for a quantitative assessment of other criteria that would extend beyond the current generations and current emission patterns. The Environmentally Compatible Energy Strategies Project at IIASA is undertaking such an assessment. A parametric framework is being developed to facilitate quantitative analysis of *inter alia* different allocation criteria, other greenhouse gases in addition to carbon dioxide, and varying time horizons for achieving stabilization or specified emission reductions.

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Leader
Environmentally Compatible Energy Strategies Project

Energy Vol. 16, No. 11/12, pp. 1397–1416, 1991
Printed in Great Britain.

0360-5442/91 $3.00 + 0.00

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(Received 16 August 1991)

Abstract—We analyze the different regional and generational contributions to increases of CO_2 concentrations resulting from fossil-fuel use since the onset of the industrial revolution. Equitable future per capita emission allowances under a range of concentration stabilization scenarios (additional 140, 280, and 420 ppm over pre-industrial levels) by the year 2100 are outlined. The intra- and inter-generational equity criterion adopted considers that each human being is allowed an equal emission right per year, independent of time or place lived. A distinguishing characteristic of the analysis is the integration of emissions and population over time. Quantifications of historical contributions to concentration increases and future emission scenarios on a per capita basis are broken down into nine world regions.

1. INTRODUCTION

Large scientific uncertainties pertain to causes, effects and required policy responses associated with increasing concentrations of greenhouse gases (GHG) in the Earth's atmosphere. Further, the policy responses, their costs and how they should be fairly distributed are politically sensitive. Prevailing scientific consensus such as contained in the documents of the Intergovernmental Panel on Climate Change (IPCC)[1] suggests taking precautionary measures to stabilize or even reduce GHG emissions in order to delay climate change and mitigate its adverse consequences.

However, the interplay between GHG concentrations, resulting temperature rise, climate changes and their effects is highly uncertain, making it difficult to establish precise emission reduction targets at present. Nevertheless, it should be possible to formulate some upper boundary conditions; current rates of increase in GHG emissions would have to be significantly slowed to assure atmospheric CO_2 concentrations do not double the pre-industrial level by the second-half of the 21st century.[1] For instance, the business-as-usual scenario of the IPCC[1] projects CO_2 concentrations of up to 850 ppm by the year 2100, and a resulting temperature rise of some 4°C (2.6–5.8°C range) compared to pre-industrial times. Such scenarios appear difficult to reconcile with precautionary principles and current understanding of the pace with which humankind and natural ecosystems[2] could adapt to a changing climate.

In the absence of widespread consensus on extent and timing of emission reduction targets, we use a scenario approach; CO_2 emission targets are derived for three scenarios aiming at a stabilization of atmospheric CO_2 concentration between 420 and 700 ppm (or an increase of 140–420 ppm over pre-industrial levels). The resulting emission targets represent upper-bound values for cautionary policy measures, which should be modified as scientific certainty increases. Taking into account past concentration increases, the degrees of freedom for future CO_2 emissions can be estimated for a range of future concentration targets. These estimates will be subject to the uncertainty of both the global carbon cycle and the accounting scheme adopted.

A variety of implementation policies of global emission stabilization or reduction targets have been proposed, including across-the-board proportional cuts (similar to the 30% flat-rate reduction in sulfur emissions of the European Convention on Long Range Transboundary Air Pollution), licensing and tradable permits.

The choice of the accounting framework and the allocation criteria of a limited global GHG emission "allowance" that would underlie reduction strategies are important in designing effective and equitable responses to the risks of climate change. Therefore, determining which greenhouse gases to consider, what normalizing allocation variables (per country, per capita, unit land area, etc.) should be used, allocating resulting "quotas", and finally, specifying the time horizon over which such an accounting framework is designed to operate involve important ethical and policy elements beyond the scientific and technical domains.

2. ACCOUNTING FRAMEWORKS FOR EMISSION REDUCTION

A number of accounting schemes and emission allocation criteria have been suggested. Various greenhouse equivalence indices[3] have been proposed in order to compare the impacts of different GHGs. These take into account the direct (instantaneous greenhouse forcing) and indirect (e.g., CO, O_3 and CH_4 interactions) effects as well as the different residence times of various GHGs. Valuable quantification in the concept of global warming potential (GWP) of different GHGs has been provided by Lashof and Ahuja[4] and Rodhe[5] among others. The concept of GWP has also been adopted in the reports of the IPCC.[1]

Victor[6] correctly cautions against an integrated assessment of all GHGs. He points to the large uncertainties of the global carbon cycle, the difficulties in deriving scientifically and politically sound GWPs in view of widely varying estimates of atmospheric residence times of CO_2, and the absence of reliable estimates and measures for non-CO_2 gases. He concludes that in view of political realities and scientific uncertainty, plans to control CO_2 independent of other GHGs would be a pragmatic solution. Hammond et al[7] propose a GHG accounting framework that dismisses the uncertainty about the effective residence time of CO_2 altogether, concentrating on the instantaneous heating effect of GHG emissions, i.e., a time horizon of 1 yr. They suggest a policy that assumes the past is past and instead distributes emission allowances based on actual increases measured in atmospheric GHG concentrations.

Subak and Clark[8] review a number of possible accounting frameworks for CO_2 emissions. They do not recommend any particular scheme but highlight the biases inherent in the different frameworks chosen. They emphasize the importance of accounting frameworks, arguing that all parties involved should seek assessment frameworks that are as fair as possible in allocating responsibility for GHG emissions among the peoples, nations, and generations sharing planet Earth. Nitze[9] reviews the process by which a corresponding international convention designed to gain acceptance by all key countries could be formulated.

If measures to reduce GHG emissions will indeed be taken, the accounting framework, as well as the time horizon adopted (1 yr, as opposed to the entire residence time of GHGs in the atmosphere) hold important equity implications both from a spatial (North–South) and an inter-generational (past, present and future) perspective. We will try to illustrate the point in this paper on the basis of CO_2 emissions, in particular those stemming from fossil-energy use. Emissions of CO_2 are the single most important source of GHG emissions.[1] We concentrate on CO_2 emissions from fossil-fuel use. Other GHG emissions are subject to large uncertainties in present emission levels, historical profiles, and distribution between countries. In concentrating on energy related CO_2 emissions, our calculations may be considered an upper boundary case for future use of fossil fuels under various CO_2 concentration stabilization scenarios.

Policy measures for CO_2 emission reduction face in particular the intricate interrelations between reduction targets to be agreed upon on and their underlying equity criteria. Any successful agreement on reduction targets (how much, by whom and when) presupposes a prior agreement on the (equity) criteria to be used to distribute a scarce resource, i.e., CO_2 emission rights under a reduction regime.

Equity criteria of a GHG accounting framework go well beyond purely technical issues (such as accounting for different GHGs in the form of their GWP). The time frame adopted (i.e., how to account for past emissions), what kind of GHGs to include (only anthropogenic or all sources), and the distributional criteria (population, GNP, or land area, see e.g., Grubb[10]) hold important implications for an accounting framework and resulting emission targets/quotas. Various combinations have been examined for CO_2 emissions. Subak[11] concludes that each account exhibits predictable different biases and that no single standard is likely to be uniformly popular with different groups of countries. Nevertheless, any accounting framework in an international negotiation process should at least explicitly consider the significant inter-generational and spatial disparities in past and present CO_2 emissions.

Increases in atmospheric CO_2 concentrations cannot be attributed solely to the present generation. They are the result of 200 yr of industrialization. Based on our current understanding of the carbon cycle, some of the carbon emitted by Watt's first steam engine may still be in the atmosphere. If the actions of past generations influence the allowable carbon-emission levels of our generation, we must also consider the repercussions of our (in)action on future generations. Even more important: emission allowances that do not take future population growth into account are unlikely to be agreed upon. Stabilizing emissions with a zero-growth or even declining population as in the industrialized countries may be relatively easy to implement. Conversely, stabilization of emissions in a country where population continues to grow, as in most developing countries, would represent a severe burden, exacerbated by the aspirations of present and future generations to economic development and an improved standard of living. Grubb[10] argues that carbon-emission quotas on a per capita basis would provide a disincentive to stabilize population growth. Consequently, he suggests allocation of emission entitlements on the basis of adult population only. However, this introduces the additional issue of equity between different age cohorts or generations of the present population into the problematique. Therefore, it is unlikely that such a criterion would find the wide acceptance necessary for effective implementation of emission allocation schemes.

It has been argued[12] that the most serious deficiency of many proposed schemes remains in partitioning allowable emissions equitably between industrialized and developing countries. Simply looking at present absolute or per capita emission levels, North–South disparities become immediately apparent. Developed countries account presently for less than 25% of the world population and emit nearly 75% of all CO_2 stemming from fossil-fuel use. Per capita carbon emissions differ by nearly a factor of 9 (in 1987, 3.3 ton C per capita in developed countries vs 0.37 ton in developing countries). Even after including carbon emissions from tropical deforestation, currently estimated to range between 0.6 and 2.8 Gton carbon annually,[1,13] a persistent per capita emission gap in a North–South perspecitve remains (0.5–1.1 ton C per capita in developing countries, including deforestation, compared to 3.3 tons per capita in industrialized countries).

Present disparities in emissions are likely to persist well into the 21st century. In the longer-term future, with growing populations and economic development, such North–South disparities in CO_2 emissions are likely to be reversed. The implementation of absolute emission stabilization or even reduction targets in a world divided between prosperous countries with stable populations and other countries, aspiring to improve the living conditions of their rising populations, will therefore be considered preposterous by the latter group. Stringent CO_2 emission quotas imposed on developing countries would make the build up of their industrial and infrastructural base, i.e., development, extremely costly, if not impossible to achieve.

Spatial disparities in carbon emissions are intrinsically linked to inter-generational aspects and the time frame of a carbon accounting system. Arguably, industrialized countries enjoy a high level of affluence and material well being because of their past industrialization and its resulting emissions and environmental impacts. These ought to be taken into account in an equitable accounting scheme.

A similar problematique also affects the use of land area or GNP as a denominator in a CO_2 accounting scheme. Criteria incapable of accounting for different population sizes, degrees of affluence and industrialization (as in the case of a land-based criterion), or that penalize countries in the early industrialization phase, which—as the history of the industrialized countries (Fig. 1) clearly demonstrates—is characterized by high carbon intensity of economic activity, appear difficult to reconcile with considerations of inter-generational and spatial equity.

Questions of equity lead to the issue of an appropriate time frame for a CO_2 accounting scheme. How should we account for past, present and future emissions, bearing in mind the need for intra- and inter-generational equity? In our view, the time frame has to take into account at least two factors: first, the long residence time of CO_2 in the atmosphere which,

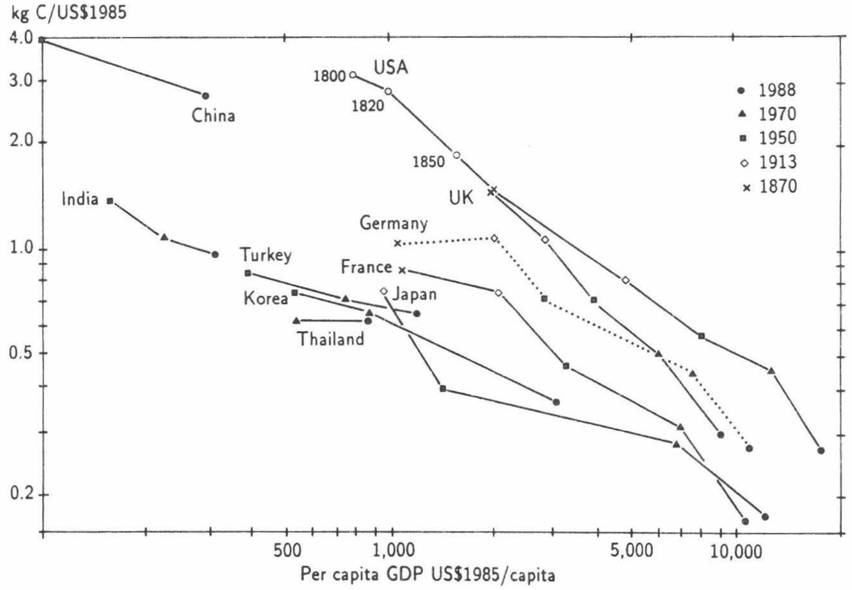

Fig. 1. Energy carbon intensity per constant GDP, in kg carbon per U.S.$ 1985 vs per capita GDP. Energy data include also non-commercial sources such as fuelwood. Note the improving carbon intensity of economic activities as a function of the degree of economic development and remaining decisive differences between countries for similar per capita GDP levels.

according to current understanding of the carbon cycle, ranges from several decades to centuries; secondly, the time scale adopted which implies an ethical choice between generations. The choice will influence the climate and corresponding natural environment which future generations will inherit. Weiss[14] suggests that each generation should be seen as both trustee and beneficiary, or custodian and user, of our planet. This means that both quality and access to the use and benefits of the global environment ought to be preserved for future generations.

Spash and d'Arge[15] argue that it is logical for anyone who does not know to which generation (past, present or future) one belongs to opt for equal treatment among generations. This implies that the discount rate between generations (and CO_2 emissions) ought to be zero if the utility of future generations is not to be reduced or given lesser weight.[15] As an alternative, one might consider inter-generational compensation schemes[16] which provide future generations with resources and technologies to adapt to a changing climate and/or alternative productive opportunities to compensate for losses encountered by a changing climate. Provision of resources and technologies for future generations to better cope with climate change could indeed justify discounting emissions. However, the problem of determining an appropriate discount rate to account for the transfer of opportunities from one generation to the next remains a formidable task.

We also have to consider future generations in a dynamic rather than a static perspective, accounting for population growth and economic development. Inter-generational equity requires consideration of the different sizes of generations and must also allow for the economic development of present and future generations in order to reduce disparities in levels of affluence and income. The higher the level of economic development, the more likely that resources for adaptation to climate change will be available or that adverse effects of changes in climate can be mitigated.

Similar arguments also hold for the relationship between present and past generations. Present and future emission levels are constrained by the actions of the past, by the historical increases in CO_2 concentrations observed. Therefore, historical CO_2 emissions should be accounted for under inter-generational equity considerations. The latter suggests the use of a discount rate of zero, or a discount rate for emissions equivalent to the long-term absorption of CO_2 by natural (possibly enhanced, or man-made) sinks under conditions of stabilized atmospheric CO_2 concentrations.

Discounting, as typically applied in economic analysis, exhibits a characteristic myopia in environmental management. Ausubel[17] describes this myopia in terms that costs are incurred early and benefits accrue too far in the future to count in an assessment. Such an approach implies that the economic benefit accruing from present carbon emissions are weighted heavily against possible future disbenefits (damage) of associated concentration increases or future emission avoidance costs. Using a discount rate of 10% as an example, the risks associated with the loss of the entire present world GNP of some 17 trillion \$ *some 100 yr from now would correspond to a present value of less than 500 million \$.*

Implicit in such discounting approaches is the assumption that future costs of emission abatement or adaptation to climate change will be small compared to the costs of countermeasures taken right now. Evidence of long-term improvements in technologies and costs in the energy–environment nexus could support such discounting approaches, but there are also counterexamples. Consider the present costs (and "superfunds" required) of cleaning up hazardous waste dump sites, compared to the initial costs in the past of separate disposal and elementary environmental protection, like securing ground water bodies from contamination, etc. At present, we simply do not know whether more drastic measures than those at stake for the present generation will be necessarily cheaper for future generations, even assuming availability of improved technologies and higher levels of affluence for the future. Both from the viewpoint of the time horizon and the significant uncertainties involved discounting appears highly problematic. A carbon accounting system should be governed by precautionary and fairness principles, disregarding neither the past nor the future.

In this paper we develop an accounting scheme for CO_2 emissions which tries to integrate the above points into a quantitative framework. The scheme is based on an egalitarian criterion of allocation that is equitable from an inter- as well as an intra-generational perspective, independent of the degree of economic development, of time, or of one's position in the age pyramid.

We suggest an accounting system which takes into account both past and future increases of atmospheric CO_2 concentration over that of pre-industrial times, and past and future generations (populations). Since we are dealing with an anthropogenic source of environmental disturbance, we adopt a per capita criterion as denominator. Because of the large uncertainties related to GHG emissions besides CO_2 and outside the energy sector, we limit the present analysis to energy related CO_2 emissions. The time frame adopted takes into account the long atmospheric lifetime of CO_2 until final absorption. Therefore, in order to allow for inter-generational equity, the time period considered spans three centuries, from 1800 to 2100. The onset of the industrial revolution, when increases in CO_2 concentration levels were established, is used as a starting point. The year 2100 is the end point of the analysis, by which time CO_2 concentration levels are assumed to be stabilized at a range of target scenario values. This long time horizon adopted is consistent with the long response time of the global carbon cycle to changes in emissions, and allows comparisons with the IPCC scenarios which also extend to the year 2100.

3. APPROACH

Past and present estimates of CO_2 emissions from fossil-fuel use were based on a number of historical statistics of energy consumption by fuel (coal, oil and natural gas) and population growth since 1800, assembled at IIASA.† All data are disaggregated into nine world regions (Western Europe, Eastern Europe, North America, U.S.S.R., Japan, Oceania, Asia, Africa,

†Historical population data were taken from Durand[18] and augmented by data from Mitchell.[19,20] Historical energy consumption data at the world level are derived from Nakićenović.[21] Regional energy consumption data are aggregated from national time series, as for example reported in Mitchell,[19,20] Woytinsky,[22] and Darmstadter.[23] Specific carbon-emission factors are based on Ausubel et al.[24] Details of data sources and aggregation procedures are given in Fujii.[25]

and Latin America). Historical carbon emissions per capita were obtained by integrating emissions and populations by region over the period 1800–1987. (Hypothetical) future emission profiles were derived for a range of CO_2 concentration stabilization scenarios (by 2100) under our per capita equity criterion, based on population projections by world region of the World Bank.[26] The population projections adopted here are comparatively low and anticipate stabilization of world population at about 10.4 billion people by the year 2100.

The accuracy of our regional emission estimates is estimated to be within a range of ±20%. It would be desirable to complement our nine region disaggregation level in future analyses with the detailed data of national carbon emissions between 1950 and 1987 developed by Marland et al.[27] Nevertheless, estimates of CO_2 emissions from fossil-fuel use are accurate compared to that of other anthropogenic carbon sources (changes in land use) and other GHG emissions. This suggests that the latter should receive priority in improving the statistical records and in narrowing uncertainty ranges.

A simple atmospheric concentration model was used to translate emissions into atmospheric concentrations and assess the contributions of different regions to concentration increases. Generally speaking, there are two kinds of simplified approaches to describing the complex interactions between the atmosphere, the ocean and the biosphere in the terrestrial carbon cycle: the airborne fraction approach[28] and the linear response function approach.[29] A hybrid model was adopted here, based on the two approaches. Instead of simply using an airborne fraction approach, the effect of long-term ocean uptake (although its effect in the model is small under conditions of exponential emission growth) was also included in order to account for the long-term effects of carbon-emissions stabilization on atmospheric concentration levels. The model (see Appendix) is almost the same as that of Nordhaus and Yohe.[30] However, in our model, long-term ocean uptake is calculated from a concentration differential, defined as the difference between the concentration in the year in question and the pre-industrial (pre-1800) concentration.

A time constant T_0 of 300 yr was adopted for the effect of long-term ocean uptake. Maier-Reimer and Hasselmann[29] approximated their inorganic carbon cycle ocean-circulation model by a linear response function of multi-time constants† indicating that the largest amplitude exponential has a time constant of 300 yr. Our single-time-constant model is physically less realistic than a multi-time-constant variant, but it enables us to account for carbon emissions in a more simple and straightforward manner. Our model may be interpreted simply as an accounting system in which historical emissions of carbon are discounted at an annual rate of 0.333% (1/300). The discounted cumulative carbon emissions (after considering the airborne fraction) are in proportion to the corresponding additional concentrations. A ton of carbon emission in 1800 has only 37% ($1/e$) of the weight of 1 ton of carbon emission in 2100. It should be noted that the time constants of the decay of 1 ton CO_2 emitted are much less than 300 yr because the airborne fraction in our model is not equal to 1.

The airborne fraction used in our model was estimated by a least-squares fitting of the model outputs to the observed concentration data measured at Mauna Loa in Hawaii since 1958.[27] We obtained an airborne fraction of 42% on the basis of estimated historical data of carbon emissions from fossil-fuel consumption, cement production,[27] gas flaring,[27] and deforestation[31] (forest and soil for the period 1860–1980). We assumed that emissions from deforestation between 1980 and 1987 remained at 1980 levels, and also extrapolated emissions before 1860 along a least-squares fit of those between 1860 and 1920. It should be noted that estimates of carbon emissions from deforestation are largely uncertain and continue to be debated. The emission data adopted in this study are from estimates of changes in different ecosystems with their different carbon characteristics between 1860 and 1980 as made by Houghton.[31] This data set was used because, when running our simple carbon-cycle model backwards in combination

†Maier-Reimer and Hasselman[29] conclude that a relatively good analytical approximation of the impulse response function can be obtained by superposition of a small number (~4) of exponential functions. The response function is of course not independent from the future emission path, as illustrated by the various emission paths analyzed. Slowing down future emission rates could significantly decrease the airborne fraction with the deeper ocean layers absorbing a larger fraction of the total emissions. This decrease of the airborne fraction under a future emission control regime will be discussed below in form of a sensitivity analysis.

with historical fossil-fuel emission profiles, it arrived at realistic pre-industrial concentration levels. A pre-industrial concentration level of 278 ppm was obtained, in good agreement with CO_2 measurements based on analysis of air occluded in natural ice of known age.[32] Alternative biota emission data estimates by Peng et al[33] were also examined. They compute profiles of historical carbon emissions on the basis of the observed $^{13}C/^{12}C$ change in tree rings through the use of a modified multi-box ocean model. Although the methodology is advanced, their values appear unlikely, resulting in pre-industrial CO_2 concentrations as low as 250 ppm.

Cumulative carbon emissions from forest and soil between 1860 and 1980 are estimated at 180 Gton carbon and the 1980 emission flux at 2.6 Gton, based on Houghton et al.[31] More recent estimates by the IPCC[1] indicate cumulative carbon emission from land-use changes on the order of 115 ± 35 Gton between 1850 and 1985 and present annual fluxes between 0.6 and 2.5 Gton. By using lower biota emissions, our model would have to be modified by adopting a higher airborne fraction coefficient. The role of biota in the global carbon cycle, and their influence on the fraction of CO_2 emissions retained in the atmosphere is at present still surrounded by controversy.[28,34] Adopting Houghton's data,[31] the biosphere is seen to be a large source of CO_2 that supplements fossil-fuel emissions, resulting in an atmospheric retention factor of about 40%. On the other hand, oceanographers argue for an airborne fraction of about 60%, a view supported by ecologists who claim that increased CO_2 fertilization effects significantly diminish the role of terrestrial biota as a net carbon source.[35]

Changing the airborne fraction implies reassessment of the relative importance of biota and fossil fuels as sources of the increasing CO_2 concentrations observed. Higher airborne fractions also imply that the problem will grow more rapidly. Thus, our analysis sketches future emission profiles which possibly favor the use of fossil fuel, assuming high historical carbon emissions from forest and soil, and an airborne fraction at the lower range of carbon models. It should be noted that the relative contributions of different geographical regions to increases in global CO_2 concentrations resulting from fossil-fuel use is not affected by this uncertainty. Only the relative importance of fossil fuels vis-à-vis biotic carbon sources would be changed if lower biota emissions and a resulting higher airborne fraction were to be adopted in the model.

Although our simple model performs reasonably well in reproducing increases in atmospheric CO_2 concentrations from 1800 to the present, we have to emphasize the uncertainties in using the model to account for emissions until the end of the 21st century. Future rates of deforestation (not considered in the emission "allowances" discussed here) are uncertain. Continued deforestation would further limit the use of fossil fuels under the range of atmospheric CO_2 concentration stabilization scenarios adopted here. The airborne fraction may change in an emission stabilization scenario, as illustrated by Harvey.[36] However, predicting changes in the airborne fraction over the next 100 yr, when climate, land-use patterns, emission profiles and other significant factors will alter considerably lends another aspect of uncertainty to modeling the future carbon cycle. Therefore, a sensitivity analysis is carried out of future carbon allowances under a range of airborne fraction values. At present it is also difficult to predict how future ocean uptake will be affected by changing CO_2 concentration levels and a warmer climate.

Despite the uncertainties involved in our simple carbon model, we still consider it a useful tool in outlining disparities in historical regional carbon-emission profiles and as an instrument to outline (hypothetical) equitable future carbon-emission profiles as upper bound scenarios for the use of fossil fuels.

4. HISTORICAL CARBON EMISSIONS

Figures 2 and 3 record historical carbon emissions from land-use changes, cement production and fossil-fuel consumption, with fossil-fuel emissions disaggregated into nine world regions. It is apparent from Fig. 3 that around 85% of the past carbon emissions from fossil-fuel use were emitted by the industrialized countries of the northern hemisphere. In the 19th century most emissions were small compared to the present global emission levels and came from Western Europe, mostly the United Kingdom. North America emerged as a

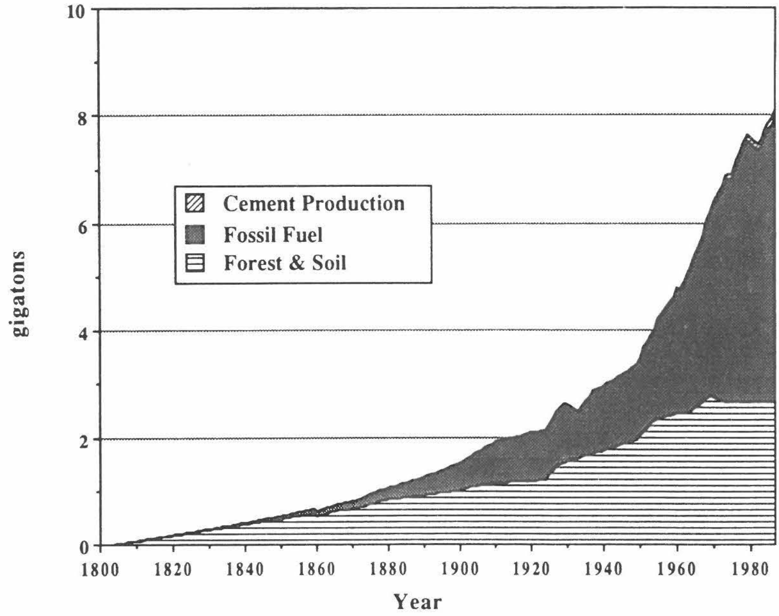

Fig. 2. Historical carbon emissions from fossil-fuel use,[25] cement production,[27] and forest and soil[31] in gigatons for 1800–1987.

dominant carbon emitting region before the end of the 19th century, rivaling and eventually surpassing Western Europe. Eastern Europe and the U.S.S.R. became large-scale-fossil energy consumers only after the 1930s, and the developing countries, most notably in Asia (China and India), became important even later.

As shown in Fig. 4, of all fossil fuels, the largest single source of carbon emissions is coal

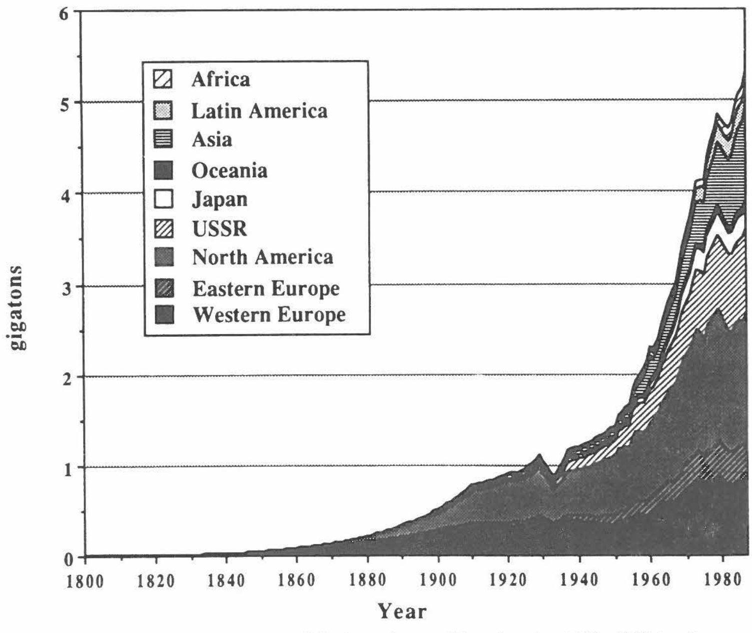

Fig. 3. Carbon emissions from fossil-fuel use by world region for 1800–1987 in gigatons.

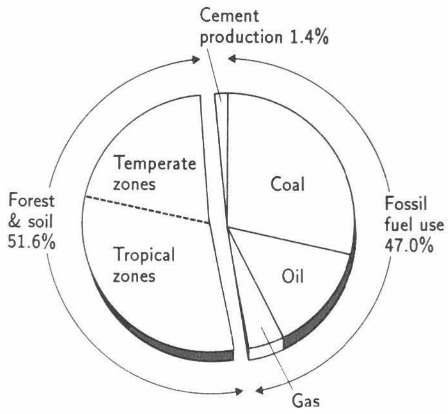

Fig. 4. Contribution to the increase in atmospheric CO_2 concentrations since 1800 by carbon source (in percent). The division of forest and soil carbon emissions by latitude zones is approximate and affected by uncertainties of the global carbon cycle.

(about 60% of all fossil-fuel emissions), followed by oil (around 30%) and gas (<10%). Although oil surpassed coal as the dominant primary energy carrier at the global level around 1960,[37] coal remains the dominant source of historical carbon emissions, illustrating how coal intensive the historical industrialization path was in both energy and carbon-emission terms. Natural gas contributes only a small fraction of the cumulative carbon emissions from fossil-energy use because of its relatively recent introduction, smaller contribution to the world's primary energy mix, and lowest carbon content per heat value. This points to the large potential a natural gas economy could play in climate change mitigating strategies.[28]

Based on data adopted here, carbon emissions from biota, forests and soils remained the dominant source over fossil fuels well into the 1950s. Current biota emissions are basically all from tropical latitudes, i.e., from developing countries. This should not, however, lead to the conclusion that we observe a reversed North–South divide when comparing historical biota and fossil fuels as carbon sources. Although estimates are uncertain, land-use changes and deforestation in temperate latitudes were historically significant. Estimates[1,13,38] indicate that up to 40% of cumulative biota carbon sources originate from the northern hemisphere (Fig. 4). However, we do not feel confident enough of the accuracy of such estimates at present to include them in a more disaggregated regional breakdown of historical carbon emissions.

It is possible to evaluate the contributions of different carbon sources or different regions to atmospheric CO_2 concentration since 1800 based on our data set. As reported in Fig. 5 (bottom), the contributions to the increasing concentrations of CO_2 due to fossil-fuel use over the period 1800–1987 are disaggregated into nine world regions. For comparison, the top of Fig. 5 shows the same regional disaggregation for 1987 fossil-fuel carbon emissions. Significant differences between the contributions of each region to current emissions and to past concentration increases become apparent. They confirm that carbon releases from fossil-fuel use are predominantly from developed countries, especially when past emissions are considered. In 1987, developing countries accounted for 26.4% of fossil-fuel carbon emissions, with their share in cumulative emissions over the period 1800–1987, and thus to increases in atmospheric CO_2 concentrations, being as small as 14.1%.

The above analysis, however, does not help assess the contributions of different regions to CO_2 concentration increases, based on some equity criterion. We adopt per capita emissions as the criterion for inter-generational and spatial equity. Therefore populations in the various regions, with their different levels and growth patterns, have to be included in our calculations. A dynamic perspective is adopted in order to calculate cumulative per capita emissions. Cumulative carbon emissions are usually normalized per head of current population, i.e., a semi-dynamic approach, as for instance used by Subak and Clark.[8] Instead, we divide the

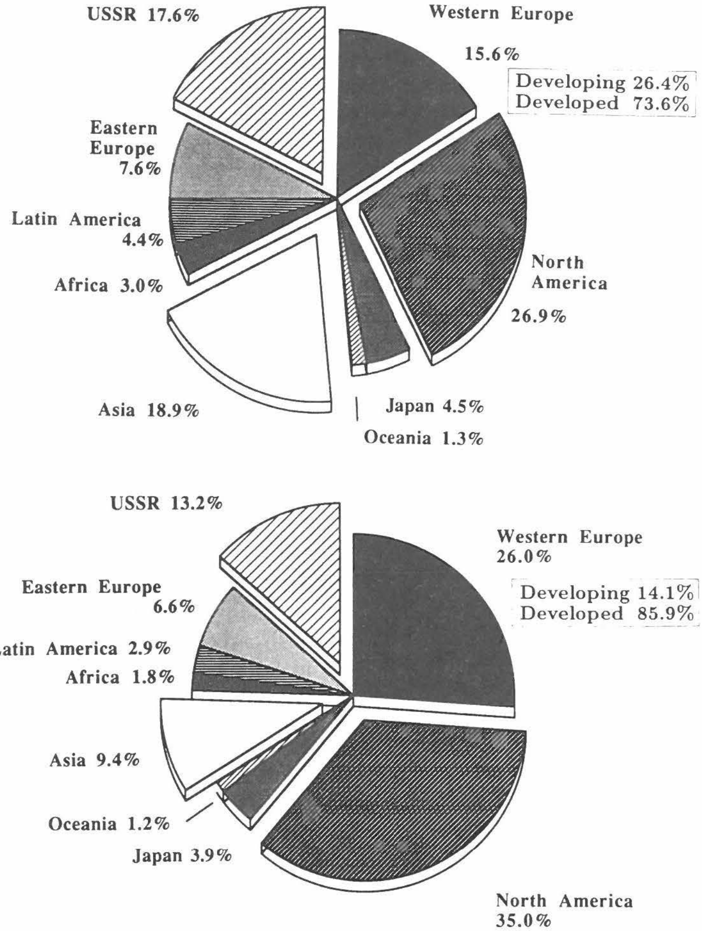

Fig. 5. Share of different regions in current (1987) energy-related carbon emissions (top) and in contribution to the increases in atmospheric concentration since 1800 (bottom), in percent.

integral of annual emissions since 1800 by the integral of the annual population data over the same period (see Appendix). Our cumulative carbon emissions per capita may be conceptualized as the average carbon emissions per person-year lived over the period 1800–1987.

Figure 6 shows cumulative carbon emissions from fossil-fuel use per capita of the population that lived during this period, compared to 1987 per capita carbon emissions for nine world regions. Cumulative per capita emissions are practically the same as the per capita contributions to atmospheric concentration increases, and thus a proxy for assessment of regional and generational responsibilities of these concentration increases under our equity criteria. Two characteristic features emerge from Fig. 6: first, the systematically higher per capita carbon emissions of the present generation compared to previous ones; and secondly, significant interregional differences between North and South in both current and cumulative per capita emissions. The cumulative per capita gap is particularly large: a factor 40 difference between the highest and lowest regional cumulative per capita emission values.

One has to note that while large per capita emission differences exist between North and South, the differences within and between regions of similar degrees of economic and industrial development are also extremely wide. Both Switzerland and the U.S.A. have GNP in excess of 20,000 U.S. \$ per capita, whereas their per capita carbon emissions from fossil-fuel use differ by nearly a factor of three (1.8 compared to over 5 ton carbon per capita for Switzerland and the U.S.A., respectively). Even where per capita emissions are similar, they are often due to

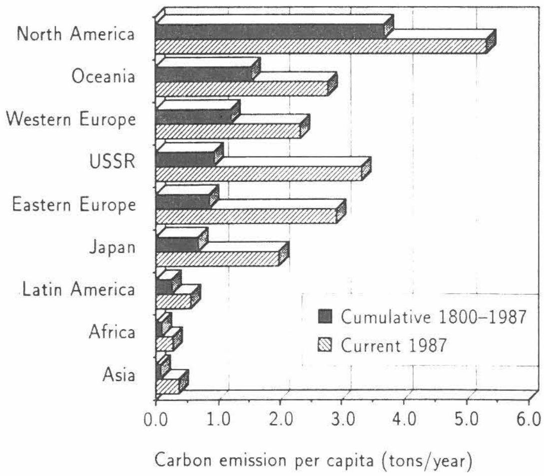

Fig. 6. Current (1987) and cumulative (1800–1987) per capita carbon emissions from fossil-fuel use by world region (in tons of carbon/yr per capita and person-yr).

entirely different reasons. The U.S.A. and the former G.D.R. both have per capita emissions in excess of 5 tons carbon/yr. In the U.S.A., this is due to high energy consumption, affluence, and energy intensive lifestyles (e.g., high oil consumption for private transportation). In the former G.D.R., it is due to the structure of the economy, which stresses energy intensive basic material production; and to the energy supply system, with its high share of brown coal in the energy balance. This illustrates that there is a large potential for minimizing CO_2 emission levels by restructuring economic activities and the energy system in the long-term.

Our high level regional disaggregation cannot capture all the detailed and decisive differences between individual countries. Bearing this caveat in mind, let us further examine certain regional characteristics of per capita carbon emissions up to the present as shown in Fig. 6. North America has emitted decidedly the largest amounts of carbon per capita, in both current and cumulative terms. Its per capita emissions are much higher than those of other developed regions, not to mention developing regions. In addition, it also contributes the largest share (35%) to the concentration increase of all regions (Fig. 5). Per capita cumulative emissions from Western Europe are not so large despite its earlier industrialization, though it is the second largest contributor to fossil-energy CO_2 concentration increases (Fig. 5). This is due to the size of its population in relation to its emissions, which was already relatively large by the beginning of the 19th century. Although the U.S.S.R. and Eastern Europe currently emit considerable amounts of carbon per capita, their cumulative emissions are smaller than those of the other developed regions (except Japan). These two regions began to increase their carbon emissions rapidly only after World War II. In comparison to the industrialized countries, current emissions of developing countries and their contribution to past concentration increases are small both in absolute amounts and in per capita terms.

5. INTER-GENERATIONAL CARBON ACCOUNTS AND STABILIZATION SCENARIOS

We have identified significant total and per capita differences in carbon emissions stemming from fossil-fuel use over time between different regions of the world. If current emissions are to be reduced in the future, one needs to ask whether or not it is right to freeze emissions at current levels before setting stabilization or reduction targets. The emission levels of most developing regions increased only over the last decades and their populations are expected to expand enormously over the next century. They will obviously have to shoulder a much heavier burden than the developed regions if their emissions are to be frozen at current levels. Hence, we propose a carbon accounting system aimed at equitable emission quotas for regions and between generations.

The reasoning underlying such an accounting system and its resulting emission quotas is quite simple. Consider an ultimate limit to the total (cumulative) quantity of carbon that can be deposited in the atmosphere as a global resource or carbon credit available to humanity. How is this global credit to be distributed fairly among different generations and among different regions of the world? We postulate as an underlying equity criterion that: *everyone has an equal carbon emission quota, irrespective of the country or generation to which one belongs.*

This simple postulate may be considered extremely egalitarian, but contrary to other criteria proposed based on country, area, or GNP, it would provide for both inter-generational and interpersonal equity and also be independent from the degree of economic development. However, as our analysis of historical carbon emissions has shown, such a criterion also implies that some of the developed regions have accumulated an excess of historical carbon emissions and a resulting deficit of future per capita quotas in such an accounting scheme.

Our emission quota is proportional to the increase in CO_2 concentration expected by the year 2100. We are presently in no position to propose a definitive upper boundary for CO_2 concentration and a resulting global carbon credit available for distribution with our allocation criterion. Consequently, we adopt a scenario approach, analyzing three limit values for stabilization of CO_2 concentration by the year 2100 at levels of 140, 280 and 420 ppm higher than in 1800. The ultimate cumulative carbon emissions from future fossil-energy use are then determined by these limits. Assuming that terrestrial biota is no longer a net source of CO_2 emissions in the future, these scenarios would result in a stabilization of atmospheric CO_2 concentrations by the year 2100 at levels of 420, 560 and 700 ppm respectively. Per capita emission quotas then depend on two variables: the total carbon credit to be distributed, and populations over time and by region (see Appendix).

Once an equitable emission quota is derived, we can draw a break-even line of inter-generational carbon accounts. The line in Fig. 7 indicates cumulative carbon emissions by the year in question, when we assume a certain increase (in this example, an additional 140 ppm) in atmospheric CO_2 concentration by 2100 and wish to maintain an equitable inter-generational per capita emission allowance. Note also that on the vertical axis we show the equivalent amount of carbon emissions in 2100 at an annual discount rate of 0.333% derived from the long-term ocean uptake part of our carbon model. Break-even lines of inter-generational equity were computed for different regions and for the world total (Figs. 8 and 9).

Let us illustrate how to interpret Figs. 8 and 9. As can be seen in Fig. 7, typically there are two cases (A and B) with regard to the relative position between the historical emission path and the inter-generational equity break-even line. In case A, a larger amount of carbon has

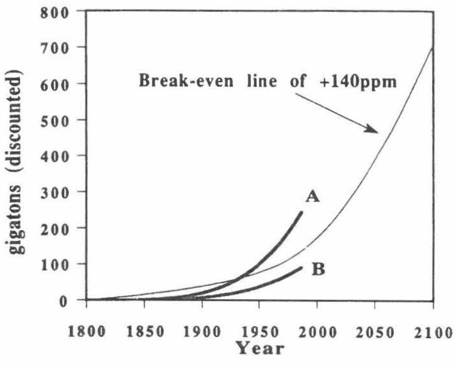

Fig. 7. Cumulative carbon-emission trajectories in a hypothetical scenario allowing an increase of atmospheric CO_2 concentrations of 140 ppm over pre-industrial times by 2100. The break-even line of the inter-generational equity emission trajectory is shown as well as inter-generational carbon debt (A) and credit (B) emission trajectories. Cumulative emissions remaining in the atmosphere are discounted at an annual rate of 0.333% to represent the effect of long-term ocean uptake.

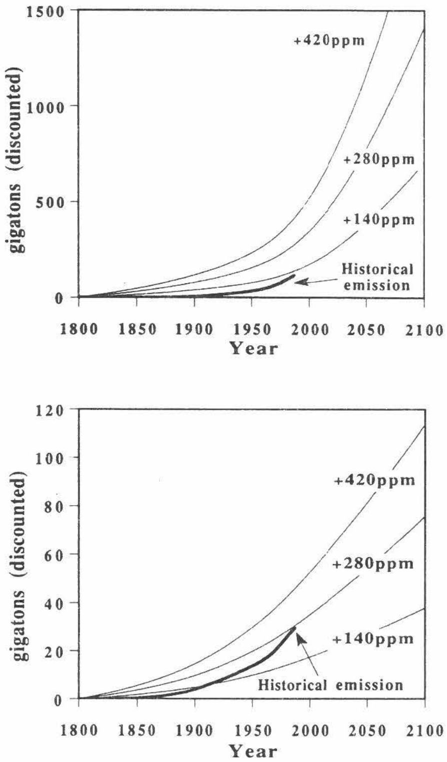

Fig. 8. Cumulative carbon-emission trajectories, historical emissions and inter-regional, inter-generational equity emission paths for three scenarios of increases in atmospheric CO_2 concentration (additional 140, 280 and 420 ppm, respectively, by 2100). The World total is shown at the top and Western Europe at the bottom.

been emitted than to be expected from the viewpoint of intergenerational equity. In this case we are in "carbon debt" to future generations. On the other hand, if the historical emission is below the equity break-even line (case B in Fig. 7), we have a "carbon credit" and inherit an additional emission quota from past generations.

Figures 8 and 9 show the historical emission paths of the World, of Western Europe, North America, and Asia as illustrative examples. The historical emissions shown in these figures do not include carbon emissions from biota. As can be seen in Fig. 8, the world is just reaching the inter-generational equity break-even line for an increase of CO_2 concentrations of +140 ppm. Thus, up to now, *the excessive amounts of carbon emissions from the developed regions are offset by the carbon credit of the developing world.*

Western Europe (Fig. 8) arrives at a break-even line for a concentration increase of +280 ppm. This means that, if the target for stabilization of emission concentration is set at 560 ppm (280 + 280 ppm) in 2100, its present generation has neither a debt nor a credit of carbon emissions. North America (Fig. 9), on the contrary, is far beyond its equity break-even line even for a concentration increase scenario of +420 ppm. Although we only account for emissions from fossil fuels, the historical emission trajectory of North America has been in the vicinity of an equity break-even line equivalent to an increase of atmospheric CO_2 concentrations of +800 ppm. Figure 9 also indicates that North America has already emitted the total amount of carbon allocatable under our inter-generational and spatial equity criteria for a scenario of additional +200 ppm CO_2 concentration by the year 2100. This shows that any target of stabilizing atmospheric CO_2 concentrations below 480 ppm (280 + 200 ppm) by 2100 cannot be achieved in an equitable way for this region under the allocation criteria adopted. Such a scenario could become feasible if one considers carbon disposal or internationally tradable carbon permits. In comparison with the developed regions, Asia (Fig. 9) has emitted a

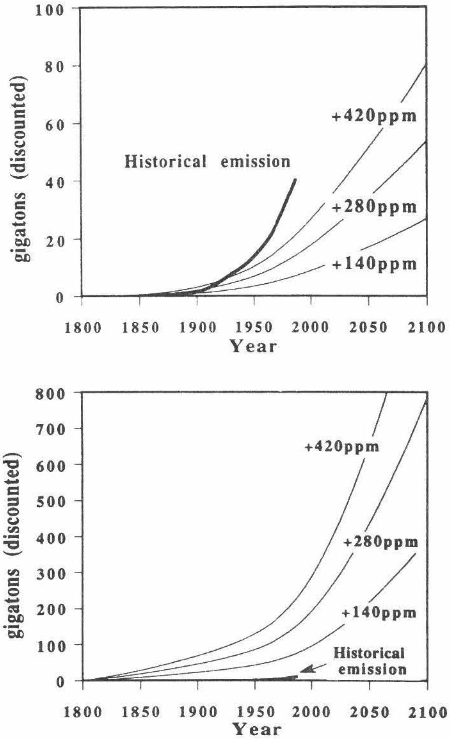

Fig. 9. Cumulative carbon-emission trajectories, historical emissions and inter-regional, inter-generational equity emission paths for three scenarios of increases in atmospheric CO_2 concentration (additional 140, 280 and 420 ppm, respectively, by 2100). North America is shown at the top and Asia (excluding Japan) is shown at the bottom.

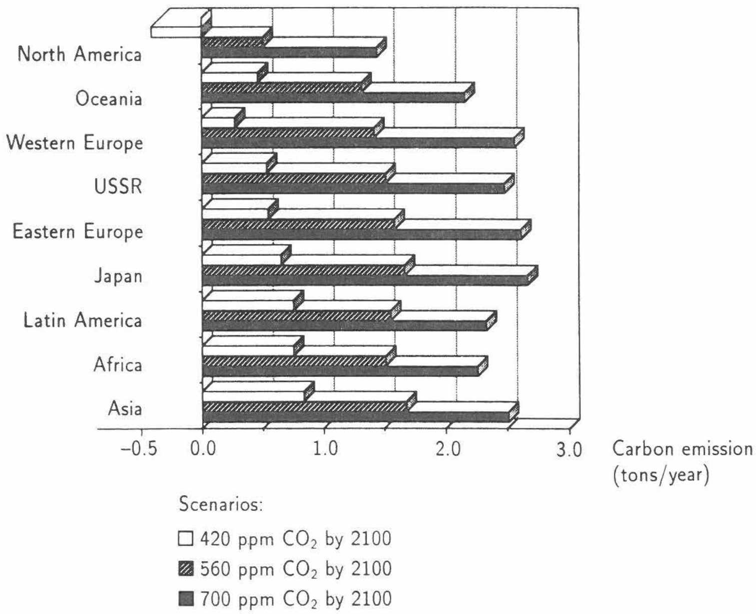

Fig. 10. Regional annual per capita CO_2-emission allowances for the period 1988–2100, assuming inter-regional and inter-generational equitable emission allowances for three scenarios of stabilization of atmospheric CO_2 concentrations by 2100 (at 420, 560 and 700 ppm, respectively) in tons carbon/yr per capita.

smaller amount of carbon than is expected on the basis of its historical population data and our equity criteria.

The annual per capita carbon-emission allowances for the period 1988–2100 derived from our inter-generational and spatial equity criteria are shown in Fig. 10 for three scenarios of CO_2 concentration stabilization by the year 2100. They can be compared to the cumulative per capita figures shown in Fig. 6 previously. From a regional perspective, the North–South difference in past per capita emissions is reversed to some extent for future emission allowances.

It is interesting to note that in the medium (+280 ppm) and high (+4420 ppm) concentration increase and stabilization scenarios, there is little difference in future per capita emission allowances between regions except for North America. *Developing regions have inherited some amount of additional emission quotas from their past, but the huge size of their future populations reduces the value of such additional credits on a per capita basis.*

Under a low (+140 ppm) concentration increase scenario, future emission allowances (Fig. 10) are modest, being significantly below 1 ton carbon per capita on average over the period 1988–2100. Developing countries would have slightly higher per capita allowances than developed ones. However, North America would have no carbon credit left for future emissions if concentrations indeed have to be stabilized at a level of 420 ppm. This is due to the already large emissions in the past and the stringent equity criteria adopted here.

Through the use of the accounting system proposed here, it is also possible to draw equitable future regional emission profiles. We must emphasize that the regional emission profiles sketched here are illustrative only of the implications of a policy of strictly implemented inter-generational and spatial equity principles as applied to per capita emission allowances. We do not imply that we consider such scenarios to be necessarily realistic. However, the regional emission profiles indicate clearly the differences in past per capita emission levels, and the different responsibilities for past concentration increases. They can provide guidance for the extent of measures to be taken to limit CO_2 emissions across different regions or for the extent of interregional trading of carbon-emission allowances.

Figure 11 shows such regional per capita carbon-emission paths for the medium (+280 ppm) case. In order to stabilize CO_2 concentrations by the year 2100 at twice the pre-industrial level, i.e., at 560 (280 + 280) ppm, our carbon model calculates a possible emission level of 4.7 Gton

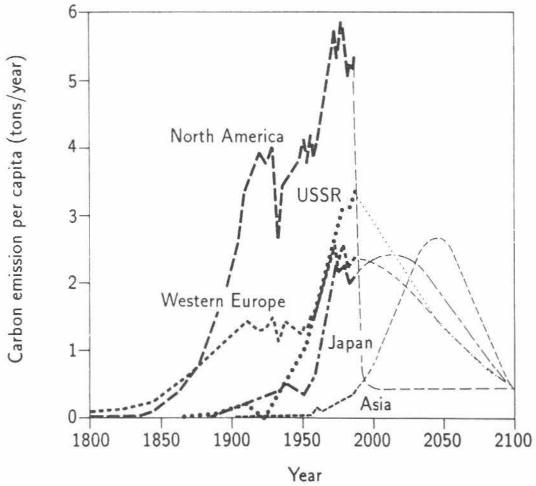

Fig. 11. Historical and hypothetical future per capita carbon-emission profiles per region under inter-regional and inter-generational equitable emission allowances in a scenario aiming at stabilizing atmospheric CO_2 concentrations at twice the pre-industrial level by the year 2100 and onwards. Only fossil fuel carbon emissions are considered. The hypothetical future emission paths exclude trading of carbon-emission allowances, reforestation or CO_2-abatement technologies.

carbon per year, which results (at a projected world population of 10.4 billion) in a per capita emission allowance of 0.46 tons carbon yr. Therefore all emission paths converge to this value by the year 2100. As can be seen from Fig. 11, most developed regions would have to reduce their carbon emissions throughout the next century. The cut-back in per capita emissions in the North American region would have to be particularly drastic in such a scenario. By contrast, Asia has a large enough carbon quota inherited from the past to raise its emission level beyond 2 ton carbon per capita in the middle of the next century.

Note that Fig. 11 shows possible future emission profiles under the intra- and inter-generational equity criteria adopted to reach the goal of stabilizing of CO_2 concentrations by the year 2100. These emission profiles are not predictions but are hypothetical calculations designed to illustrate equity issues inherent in any emissions reduction strategy. Also the hypothetical emission paths do not consider any active CO_2 abatement strategies or the possibility of tradable emission permits. Therefore, we are not implying that North America *must* reduce its carbon emission by 90% immediately or that Asia *must* increase its present per capita emission to Western European or Japanese levels.

6. SENSITIVITY ANALYSIS

The regional emission allowances and their profiles up to the year 2100 discussed previously are based on a simplified carbon-cycle model. We have assumed for our calculations that the parameters of the model, in particular the airborne fraction and the long-term ocean uptake coefficients, would not change over the time horizon considered. This hypothesis appears warranted when considering emission paths under a quasi-exponential growth regime, such as was the case in the period 1800 until the present. However, the airborne fraction coefficient is not independent from the future emission paths considered, especially under atmospheric concentration stabilization scenarios.

For instance, Rothmans et al[39] in using the IMAGE model estimate future airborne fractions between 45 and 55% in scenarios of a linear increase in atmospheric CO_2 concentration levels to approximately 500 and 700 ppm respectively by the year 2100. In case atmospheric concentrations are stabilized at around 400 ppm, the airborne fraction would fall continuously to below 20% by the year 2100. A similar response is also illustrated by Harvey.[36] Assuming a stabilization of global carbon emissions at a level above 2 Gton, he calculates a range of airborne fractions dropping to between 25 and 30% by the year 2100.

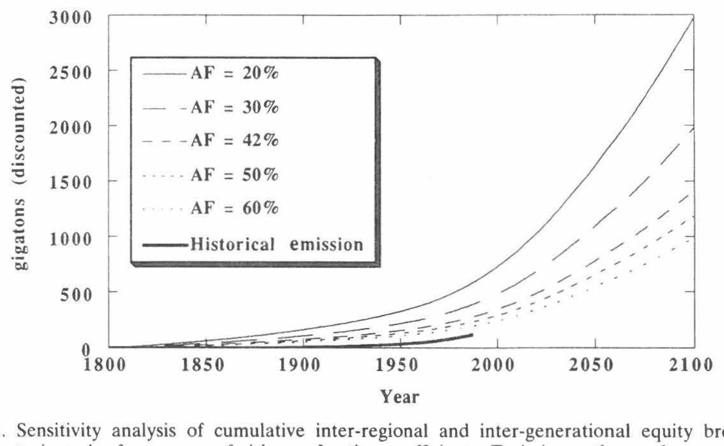

Fig. 12. Sensitivity analysis of cumulative inter-regional and inter-generational equity break-even emission trajectories for a range of airborne fraction coefficients. Emission paths are for a scenario of an increase in atmospheric CO_2 concentration levels of +280 ppm by 2100.

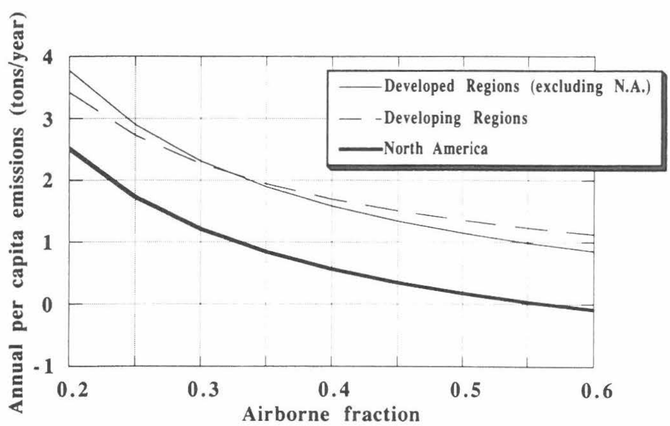

Fig. 13. Sensitivity analysis of regional per capita carbon-emission allowances for a range of airborne fraction coefficients. Emission allowance is average per capita for the period 1988–2100 for a +280 ppm increase scenario by 2100.

Thus, somewhat counter-intuitively, slowing emission increases would lower the airborne fraction and thus tend to *increase* future allowable emission levels. In addition to the uncertainty related to future emissions, changing climate and evolving land-use patterns are further sources of uncertainty for the evaluation of future airborne fraction coefficients. Figures 12 and 13 report therefore the results of a sensitivity analysis for changing airborne fraction values.

If we consider a lower airborne fraction than retained in our simple model (0.42), the allowable emission quantities under a given stabilization scenario would be higher. This is illustrated in Fig. 12 for the cumulative carbon emission break-even lines under the assumption of inter-generational equity for a stabilization scenario of +280 ppm by 2100 (cf. Fig. 8). Should the airborne fraction drop to 0.3, emissions could be 40% higher than in the reference case. If the airborne fraction would drop to 0.2, emissions could be twice as large as in the reference case.

Figure 13 shows the impact of different airborne fractions on regional per capita emission allowances. It is interesting to note that for any range of airborne fractions there are no significant changes in the relative per capita emission allowances between regions.† For any airborne fraction, North America has a lower per capita emission allowance than other regions. The difference relative to the per capita emissions allowances of other regions (1 ton carbon per capita less) also remains fairly constant over the range of airborne fractions shown in Fig. 13. A similar sensitivity analysis was also performed for variations in the long-term ocean uptake coefficient of our carbon-cycle model. The results are practically identical to the sensitivity analysis of the airborne fraction.

Different assumptions on the coefficients of our simple carbon-cycle model influence thus the absolute amount of emission allowances. However, the *relative emission allocations between regions and the ranking of regions in their per capita emission allowances proved robust in the sensitivity analysis performed.*

7. CONCLUSIONS

Our historical analysis has identified significant differences in both generational and regional carbon emissions from fossil-fuel use, with a particularly strong North–South dimension in

†The changing differences in the per capita emission quotas between developed countries outside North America and developing countries are the result of the different weighting of past emissions resulting from various airborne fraction coefficients. When the airborne fraction falls below 0.35, the developed countries outside North America would have a slightly higher allowance than developing countries. This result appears counter-intuitive but can be readily explained. Given the target atmospheric concentration in the year 2100, lowering the airborne fraction will increase the emission allowance for each region. The weight of historical emissions is reduced, allowing for greater future emissions, the relative weight of which increases the closer emissions are to the stabilization date 2100 (due to long-term ocean uptake). All this enhances the impact of future population growth in developing countries.

their regional distribution. Globally, it appears that up to now the significantly higher per capita carbon emissions in developed countries ("carbon debt") are balanced by corresponding lower per capita emissions ("carbon credit") from developing countries in an inter-generational perspective. However, significant differences within developed countries were also found, with emissions from the North American region being particularly high. Our analysis for developing countries indicates that the carbon credit inherited from the past will be largely reduced by the significant population increases projected over the next century. This highlights the crucial role of future population growth in dealing with the global environmental commons. Future emission profiles are outlined for a range of scenarios aimed at stabilizing atmospheric concentration levels by the year 2100. In aiming at inter- and intra-generational equity, and a target value of 560 ppm (i.e., at a doubling of pre-industrial concentration levels) per capita emissions in developed countries would have to be reduced throughout the 21st century. In most developed regions, per capita emissions would have to be reduced at an average rate of 1%/yr up to the year 2100. The corresponding rate for North America would be over 7%/yr.

Our findings illustrate the magnitude of the equity issues involved and should provide some guidelines for an accounting system to be adopted in international negotiations and for policy responses to the CO_2 problem. However, the limitations of our approach and the large uncertainties pertaining to the area of the global carbon cycle, GHG emissions and their future evolution have to be emphasized. Perhaps the most crucial uncertainties are future populations, particularly in the developing countries. The World Bank population projections adopted here are comparatively conservative. Should population growth be significantly higher in the future, the cake to be distributed (i.e., future carbon-emission allowances) would have to be shared among more people and the resulting distributional conflicts would be correspondingly more difficult to resolve. Also, our analysis only dealt with CO_2 emissions from fossil-fuel use and did not include biota sources such as deforestation, or other GHGs. This does not reduce the usefulness of such an analysis, as carbon emissions from fossil-fuel use alone could be large enough to raise atmospheric CO_2 concentration levels before 2100 to unacceptable levels.

Large data gaps, particularly for historical emissions, and uncertainties regarding an appropriate accounting scheme integrating all GHGs remain to be resolved. A particularly urgent task is the narrowing of uncertainties about the role of biota sources and sinks in the global carbon cycle. Other areas of significant uncertainty are future world population prospects and their energy consumption. Furthermore, we described the complex terrestrial carbon cycle with its non-linear characteristic by a simple model in order to obtain analytical solutions. These significant uncertainties and model limitations hold implications for the accounting scheme of energy related CO_2 emissions discussed here. If alternative population projections were to be adopted, if biota sources and other greenhouse gases were to be included, or if the airborne fraction should change in future, the resulting emission allowances for energy related CO_2 emissions would be different, and in most cases (except for a lower population and a smaller airborne fraction) significantly lower than outlined here.

Although many developing countries with low fossil-fuel energy consumption emerge as high CO_2 producers under a range of current estimates of land-use changes and deforestation, we do not feel that this would drastically change the relative rankings of various regions. Historical releases by the North remain substantial relative to past and current releases by the South. However, this situation may reverse in the longer term, should projected trends of deforestation materialize and biota sources rival fossil fuels in emission levels. Finally, our accounting scheme has only considered how to account equitably for our carbon debt (i.e., carbon sources). There is however, also the problem of whether, if and how to allocate carbon credits (e.g., how to account for global carbon sinks, like the world's oceans).

A formidable task is thus still ahead of us in narrowing down uncertainties and obtaining more reliable estimates of historical, present and future trends in GHG emissions. The energy issues addressed here might be considered an area where our knowledge and data are perhaps the best established, as uncertain as they still are. The final, and perhaps most arduous task is to *implement* equitable GHG emission policies: politically, economically and in restructuring the energy system and the economic and social activities it serves.

Acknowledgements—We thank David Victor for his detailed and useful comments on this paper, and Aviott John and Patricia Monahan for editorial assistance.

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APPENDIX

Method of Calculation

The simple carbon-cycle model underlying the accounting of CO_2 emissions is given by the following first-order, linear differential equation:

$$\frac{dM(t)}{dt} = 0.471 \times \mathrm{AF} \times X(t) - \frac{M(t)}{T_0}, \qquad M(t) = C(t) - C(1800), \tag{A1}$$

where AF = airborne fraction, $X(t)$ = carbon emission, $C(t)$ = concentration level, $C(1800)$ = pre-industrial concentration level (280 ppm), T_0 = time constant of long-term oceanic uptake (300 yr, based on Maier-Reimer and Hasselmann[29]). The coefficient of 0.471 is a conversion factor from gigatons of carbon to ppm atmospheric concentration.

The cumulative emission per capita were calculated from:

$$CE_i = \sum_{t=1800}^{1987} E_{ti} \Big/ \sum_{t=1800}^{1987} \mathrm{POP}_{ti}, \tag{A2}$$

where i = index for region ($i = 1, \ldots, 9$), t = index for year ($t = 1800, \ldots, 1987$), CE_i = cummulative per capita emission in region i, E_{ti} = annual carbon emission in year t and region i, POP_{ti} = population in year t and in region i.

The per capita emission quota based on intra- and inter-generational equity is calculated as follows:

$$M(2100) = 0.471 \times AF \times \sum_{i=1}^{9} \sum_{t=1800}^{2100} \times \left\{ \mathrm{POP}_{ti} \times C_0 \times \left(1 - \frac{1}{T_0}\right)^{2100-t} \right\}, \tag{A3}$$

where $M(2100)$ = increase in atmospheric CO_2 concentration by 2100, C_0 = the per capita emission quota.

The inter-generational equity break-even line of cumulative carbon emissions is computed from:

$$IC_{Ti} = \sum_{t=1800}^{T} \left\{ \mathrm{POP}_{ti} \times C_0 \times \left(1 - \frac{1}{T_0}\right)^{2100-t} \right\}, \tag{A4}$$

where IC_{Ti} = ideal cumulative carbon emission by the year T in region i.