Report nr. 222901012

Allocating CO_2-Emissions by Using Equity Rules and Optimization

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December 1992

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Contents

Abstract

In order to reduce the risks of a climate change, a major problem in developing an effective international policy, is the allocation of the responsibility for reducing greenhouse gas emissions among regions.

This report presents two approaches to provide for the allocation problem of emission reductions of the most important greenhouse gas CO_2. The first deals with a description of the emission debt concept. We use an equity rule by which all past and future dwellers on earth are permitted to emit an equal CO_2 quotum per year. Furthermore, the level of the equal emission quotum is dependent on the policy related CO_2-equivalent concentration targets. The regional emission debt is the amount of CO_2, based on a equal share per capita, emitted in a region in the past exceeding the amount allowed. The resulting initial allocation of emission rights may be used as a start for a concept of tradable emission rights.

In the second approach the allocation problem is formulated as an optimization problem. This contains an 'optimal' trade off between rough estimates for social and economic consequences of reducing fossil CO_2-emissions in order to meet policy targets, as expressed in a CO_2-equivalent concentration level. The optimization algorithm developed is a first attempt in solving the optimization problem, where restrictions are dependent on simulation runs with IMAGE (an Integrated Model to Assess the Greenhouse Effect). The algorithm is used to find an allocation of regional fossil CO_2-emissions in order to maximize welfare of future generations, given a maximum allowable concentration level.

Results of both approaches indicate that if the world community is to accept constraints on CO_2-emissions, industrialized regions will have to take the main responsibility in reducing CO_2-emissions either by reducing emissions in their own regions and in developing regions.

Samenvatting

Een belangrijk probleem bij het ontwikkelen van een effectief internationaal klimaatbeleid, is de verdeling van de verantwoordelijkheid voor het reduceren van emissies van broeikasgassen.

Dit rapport presenteert twee benaderingen die het allocatieprobleem van emissiereducties van het belangrijkste broeikasgas CO_2 kunnen ondersteunen. De eerste benadering behelst een uitwerking van het begrip emissieschuld. Hierbij wordt een gelijkheidscriterium gehanteerd, dat er van uitgaat, dat ieder mens op aarde, zowel in het verleden als in de toekomst recht heeft op eenzelfde hoeveelheid CO_2 emissie per jaar. Verder is de gelijke hoeveelheid CO_2 per inwoner per jaar afhankelijk gesteld van de gekozen doelstelling voor het toekomstige CO_2-equivalente concentratieniveau. De regionale emissieschuld is de hoeveelheid CO_2 die in het verleden meer is uitgestoten in een regio dan waar de betreffende regio op basis van het gelijkheidscriterium recht op had. De hieruit voortkomende initiële allocatie van emissierechten voor de toekomst zou gebruikt kunnen worden voor een concept van verhandelbare emissierechten.

In de tweede benadering is het allocatieprobleem als een optimalisatie probleem beschouwd. Dit omvat een "optimale" afweging van ruwe schattingen van sociale en economische gevolgen van het nemen van emissie reducerende maatregelen, opdat milieubeleidsdoelstellingen in termen van CO_2-equivalente concentratieniveau's, gehaald worden. Het ontwikkelde optimalisatie-algoritme is een eerste aanzet tot het oplossen van een optimaliseringprobleem, waarbij restricties gerelateerd zijn aan simulatieruns met het IMAGE-model (an Integrated Model to Assess the Greenhouse Effect). Het algoritme is gebruikt om een verdeling te vinden van fossiele CO_2-emissies waarbij welvaart gemaximaliseerd wordt voor de volgende generaties, gegeven een bovengrens aan het CO_2-equivalente concentratieniveau.

Resultaten van beide benaderingen wijzen erop dat wanneer de wereldgemeenschap de uitstoot van CO_2 wil beperken, de geïndustrialiseerde landen daarvoor de grootste bijdrage moeten leveren door emissies te reduceren in eigen regio en in ontwikkelingslanden.

1 Introduction

The possibility that increasing atmospheric concentrations of greenhouse gases may lead to significant climate changes confronts society with a problem of unusual complexity. International response to reduce the anticipated risk of climate change is needed and is even now considered appropriate by the majority of developed and developing countries. Most of the OECD countries have already announced or adopted policies to stabilize or reduce their emissions of carbon dioxide (the most important greenhouse gas) as well as, in some cases, other greenhouse gases. However, time delays in adapting socio-economic and technological systems to achieve a global sustainable development will lead to inevitable future emissions. This makes a certain amount of climate change in the future unavoidable. Therefore, the response policies will have to be both adaptive and preventive in reducing the anticipated risks of climate change to accepted levels.

As a tool for developing policies which limit the effects of climate change, the Advisory Group on Greenhouse Gases (AGGG) identified several targets for climate policies to protect the structure and functions of vulnerable ecosystems: for example, limiting the rate and magnitude of the change in temperature or sea level rise (AGGG, 1990). Achieving these international targets requires the implementation of policies that will involve reduction of greenhouse gas emissions. This requires significant changes in industrial technology and may have profound economic impacts on modern societies, which will certainly affect the economy of a country.

This brings us to another important characteristic of such an effective international climate policy; how will the responsibility for future reductions in greenhouse gases be allocated among countries? In this study two approaches are discussed which can contribute to solving this question. The first relates the present and past inequities between developing and developed countries. The issue of north-south equity will certainly be addressed in the current negotiations on a common response to climate change. Developing countries should be enabled and supported to continue their development towards higher standards of living in a fashion consistent with the sustainability of the global biosphere. On the other hand, the industrialized countries are responsible for the majority of the present emissions, and even more, for the accumulated past emissions of greenhouse gases released during the growth of these economies towards their present level of prosperity. The concept of an 'emission debt' quantifies the fact that some world regions have emitted more carbon dioxide in the past than they were allowed to. Based on an equal share per capita this debt can be used to determine an initial allocation of future regional emission rights, which can be used for a concept of tradable emission rights. A policy orientated discussion about the emission debt concept can be found in den Elzen *et al.* (1992).

Although the issue of equitable sharing of the global burden for controlling climate change is important in the present negotiations, it does not take into account the real regional costs and benefits of emission control policies. Therefore, in the second part of this study we will define the allocation problem as an optimization problem. The objective is to allocate the emission reductions of fossil-fuel-related carbon dioxide emissions to world regions in order to minimize costs or maximize welfare. The constraint is to prevent the derived response policy exceeding an imposed CO_2-concentration level. The problem is then formulated as a global optimization problem, with a concentration restriction which depends on the simulation model IMAGE, an Integrated Model to Assess the Greenhouse Effect. The optimization algorithm developed is a first attempt to solving the optimization problem defined above. Since reliable assessments of regional costs and benefits of response policies, necessary to quantify the objective functions, are still not available, we will discuss only the results based on a rough estimate of a welfare function.

For both approaches we have used a slightly adapted version of the integrated climate assessment model IMAGE 1.0 (Rotmans, 1990; den Elzen *et al.*, 1991a and 1991b). IMAGE is a model which links models from various scientific disciplines with policies for controlling global climate change and describes the cause - effect chain of the problem. Appendix 1 shows the modular structure of IMAGE.

The structure of the report is as follows: in Chapter 2 an estimation of historical regional CO_2-emissions is given and the concept of emission debt is discussed. The optimization problem is formulated in Chapter 3 and the optimization algorithm is developed is presented. Furthermore, distributions of CO_2-emissions which maximize the welfare of future generations are given. An evaluation of the results, derived from the emission debt concept and optimization, is given in Chapter 4.

2 Allocating CO_2-Emissions by Using Equity Rules

2.1 Introduction

In this chapter we will attempt to quantify historical inequalities between world regions through the concept of 'emission debt', which can be based on, for example, an equal emission quotum per capita per year irrespective of both the country a person lives in and the generation that person belongs to. The emission debt is the amount of CO_2 which some world regions have emitted over and above of what they were allowed to using an equal emission quotum per capita. In section 2.4 we will introduce two methods of calculating the equal per capita emission quota which determines the emission debt. The first method, the intergenerational approach, is based on an emission scenario where persons living between 1800 and 2100 are allowed to emit equal emission quota per year. This results in a target concentration level. The second method is the global carbon budget approach in which the equal emission quotum is the same as the average amount of carbon per capita per year of a global carbon budget, which is based on historical emissions and future scenario-based emissions.

First, we will present an estimation of the historical regional carbon dioxide emissions due to fossil fuel combustion and land use changes in the different world regions (section 2.2). For greenhouse gases other than CO_2 we have not estimated the historical regional emissions because of lack of sufficiently reliable data. Furthermore, in section 2.3 we will present the regional contributions to the past rise in atmospheric CO_2-concentration estimated with IMAGE. This chapter will be closed by a discussion on results of the statistical relation between emission and financial debt (section 2.5).

2.2 Historical Regional CO_2-Emissions

2.2.1 Introduction

In this section we will examine the regional CO_2-emissions over the time period 1800 - 1990 from fossil fuel combustion (plus minor industrial sources like cement production) and changes in land use, which have been the primary cause of the observed increase in atmospheric CO_2. We distinguish the following eleven regions:

- European Community (EC)
- Rest of the OECD: Rest of Western Europe (RW.Eur.), OECD East (OECD E.), North America (N.Am.)
- Former centrally planned countries: Eastern Europe (E.Eur.), CIS (former Soviet Union)
- Developing regions: Latin America (Lat.Am.), Africa, Middle East (M.East), Centrally planned Asia (CPA) and South/Southeast Asia (SSEA).

We will first discuss the CO_2-emissions caused by fossil fuel combustion followed by those caused by land use changes.

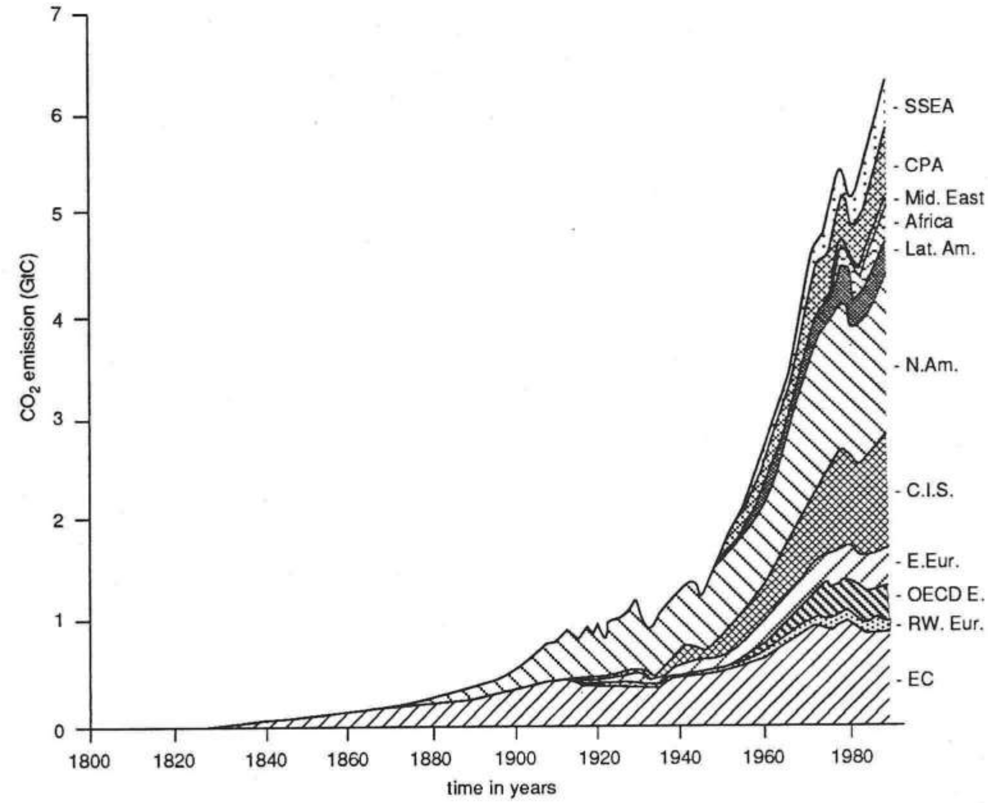
2.2.2 Fossil Fuel Combustion

The global annual emissions of CO_2 from fossil fuel burning and cement manufacturing (although the latter contributes less than 2%) have shown an exponential increase since 1800 (about 3% yearly). There have been major interruptions during the two World Wars, the economic crisis in the thirties and the oil crisis in the seventies (see Figure 2.1). The cumulative release of CO_2 from fossil fuel use from 1850 to 1987 is estimated at 201 GtC, which is within the uncertainty range of 200 GtC $\pm$ 10% (Marland *et al.*, 1989). In 1989 the global emission was about 6.0 GtC (Marland *et al.*, 1989). There is a main difference, however, between the contribution of the industrialized countries and the developing countries: about 85% of the fossil CO_2-emissions in the past is emitted by industrialized countries, where annual releases reach up to 5 tC per capita (Rotty and Marland, 1986). In most developing countries CO_2-emissions are between 0.3 and 0.6 tC per capita per year, although the relative rate of increase in the developing countries has been much larger during the last few decades (about 5% per year in developing regions in contrast to 1% per year in the industrialized regions during the last decade). The historical CO_2-emissions by fossil fuel combustion before 1800 are expected to be small, while the fossil fuel consumption in 1800 is already very low (Mitchell, 1981) and thus has a negligible contribution to the observed present atmospheric CO_2 increase.

In Table 2.1 we have summarized the sources used to estimate the fossil CO_2 fluxes for the period 1800 - 1990 (see also Janssen, 1992). The differences between total CO_2-emissions calculated from the different sources and global emission data from Watts (1982), Marland and Rotty (1984), Rotty (1987) and Marland *et al.* (1989) are within the uncertainty ranges of about 5%.

Table 2.1: Sources used in estimating fossil CO_2 fluxes

Source	Time period	Data	Type of data and period used
Mitchell (1981, 1982 ,1983)	1800 - 1975	Production and in- and export	Only almost complete source of national data for Europe, Russia, North /Latin America <u>before 1925</u>
Darmstadter (1971)	1925 - 1965	Consumption	National data for the whole world <u>1925-1950</u>
Marland *et al.* (1989)	1950 - 1989	CO_2-emissions	National data for the whole world <u>after 1950</u>



EC = *European Community*
RW Eur. = *Rest Western Europe*
OECD E = *OECD East*
E. Eur. = *Eastern Europe*
C.I.S. = *Former USSR*
N. Am. = *North America*
Lat. Am. = *Latin America*
CPA = *Centrally Planned Asia*
SSEA = *South/Southeast Asia*

Figure 2.1: Regional CO_2-emissions due to fossil fuel combustion and cement production in the period 1800 - 1990.

2.2.3 Land Use Changes

Changes in land use over the past two centuries have caused a significant release of CO_2 from terrestrial biota and soils to the atmosphere. About one-third of past CO_2-emissions is supposed to have come from land use changes (Siegenthaler and Oeschger, 1987; Houghton and Skole, 1990). During the last century the emissions induced by land use changes were even larger than those from fossil fuels. Europe, North America and the CIS have caused the largest contributions to emissions through expansion of croplands. In this century land use changes in temperate and boreal zones have declined, while in tropical regions they have accelerated. The major cause of this accelerating change in land use is the tremendous pressure from increasing demands of growing populations. Other damaging effects of large-scale changes in land use are the extinction of species, increased erosion, threats to indigenous people and the destruction of a wide variety of possible important assets.

Estimates of CO_2-emissions from land use changes depend on the rates of these changes, the amount of carbon in soil and biomass, rates of oxidation of wood products (through burning or decay) and rates of decay of organic matter in soil. In this study the net release of regional CO_2-emissions due to land use changes has been estimated for the period between 1800 and 1990 (see also Janssen, 1992). The changes in carbon storage are mainly caused by forest clearing, which converts forest to permanent agriculture and pasture. The contributions of selective logging and shifting cultivation are much smaller (Detwiler and Hall, 1988). Rates of land use changes for the period 1800 - 1980 are derived from Houghton *et al.* (1983). The conversion rates are extrapolated for the period between 1980 and 1990. For other than tropical regions, the extrapolated rates are assumed to be the same as in 1980. For the tropical regions, the extrapolated rates of conversion of ecosystems are based on FAO data (FAO, 1988; 1991). As Houghton *et al.* (1983) we have used a simple bookkeeping model, to calculate the yearly changes of carbon in ecosystems (Figure 2.2), by using estimates of carbon in soil and vegetation before and after changes in land use (Houghton *et al.*, 1983; 1987).

Houghton (1991) gives four factors which cause uncertainties in estimating CO_2 fluxes from land use changes. Firstly, the rates of deforestation differ, depending on the study, even if they have used satellite imagery. This is largely because of differences in purpose and definitions. Secondly, large differences in estimates of carbon stocks cause uncertainties. Estimates vary by almost 100%, which may be caused by possible errors in emission factors and differences in surveys (Houghton, 1991). Thirdly, differences are caused by the fate of deforested land or land use. Is deforestation permanent or temporary? Finally, uncertainties are caused by exchanges of biotic CO_2 which are not associated with deforestation.

Comparisons of different studies show the large uncertainties in estimating CO_2-emissions by land use changes (Table 2.2). The fluxes derived in this study for 1980 are within the uncertainty ranges of other studies, which is also the case in 1990 with fluxes in tropical regions. IPCC (1990) gives an 1850 - 1986 estimate of 117 $\pm$ 35 GtC, while our estimate over this period amounts to 107 GtC.

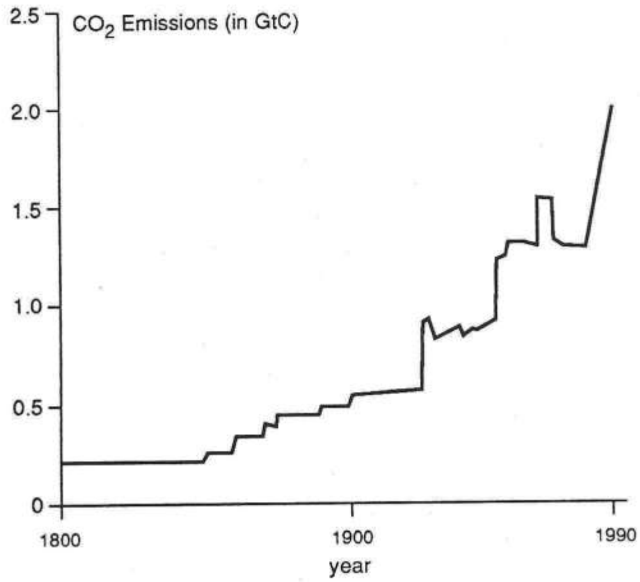


Figure 2.2: Global CO_2-emissions by land use changes.

The IMAGE deforestation module of is a simulation model where the underlying driving forces are modelled separately. In this module only the tropical parts of the world regions America, Africa and Asia are modelled. These are, however, responsible for about 80% of the CO_2-emissions from land use changes between 1900 and 1990. The net flux of CO_2 estimated by IMAGE, results in a lower flux than estimates in this study. The CO_2-emissions during the eighties estimated by IMAGE are 1.3 GtC yr^{-1}, where our estimates result in 1.6 GtC yr^{-1}. Note that these estimates are both within the range of uncertainty for the last decade of 0.6 GtC yr^{-1} to 2.6 GtC yr^{-1} (IPCC, 1990).

Table 2.2 Ranges of CO_2-emissions (in GtC) from land use changes according to different studies.

Sources	1980 World	1980 Tropical regions	1980 Temperate and boreal regions	1990 Tropical regions
Moore *et al.* (1981)	2.2 - 4.7	1.8 - 3.8	0.4 - 0.9	
Houghton *et al.* (1983)	1.8 - 4.7	1.3 - 4.2	0.5	
Houghton *et al.* (1987)	1.0 - 2.6	0.9 - 2.5	0.1	
Molofsky *et al.* (1984)		0.6 - 1.1		
Detwiler *et al.* (1985)		1.0 - 1.5		
Detwiler and Hall (1988)		0.4 - 1.6		
Hao *et al.* (1990)		0.9 - 2.5		
Armentano and Ralston (1980)			-1.0 - -1.2	
Johnson and Sharpe (1983)			-1.6 - -1.9	
Houghton (1991)				1.1 - 3.6
IPCC (1992)				1.1 - 2.3
IMAGE 1.0		1.2		1.3
This study	1.2	1.3	-0.1	2.1

2.3 Regional Historical Contribution to Increased CO_2-Concentration

Until now industrialized countries have contributed much more to CO_2-emissions than the developing world. Using the IMAGE model we have estimated the regional contribution both from fossil fuel use and land use changes, to the increase in the CO_2-concentration since 1800. This has been done by calculating the difference in CO_2-concentration increase in 1990 with and without the emissions of the region under concern. For these calculations we had to adapt IMAGE in order to start in 1800. For the ocean model, the initial values of the amount of carbon in the surface layers were taken from Goudriaan and Ketner (1984). For this version also the deforestation and terrestrial modules are set off. This implies that the CO_2-uptake by the terrestrial biosphere through negative feedbacks is not simulated, resulting in an unbalanced carbon budget over the period in the past, and a simulated CO_2-concentration of 371 ppmv in 1990 (while the observed value is 354 ppmv). Also the fact that the CO_2-fluxes from land use changes in this study are higher than those of IMAGE causes a higher concentration level, but this does not affect the relative contributions of the regions.

Figure 2.3 shows the relative contributions of the world regions to the rise in atmospheric CO_2-concentration. The contribution from Western Europe and North America amounts to about 40%; for Eastern Europe (including the CIS) about 20%, and OECD East about 5%, the combustion of fossil fuels being the major cause. On the other hand, the relative contributions from Africa, Latin America and South/Southeast Asia (exceeding 30%) are for about 75% due to land use changes.
When the relative part of emissions in the past is used to estimate the regional contribution (e.g. Krause *et al.*, 1989) to climate change, regions with relatively large emissions in the last century will be overestimated, in contrast to those of which emissions have accelerated in the last few decades. This overestimation is caused by the long atmospheric lifetime of CO_2, which is about 50 to 200 years (IPCC, 1990).

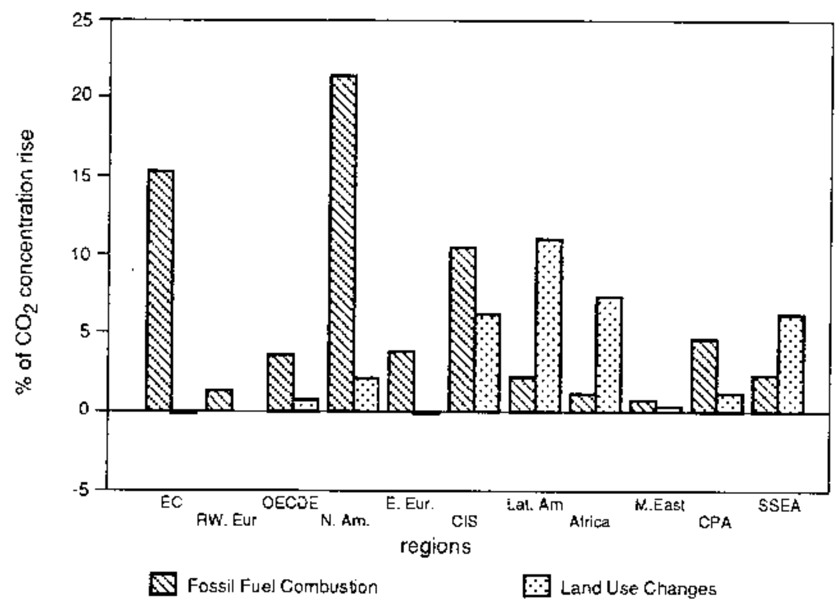


Figure 2.3: Relative regional contribution to the CO_2-concentration rise caused by fossil fuel combustion and land use changes.

2.4 Emission Debt

2.4.1 Introduction

If the world community is to accept constraints on CO_2-emissions, how can future CO_2-emission rights be allocated to the world regions? In the last section it was shown that the CO_2-concentration increase in the past is largely caused by industrialized regions, while Figure 2.4 shows that historical CO_2-emissions per capita are unevenly divided among the world regions. In this section we will try to quantify the fact that some regions have emitted more CO_2 in the past than they were allowed to by equity rules. This so-called emission debt is defined here in terms of population levels.

Although the results in this study are based on population levels, several other indicators for allocating future emissions to regions can be considered. Actually, the process of finding acceptable indicators as a base for allocation of payments or permits is now gaining momentum, as part of the attempts to set up a global climate agreement. Indicators for such an allocation could be based on present and past emissions, area, population levels (equal allocation per capita carbon budget), state of the economy (equal allocation per unit GNP budget), energy intensity or a combination of these factors (Krause *et al.*, 1989; Grubb, 1989; Grübler and Fujii, 1991; Grubb and Sebenius, 1992).

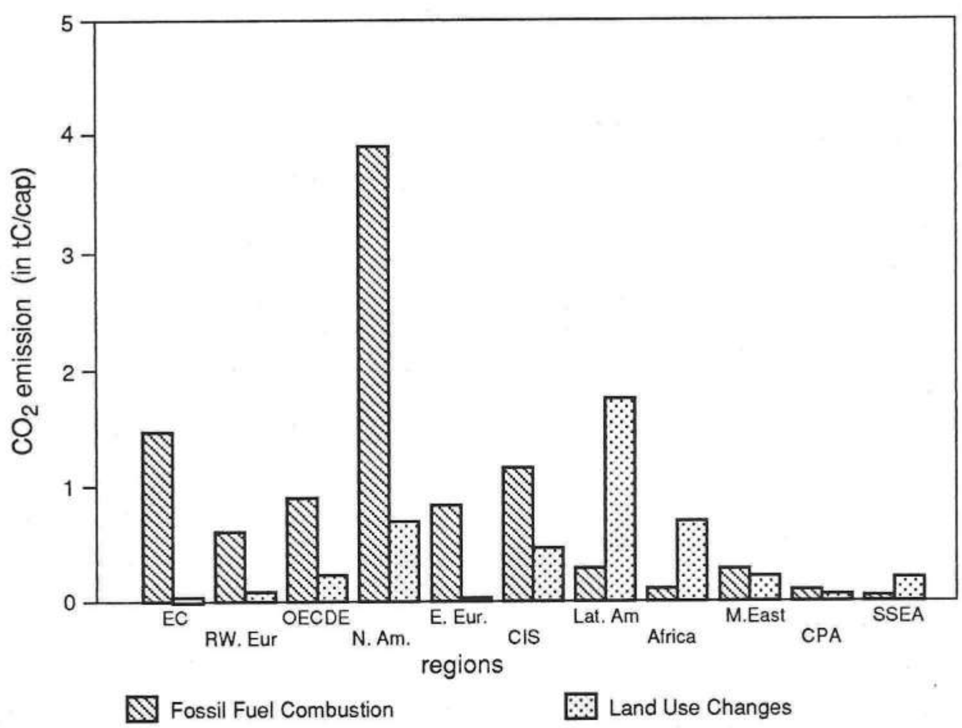


Figure 2.4: Average emission per capita for the period between 1800 and 1990. Regional differences exist in source and levels of emission.

Because the per capita quotum approach[1] is conceptually attractive and computationally simple, it is used here for quantifying the fact that some regions have emitted more in the past than they were allowed to. The per capita approach can be translated into the following equity ideal for the allocation of the emissions: *Every human being has an equal emission quotum per year irrespective of both the region one lives in and the generation one belongs to* (Grübler and Fujii, 1991). This quotum is denoted by Q_{cap} (in tC per capita per year).

The equal emission quotum is dependent on the climate target imposed. In this section two approaches are used to estimate Q_{cap}. In the intergenerational approach, an emission scenario based on population levels for the period 1800 - 2100 is used to derive iteratively the Q_{cap} value which leads to a CO_2-equivalent[2] concentration level not exceeding an imposed concentration level. The other, a global budget approach, considers the atmosphere as a 'sink' which can absorb only a limited amount of carbon dioxide. In this case the global carbon budget in the period 1800 - 2100 is defined as the total amount of carbon emitted during that period, which is equivalent to the cumulated historical and future scenario- dependent CO_2-emissions. Then Q_{cap} can be calculated by dividing the total carbon budget by the total number of person years in this period.

The main difference between the two approaches is that in the first approach each person is permitted to emit Q_{cap} per year (also in the past), while in the second approach the average emission per capita per year differs with time (see Figure 2.5). Together with the fact that historical CO_2-emissions are partly absorbed by oceans and terrestrial biosphere, a higher total amount of CO_2-emissions is allowed in the second approach, resulting in a higher Q_{cap} value. It should be noted that Q_{cap} is also dependent on the emission scenarios of non-CO_2 gases for the period 1990 - 2100.

[1] The population data between 1800 and 1920 are based on Durand (1967) and the population data covering 1920 - 1990 have been obtained from the United Nations World Population Prospects (UN, 1966; UN, 1990). The future population figures are based on recent analysis of the World Bank (Bulatao *et al.*, 1990). Global population figures are estimated to increase from 5.3 billion in 1990 to 11.3 billion in 2100, mainly due to the growth in the developing countries.

[2] The CO_2-equivalent concentration is defined as the concentration of CO_2 that alone would cause the same increase in direct radiative forcing as produced by all of the greenhouse gases concerned.

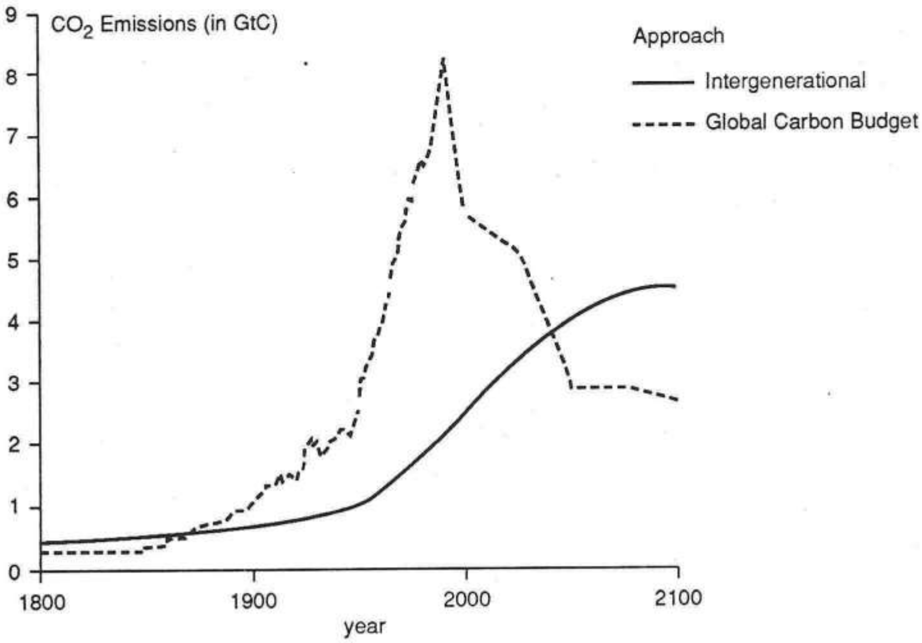


Figure 2.5: The emission scenarios of both approaches result in the same atmospheric concentration in 2100 but differ in the total emission flux between 1800 and 2100.

We will now define the regional emission debt as the difference between the amount of CO_2 allowed to be emitted by the regional population [pop(t,r) in 10^9 persons], based on the equal quotum per capita [Q_{cap} in tC per (cap x year)] and the actually cumulated regional emissions in the past [em(t,r) in GtC per year]. The emission debt in 1990 [ED(1990,r) in GtC] is described in mathematical terms:

$$ED(1990,r) = \sum_{t=1800}^{1990} em(t,r) \; - Q_{cap} \cdot \sum_{t=1800}^{1990} pop(t,r) \qquad (2.1)$$

Note that we have assumed that the emission data is gained by measurements of regional emissions and not by regional end-use of production. Ignoring the transactions between regions may bias the results. However, for lack of sufficiently reliable data, especially those related with land use changes, we are forced to use the regional emissions.

2.4.2 Methodology

2.4.2.1 Intergenerational Approach

We used the CO_2-equivalent concentration values in 2100 (projected by IMAGE) of the IPCC emission scenarios (IPCC, 1991; Appendix 2) and the Low-Risk scenario (Rotmans and den Elzen, 1992) as targets for estimating Q_{cap} values. For the emissions of CO_2 (including land use changes and fossil fuel combustion) we formulated an equitable emission scenario as Q_{cap} times population. Using the equitable scenario, we iteratively derive the Q_{cap} values belonging to the concentration targets with IMAGE. When we estimate Q_{cap} for fossil fuel combustion and cement production only, we assume that land use changes develop according to the corresponding scenarios.

The estimated Q_{cap} values for different targets and different sources are given in Table 2.3. Using World Bank projections of population growth until 2100 (Bulatao *et al.*, 1990) and considering all sources, the Q_{cap} value is 1.27 tC per capita per year for the Business-as-Usual case and drops to 0.37 per capita per year for the Low-Risk scenario. Considering only industrial sources Q_{cap} has higher values because the land use scenarios consider relatively low emissions (or even uptake by reforestation) and the (negative) biogeochemical feedbacks within the carbon cycle are switched on. Assuming a low population projection (UN, 1992), Q_{cap} rises to 0.48 tC with the Low-Risk scenario, and to 1.62 tC with the Business-as-Usual scenario. However, when population increases at a faster rate, Q_{cap} drops to 1.00 tC for the Business-as-Usual scenario and to 0.29 tC for the Low-Risk scenario. The Q_{cap} values as given in Table 2.3 are highly sensitive, both for the concentration target and for population projections, which are, however, both policy related.

Table 2.3. Concentration levels in CO_2-equivalents and Q_{cap} values with population growth (low, medium and high levels)

Scenario	CO_2-eq. conc. (ppmv) 2100	Q_{cap} [tC per (cap x year)] Tot.[a]	Q_{cap} [tC per (cap x year)] Ind.[b]
Business-as-Usual	1240	1.27 (1.00[c], 1.62[d])	1.40 (1.09, 1.80)
2060 Low Emission	780	0.72 (0.56, 0.94)	0.79 (0.60, 1.03)
Control Policies	595	0.58 (0.45, 0.74)	0.60 (0.46, 0.78)
Accelerated Policies	530	0.46 (0.35, 0.59)	0.45 (0.35, 0.59)
Low-Risk	475	0.37 (0.29, 0.48)	0.38 (0.29, 0.50)

[a] Tot. : CO_2-emissions from fossil fuel use and land use changes.
[b] Ind. : CO_2-emissions from fossil fuel use.
[c] High population projections (UN, 1992).
[d] Low population projections (UN, 1992).

Using an analytical approach Fujii (1990) estimated a Q_{cap} of 1.37 for a doubling of the pre-industrial CO_2-concentration level (= 560 ppmv), which is considerably higher than our estimates. This is mainly because Fujii ignored non-CO_2 gases, used a constant (low) airborne fraction and discounted historical emissions of CO_2 (to simulate long-term oceanic uptake) (Janssen, 1992).

2.4.2.2 Global Carbon Budget Approach

We have defined the global carbon budget in the period 1800 - 2100 as the total amount of carbon emitted during that period. This budget is a 'leftover': for non-CO_2 greenhouse gases the emission time paths are according to descriptions by the IPCC (1991). The thus defined carbon budgets for the four IPCC scenarios and for the Low-Risk scenario are shown in Table 2.4. The historical carbon budget is the same for each scenario: 346 GtC, consisting of 220 GtC from fossil fuel combustion and cement manufacturing and 126 GtC from land use changes.

Remaining budgets for the scenarios are listed in Table 2.4 for both total CO_2-emissions and for fossil CO_2-emissions only. These budgets are between 338 GtC (Low-Risk scenario) and 1625 GtC (Business-as-Usual scenario). Krause *et al.* (1989) derived a global remaining budget of about 300 GtC for fossil CO_2-emissions based on a 400 ppmv CO_2-concentration target including fossil fuel CO_2-emissions between 1985 and 2100. However, the role of non-CO_2-greenhouse gases and biospheric CO_2 releases was estimated indirectly, which results in a CO_2-equivalent concentration level of about 560 ppmv.

Table 2.4: Carbon budgets for the IPCC scenarios and the Low-Risk scenario and Q_{cap} values [in tC per(cap x year)] with future population growth.

Scenario	Remaining budget (GtC) Tot.[a]	Ind.[b]	Q_{cap} [tC per (cap x year)] Tot.	Q_{cap} (tC per (cap x year)] Ind.
Business-as-Usual	1625	1520	1.41 (1.18[c], 1.72[d])	1.25 (1.04, 1.52)
2060 Low Emission	846	858	0.85 (0.71, 1.04)	0.77 (0.65, 0.94)
Control Policies	646	658	0.71 (0.59, 0.87)	0.63 (0.53, 0.77)
Accelerated Policies	455	467	0.57 (0.48, 0.70)	0.48 (0.41, 0.60)
Low-Risk	338	350	0.49 (0.41, 0.60)	0.40 (0.34, 0.50)

[a] Tot. : CO_2-emissions from fossil fuel use and land use changes.
[b] Ind. : CO_2-emissions from fossil fuel use.
[c] High population projections (UN, 1992).
[d] Low population projections (UN, 1992).

Actually the carbon budget is dependent on the future emission path over time. This can be evaluated with the IMAGE model (Rotmans and Swart, 1990). For example, if the Business-as-Usual pathway is followed and in the year 2000 the world community decides to strive for a CO_2-equivalent concentration target of 475 ppmv in 2100 (the Low-Risk scenario), such a switch would require a 70% decrease of fossil CO_2-emissions within 50 years. The resulting carbon budget amounts to 365 GtC, slightly higher than the Low-Risk remaining budget because the high emissions between 1990 and 2000 are mainly taken up by oceans and biosphere before the time-horizon year 2100. If the decision to switch is taken in 2010, emissions from fossil fuel should drop by 90% in less than 10 years. The resulting carbon budget would decrease to 325 GtC. In these simulations it is assumed that the emissions of non-CO_2 greenhouse gases will follow the Low-Risk scenario after the response year. If these gases are not controlled and do follow the Business-as-Usual scenario, the remaining global carbon budget will be below zero GtC. This shows the role of non-CO_2 gases is not negligible in any negotiating process on future budgets.

After having estimated ranges of the remaining global carbon budgets, we can express Q_{cap} as the average emission per capita over the period 1800 - 2100:

$$Q_{cap} = \frac{\sum_r \left(\sum_{t=1800}^{1990} em_{his}(t,r) + \sum_{t=1991}^{2100} em_{scen}(t,r) \right)}{\sum_r \left(\sum_{t=1800}^{1990} pop_{his}(t,r) + \sum_{t=1991}^{2100} pop_{scen}(t,r) \right)} \tag{2.2}$$

where $em_{his}(t,r)$ and $em_{scen}(t,r)$ are the historical and future CO_2-emissions, respectively, at time t for region r (GtC per year), and $pop_{his}(t,r)$ and $pop_{scen}(t,r)$ are the historical and future regional population size, respectively, in year t for region r.
Based on this per capita quotum, the global carbon budget under the Low-Risk scenario of about 680 GtC corresponds with a permitted emission per capita of 0.49 tC. Under the Business-as-Usual scenario, Q_{cap} amounts to 1.41 tC. Assuming a low population growth (UN, 1992), Q_{cap} rises to 0.60 tC under the Low Risk scenario and 1.72 tC under the Business-as-Usual scenario. When population growth follows the high projections, Q_{cap}-values drop to 0.41 tC for the Low Risk scenario and to 1.18 tC for the Business-as-Usual scenario.

How should the remaining global carbon budget be distributed over the different regions, taking into account past and present emissions of CO_2? Here we focus on a simple allocation rule for the remaining carbon budget which comprises two elements:

1. Only the CO_2-emissions, i.e. the remaining carbon budget as defined above, will be allocated in future;
2. Distribution of this budget is based on the equal allocation per capita carbon budget criterium, i.e. an equitable share of future CO_2-emissions, taking into account the already emitted CO_2 in the past.

The future CO_2-emission rights [ER(1990,r)] consist of the CO_2-emissions allowed to be emitted in the period 1991 - 2100, based on the equal emission quotum minus the emission debt built up in the past:

$$ER(1990,r) = Q_{cap} \cdot \sum_{t=1991}^{2100} pop_{scen}(t,r) - ED(1990,r) \tag{2.3a}$$

This can also be written as the regional carbon budget minus the historical emissions:

$$ER(1990,r) = Q_{cap} \cdot \left(\sum_{t=1800}^{1990} pop_{his}(t,r) + \sum_{t=1991}^{2100} pop_{scen}(t,r) \right) - \sum_{1800}^{1990} em_{his}(t,r) \tag{2.3b}$$

2.4.3 Results

2.4.3.1 Intergenerational Approach

Using the Q_{cap} value corresponding with the Low-Risk scenario, we found that past and present generations have built up a global emission debt of 205 GtC, varying from 163 GtC to 236 GtC depending whether low or high population projections were used (UN, 1992).

If a Q_{cap} of 1.27 tC is used, which corresponds to the Business-as-Usual scenario, the past generations would have built up an emission credit of 139 GtC, varying between 36 GtC and 272 GtC depending on the population projections. Excluding CO_2-emissions from land use changes leads to an emission debt of 75 GtC under the Low-Risk scenario and to an emission credit of 314 GtC under the Business-as-Usual scenario. Estimates of regional emission debt using different concentration targets are given in Figure 2.6. This figure shows the large differences in past emission levels between the regions: North America, the European Community, the Commonwealth of Independent States (CIS) and Latin America have emission debts in all cases, while Central Planned Asia and South/Southeast Asia have emission credits in all cases.

Figure 2.7 shows that all developing regions in all cases have built up an emission credit in all cases when considering fossil CO_2-emissions only. This figure shows the major impact of land use changes in most of the developing regions.

Table 2.5: Global emission debt (in GtC) for Q_{cap} values of Table 2.3

Scenario	Fossil fuels + Land use changes	Fossil fuels
Business-as-Usual	-139 (-36[a], -272[b])	-314 (-196, -467)
2060 Low Emission	71 (132, -13)	-82 (-9, -173)
Control Policies	125 (174, 64)	-9 (44, -78)
Accelerated Policies	170 (212, 121)	48 (86, -5)
Low-Risk	205 (236, 163)	145 (109, 29)

[a] High population projections (UN, 1992).
[b] Low population projections (UN, 1992).

Figure 2.8 shows that when Business-as-Usual related Q_{cap} values are used, global emission credits were built up in the last two centuries, although, depending on the population projections, those credits have declined in the last few decades. When Low-Risk-related Q_{cap} values are considered, Figure 2.8 shows that in the last century an initial small emission credit was built up. However, as the years passed, emission per capita increased and therefore also the global emission debt.

In Figure 2.9 regional emission debts are depicted for land use changes and fossil fuel combustion using a Q_{cap} value related to the Accelerated Policies Scenario. During the last few decades all regions have increasing emission debts or decreasing emission credits. The increase in the emission debt of the Rest of the OECD has the largest rate, taken over almost the whole period. In the beginning this is caused by large deforestation rates (North America), followed by large fluxes through fossil fuel combustion. Because of the large population growth in the developing regions and increasing emissions per capita, these regions' emission debt has increased enormously in the last decades.

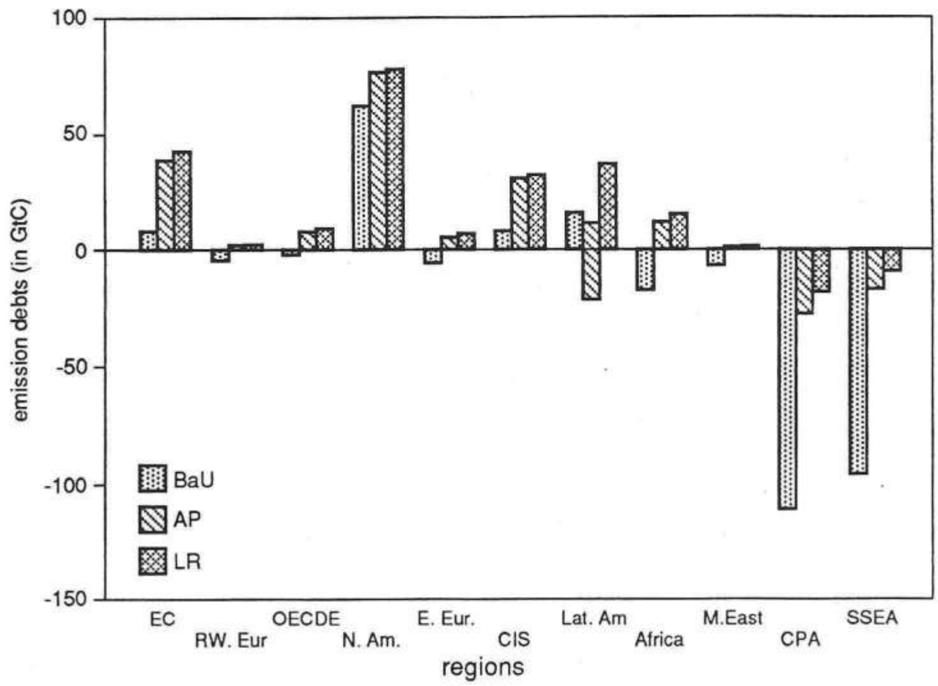


Figure 2.6: Regional emission debts for fossil fuel combustion and land use changes for the period 1800 - 2100 using different concentration targets.

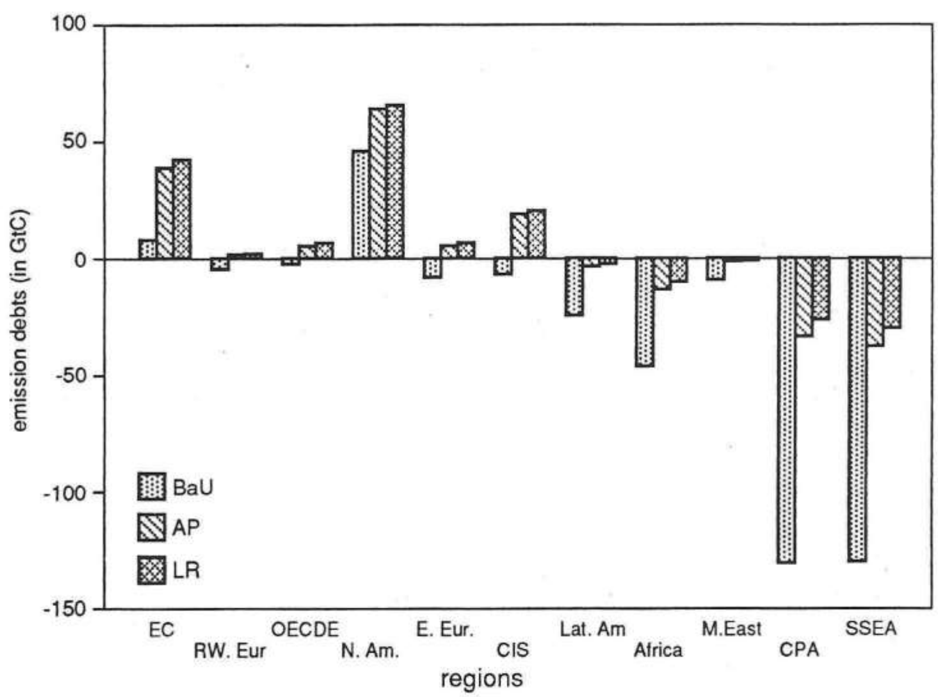


Figure 2.7: As Figure 2.6 without land use changes.

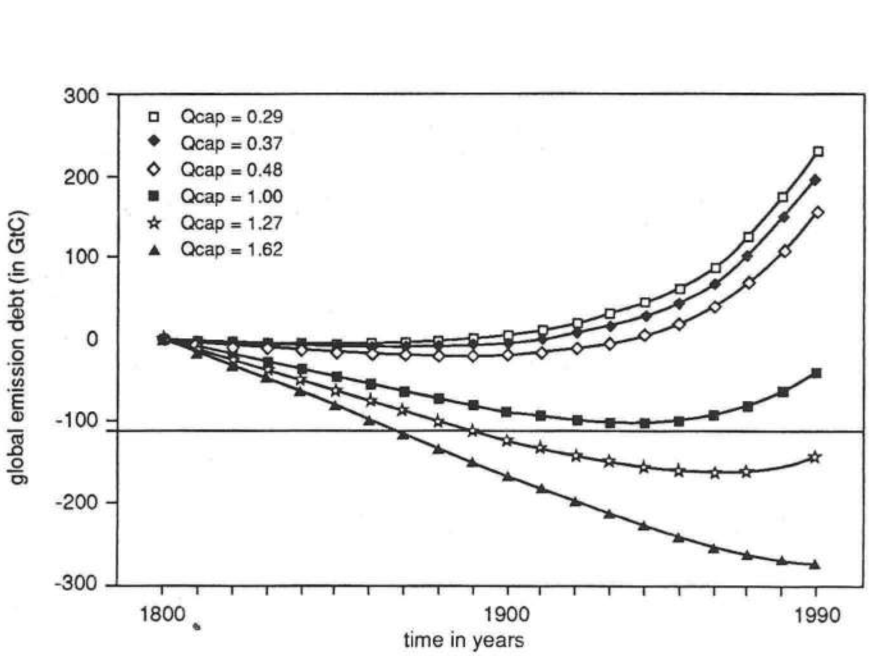


Figure 2.8: Global emission debt for different Q_{cap} values.

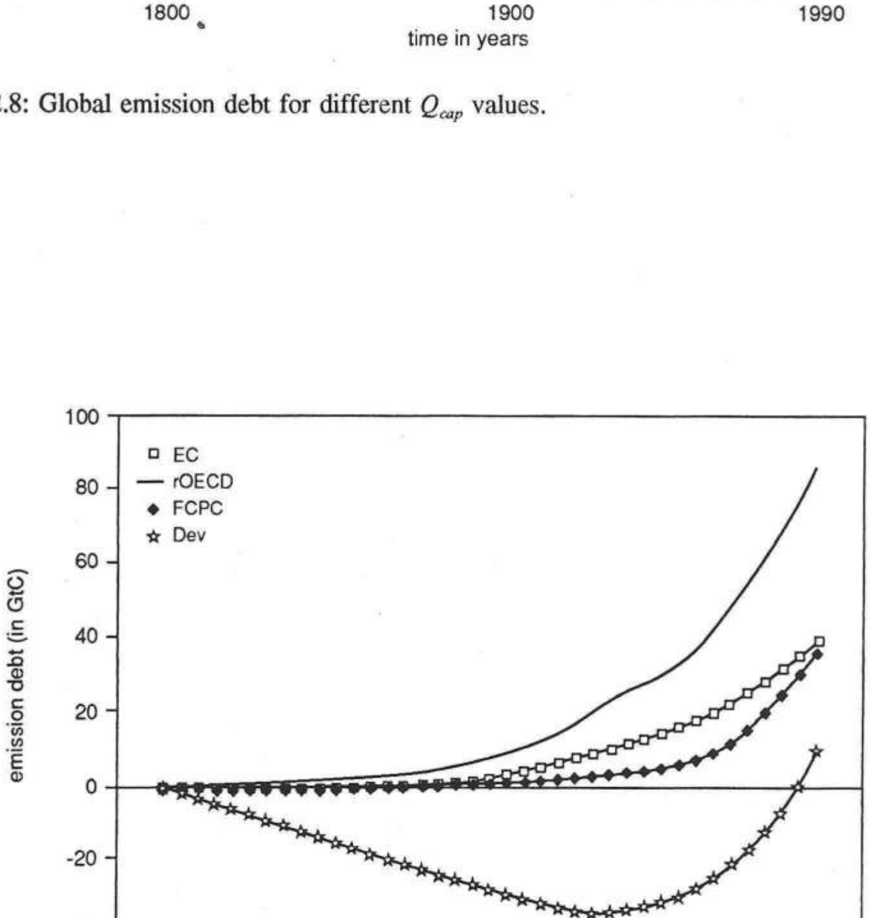


Figure 2.9: Regional emission debts for fossil fuel combustion and land use changes between 1800 and 1990 using a Q_{cap} value of 0.57 (Accelerated Policies).

2.4.3.2 Global Carbon Budget Approach

Using the per capita quotum of the Low-Risk scenario, the resulting global emission debt from past to future generations is about 159 GtC. In other words, people living in the past were allowed to consume about 27% of the budget whereas they actually emitted 51%. We and our ancestors have reduced emission quota for our descendants. If the world population grows according to the low projection levels (UN, 1992), the emission debt will drop to 117 GtC because the budget is divided among fewer people. Using high population projections, the global emission debt will rise to 189 GtC.

On the other hand, if a large carbon budget is available as in the high-risk Business-as-Usual scenario, even with a high population projection there would be an emission credit of 105 GtC. Excluding the CO_2-emissions from land use changes leads to an emission debt of 67 GtC under the Low-Risk scenario and to an emission credit of 257 GtC under the Business-as-Usual scenario.

Table 2.6: Global emission debt (in GtC) for Q_{cap} values of Table 2.4

Scenario	Fossil fuels + Land use changes	Fossil fuels
Business-as-Usual	-157 (-105[a], -311[b])	-257 (-177, -360)
2060 Low Emission	21 (75, -14)	-74 (-28, -139)
Control Policies	75 (120, 14)	-20 (18, -74)
Accelerated Policies	128 (162, 78)	37 (64, -9)
Low-Risk	159 (189, 117)	67 (90, 29)

[a] High population projection (UN, 1992)
[b] Low population projection (UN, 1992)

The resulting regional emission debts in the different scenarios are presented in Figure 2.10. The industrialized regions are, in most cases, highly indebted, in contrast to Asian regions. Note that higher Q_{cap} values in the global carbon budget approach result in slightly smaller regional emission debts when compared to the intergenerational approach. Excluding land use changes leads to a large decline of emission debts in most developing regions, who in all cases have an emission credit (Figure 2.11). The industrialized regions, however, have an emission debt for almost all the budgets.

After having estimated the regional emission debts, the emission rights left for the different world regions can now be calculated. Figure 2.12 summarizes the emission rights per capita per year based on different carbon budgets. Almost all industrialized regions and Latin America have emission rights per capita, which are all lower than present emission levels. North America has emitted more CO_2 in the past 191 years than was allowed for the whole period of 301 years and ends up with negative emission permitted for all scenarios. Most of the developing regions, however, have emission permitted per capita which are higher than the emission rights of industrialized regions, but in some cases lower than their present emission levels. This means that in a world striving towards sustainable development and equity, emission levels per capita are not allowed to increase, not even in developing regions.

When considering only fossil CO_2-emissions, the emissions permitted per capita in developing regions are somewhat higher than for land use changes, but they will never reach the present emission levels of the industrialized regions. If developing regions are empowered and supported to continue their development towards higher standards of living, large technological improvements will have to be realized.

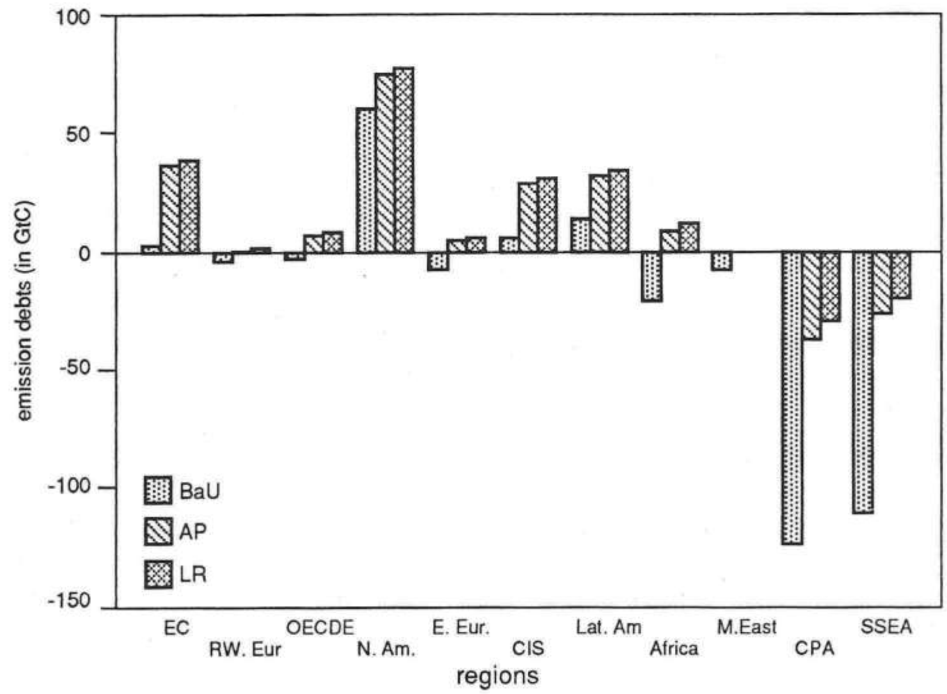


Figure 2.10: Regional emission debts for fossil fuel combustion and land use changes between 1800 and 1990, using different carbon budgets.

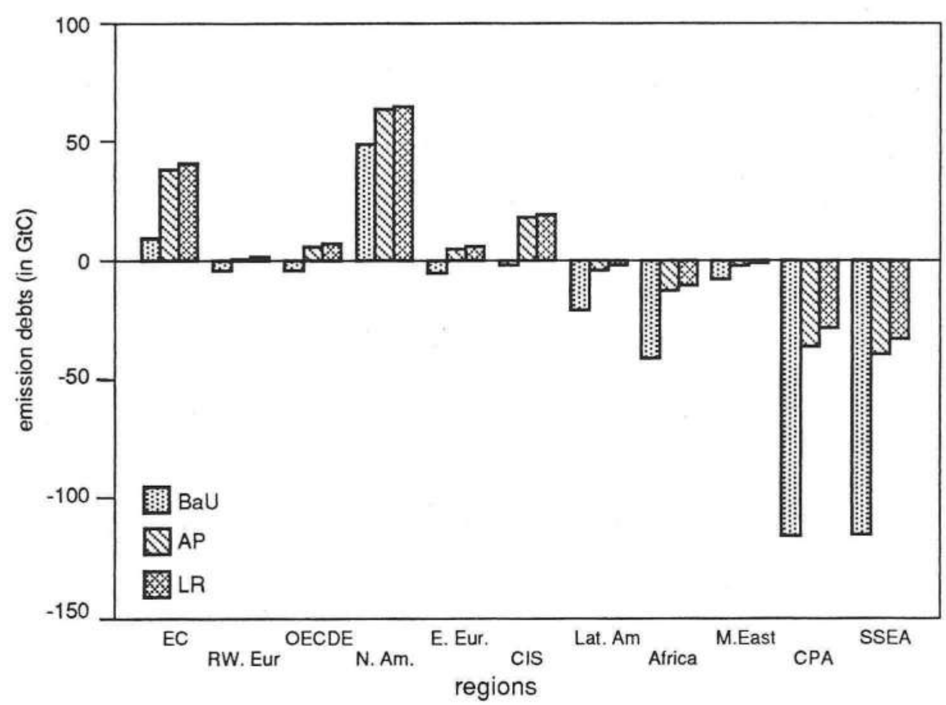


Figure 2.11: As Figure 2.10 without land use changes.

2.5 Emission Debt versus Financial Debt

In this section we will discuss whether there is a relationship between emission debt and external financial debt, which may be used as an instrument for negotiations about reducing CO_2-emissions. Figure 2.14 shows the regional differences in external financial debts[3] per unit of GNP. The largest relative financial debts are from developing regions. First we will discuss the relation between (historical) fossil CO_2-emissions and GNP.

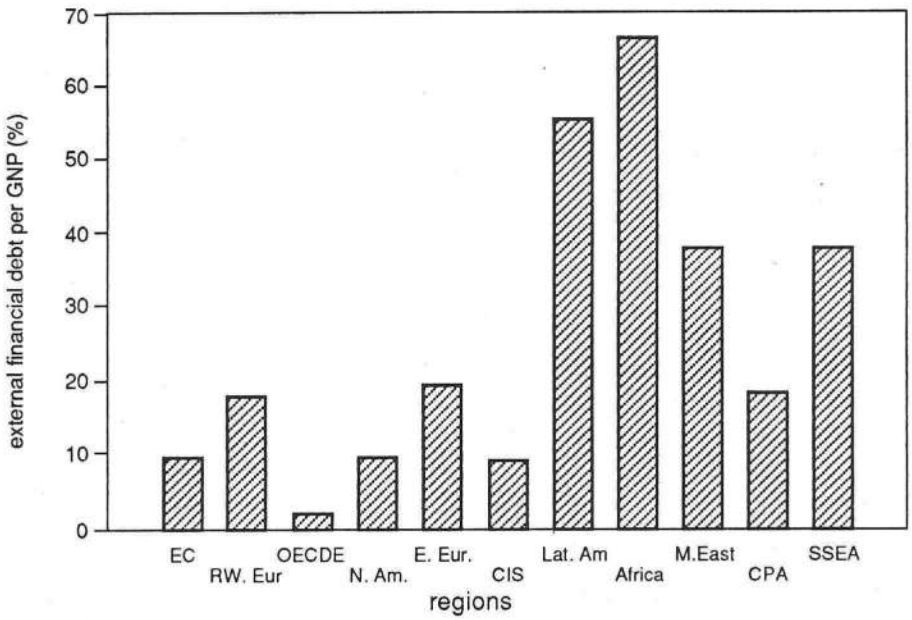


Figure 2.14: External debt as percentage of GNP for different regions at the end of the eighties.

Figure 2.15 clearly shows that there is a positive relation between welfare, measured by GNP per capita, and the relative contribution to the CO_2-concentration rise by fossil fuel combustion per capita. A regression analysis over 11 regions between GNP per capita and historical contributions to the CO_2-concentration rise by fossil fuel combustion shows that there is a significant relation (see Table 2.7). While we have only 11 observations, the R^2 of 0.67 is relative high. The relation between GNP per capita and emission debt per capita is also found to be significant (results in Table 2.7 are given using the intergenerational emission debt with a low risk concentration target). These relations show that present welfare in industrialized countries rests on large CO_2-emissions in the past.

[3] External debt data for most countries are obtained from OECD statistics (OECD, 1990). Most of the developed countries are excluded from World Debt tables (World Bank, 1990a; 1990b), while the external debt of most of the developed countries is also excluded from the World Tables (World Bank, 1989). A rough estimate of external debt for those developed regions is made by using IMF (1991) and EIU (1987) data. From the IMF (1991) data, foreign governmental debt or debt in foreign currency is used and when no IMF data are available, public or governmental foreign debt of the EIU (1987) data is used. GNP data are based on The Economist (1990), WRI (1990/1991) and IMF (1992).

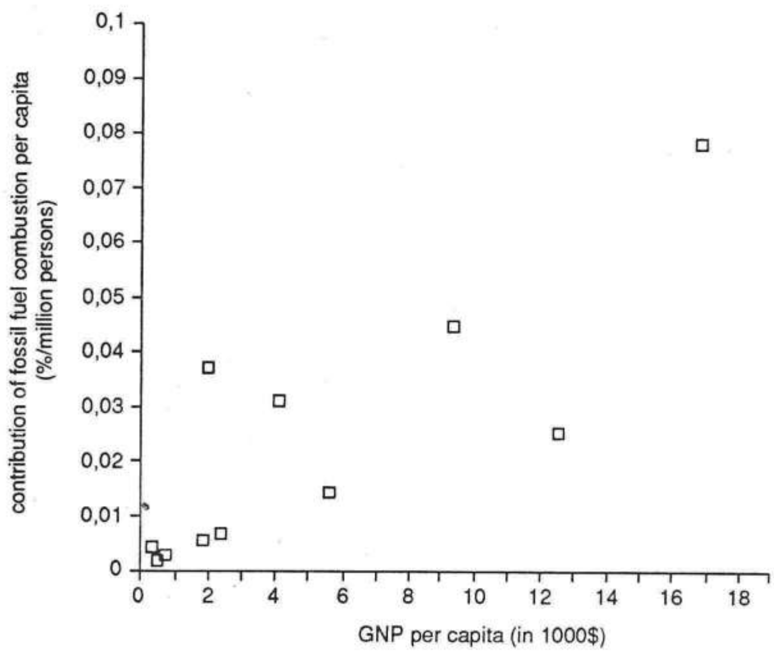


Figure 2.15: Relation between the relative contribution of fossil fuel combustion to the concentration rise per capita versus GNP per capita for the 11 regions.

Table 2.7: The estimated coefficients of relations between GNP and fossil fuel combustion

GNP/POP	RCC_{ff}/POP	R^2
coefficient t-value[4]	210 (7.0)	0.67
GNP/POP	ED_{ff}/POP	R^2
coefficient t-value	0.07 (6.4)	0.61

GNP = Gross National Product (in $ 10^9)
POP = Population (in 10^6 persons)
RCC_{ff} = Relative contribution of fossil fuel burning to the concentration rise (%)
ED_{ff} = Emission Debt (caused by fossil fuel combustion) (in 10^6 tC)

[4] If a significance level of 10 % is to be reached, the absolute value of the t-value has to be larger than 1.65 for a statistically significant relationship. This value is 1.96 for 5 % uncertainty and 2.58 for 1 % uncertainty.

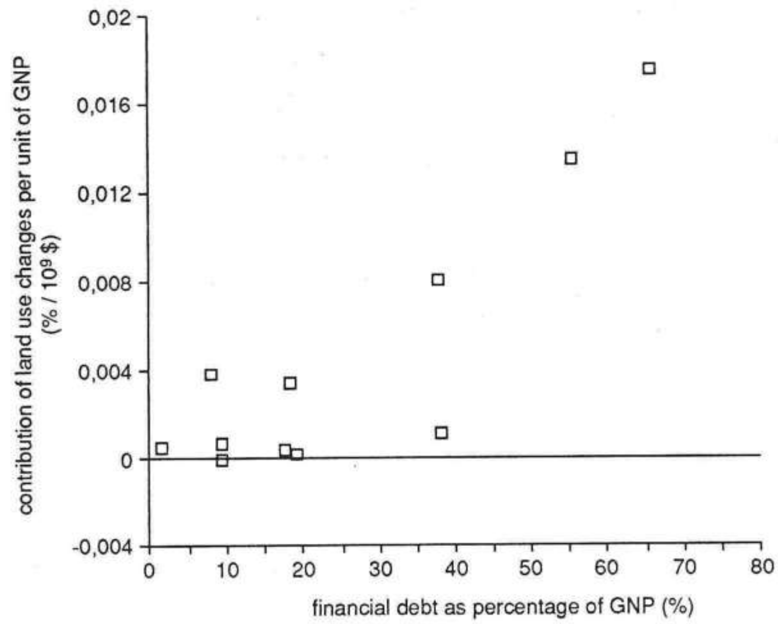


Figure 2.16: Relationship between external debt as percentage of GNP and the relative contribution to the CO_2-concentration rise due to land use changes per unit of GNP.

Figure 2.16 shows a positive relationship between financial external debt as percentage of GNP and the relative contribution to the CO_2-concentration rise due to land use changes per unit of GNP. Estimating a linear relation between those indicators results in a significant correlation (t-value = 5.4). With fossil fuel combustion, the statistical relations explaining financial external debt becomes more significant (Table 2.8). The financial debt as percentage of GNP has a negative relation to fossil fuel combustion and a positive relation to land use changes. This relation could be explained as follows: emissions from deforestation result from the early development of agricultural economies; in the next phase of industrialization and rapid growth of the per capita income levels, emissions related to the combustion of fossil fuels rapidly surpass these biotic emissions. Industrialized countries have reached a high standard of living with a low financial debt as percentage of GNP. The high financial debts and deforestation rates in Africa, Latin America and South/Southeast Asia reflect their present predicament: the squandering of their forest has become instrumental in the development of their economies and in feeding their growing population. To put it in another way: to relieve financial debts to the industrialized regions, environmental debts are built up by exporting wood and agricultural products to the rich regions.

Table 2.8: The estimated coefficients of relations between financial external debt and fossil fuel combustion and land use changes

FED/GNP	Constant	RCC_{ff}/GNP	RCC_{luc}/GNP	R^2
coefficient t-value	19.0 (1.9)	-1065 (-1.7)	2949 (5.7)	0.83
FED/GNP	Constant	ED_{ff}/GNP	ED_{luc}/GNP	R^2
coefficient t-value	19.1 (1.9)	-0.5 (-2.6)	1.2 (5.1)	0.78

3 Allocating CO_2-Emissions by Optimization

3.1 Introduction

Developing response policies may be viewed as an optimization problem. On the one hand a feasible climate policy should minimize damage on ecosystems and society, and on the other, adverse socio-economic consequences of taking measures, such as cost should be minimized. Not only can an emission strategy aim at equitable sharing of the resources between the developing and industrialized countries, but intergenerational equity can also be taken into account.

Contrary to scenario analysis, optimization enables us to find a scenario which meets policy targets in the 'best' way. However, the 'best' scenario is one out of an infinite number of possibilities, and finding such a solution within a reasonable time, especially in such a complex problem as climate change, is a difficult if not impossible task. In this section we will present an optimization algorithm, which is a first attempt for optimally allocating CO_2-emissions by fossil fuel combustion[5] to regions in next decades, according to a nonlinear objective function and under the constraint of an upper limit to the CO_2-equivalent concentration. The objective function in this optimization problem describes the social and economic consequences of a climate strategy. The constraints are related to economies and environment. The environmental constraint relates to the policy target concentration (or temperature which is, however, because of its complexity not implemented in this first attempt), whereas the economic constraint can be related to the absolute emission reduction, as well as to the reduction rate. The optimization problem is formulated as a global optimization problem, which can only be solved numerically because the environmental constraint is related to simulation runs with the IMAGE model.

Since reliable assessments of regional costs and benefits of climate policies, necessary to quantify the objective functions, are still not available, the optimization algorithm developed will only be used for a rough estimate of a welfare function. The formulation of the optimization problem and the algorithm developed to derive sub-optimal solutions are discussed in 3.2. In section 3.3 some results are presented, including maximizing the welfare of future generations.

3.2 Methodology

3.2.1 Formulation of the Problem

For the allocation of CO_2-emissions, the time period we are interested in is between 1990 and 2100. Let $x_{t,r}$ be the CO_2-emissions through burning of fossil fuels by region r (r = 1, .. ,R) in the year t (t = 1990, ... , 2100). Let $\mathbf{X} = [x_{t,r}]_{t=1991}^{2100}{}_{,r=1}^{R}$ be a matrix

[5] Because we cannot change the CO_2-emissions in the deforestation module of IMAGE directly (they are the result of a sequence of calculations), we will not consider the CO_2-emissions due to land use changes in the optimization model.

characterizing the regional CO_2-emissions. For simplicity, emissions are assumed to change linearly over certain time intervals for the time period of interest. In this study the following time intervals are used: $[T_0,T_1]$, ... , $[T_4,T_5]$, T_0 = 1990, T_1 = 2000, T_2 = 2025, T_3 = 2050, T_4 = 2075, T_5 = 2100.

The regional emission path is denoted by $\mathbf{x}_r$ for region r. **X** can be written by { $x_{1,1}$, $x_{1,2}$, .. , $x_{1,R}$, .. , $x_{i,1}$, .. , $x_{i,R}$, .. , $x_{5,1}$, .. ,$x_{5,R}$ }, with $x_{i,r}$ the CO_2-emission at region r at time point T_i. The choice of $\mathbf{X} = [x_{i,r}]_{i=1}^{5}{}_{,r=1}^{R}$ together with the known value of the initial emissions $x_{0,i}$, determines the emission matrix **X** and thus a response policy. From now on we would like to consider the $x_{i,r}$'s as the decision variables.

The problem of a socio-economic optimal allocation of carbon emissions by fossil fuel combustion to regions in the time period is now formulated as an optimization problem.

$$\begin{aligned} &\min_{X} \quad f(X) \\ &s.t. \\ &\quad G_j(X) \leq 0 \qquad \forall\, j \\ &with\ x_{i,r} \geq 0 \qquad \forall\, i,r \end{aligned} \tag{3.1}$$

The policies are valued by an objective function ($f:\mathbb{R}^n \rightarrow \mathbb{R}$) which is assumed to be a continuous real valued function. This function deals with the social and economic consequences of some policy **X**, such as costs of measures and welfare of future generations. The set of constraints ($G_j(X)$) contains concentration and economic restrictions. The problem is now formulated as a global optimization problem. The complex behaviour of the climate system will be taken into account by using IMAGE in the optimization algorithm.

3.2.2 Optimization Algorithm

An algorithm to find a solution for a constrained nonlinear optimization problem with a restriction based on IMAGE simulations has been developed by Janssen (1992) (Figure 3.1). A sub-optimal solution is found by iteratively solving the problem with an analytical approximation of the CO_2-equivalent concentration (Appendix 3) and running IMAGE for updating constants of the approximation function. Because in the analytical approximation the values of the parameters change when the decision variables change, the problem cannot be solved without running IMAGE many times. To derive a solution within an acceptable amount of running time, we will first solve a simplified version of the problem.

In this simplified problem the total amount of CO_2 which can be emitted in the next 110 years is restricted by a limited global carbon budget (B). This problem is solved by the global optimization algorithm multistart (Rinnooy Kan and Timmer, 1989), where several local searches are started in random points until a stopping rule is satisfied. The solution is used as starting point for local searches of the problem with the analytical concentration expression. Because such an expression is an approximation of simulation outcomes,

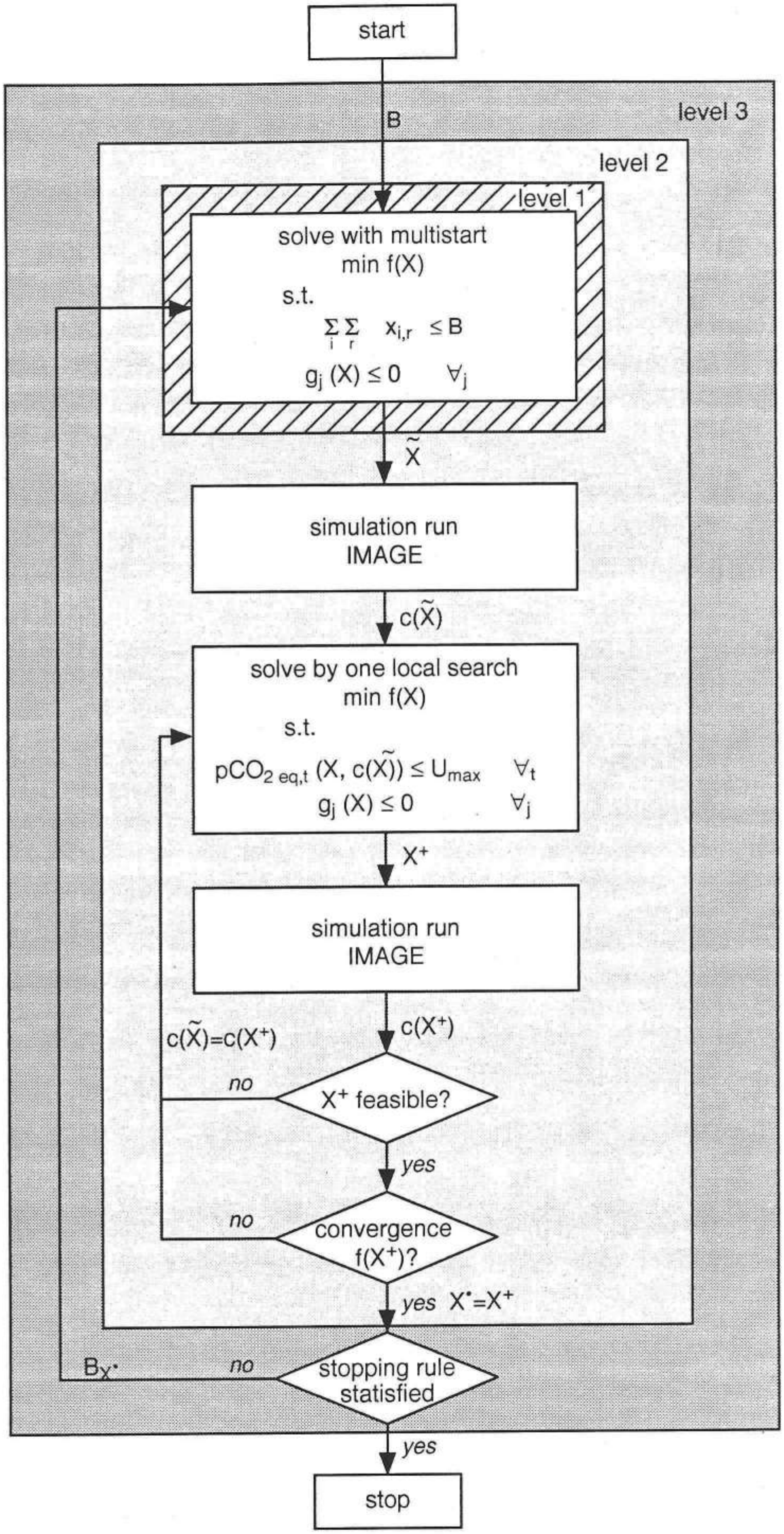


Figure 3.1: Scheme of the optimization method.

parameter values in the analytical expression have to be updated after deriving a new local optimum $f(\mathbf{X}^+)$. These parameters are the CO_2-fluxes between the ocean and the atmosphere and between the terrestrial biota and the atmosphere, as well as the radiative forcing of non-CO_2 gases. After updating the values of the parameters several times, the solution $f(\mathbf{X}^+)$ converges and a feasible local optimum $\mathbf{X}^*$ is found for the original problem.

To improve the solution the algorithm returns to the simple problem with the constrained carbon budget and adapts the maximum value of this budget to the sum of the emissions of the local optimum $\mathbf{X}^*$. If the carbon budget is changed by a large amount the solution will improve. However if the problem has many local optima and the global carbon budget is changed only slightly, the solution will not necessarily be improved. If the carbon budgets change only slightly and the expected number of not found local optima is smaller than a specific number (based on Boender (1984); Piccioni and Ramponi (1989)), the optimization algorithm is stopped. Although experiments with different objective functions give satisfying results, it cannot be proved that the algorithm converged to a global optimum.

3.3 Maximization of Welfare

3.3.1 The Problem

Objective functions, which can be used for the optimization algorithm, are difficult to derive because reliable regional assessment functions of cost and benefits of climate policies and their dynamic behaviour are not yet available. However, using a general utility function in this section, we can present preliminary results of maximizing welfare for future generations.

In general, utility theory deals with the desirability of outcomes of economic processes. Welfare of future generations is a function of individual utilities and is examined for efficiency and equity aspects. People are assumed to maximize their utility. They are assumed to be rational decision-makers and to value extra goods along a diminishing marginal rate. If we assume that:
- utility can be measured by GNP per capita,
- GNP is a function of fossil CO_2-emissions,
- the carbon intensity autonomously improves,
- each individual has the same utility function,

then we can formulate maximization of welfare for future generations as below,

$$\max_{X} W(U(X))$$

s.t.

$$(a)\ pCO_{2\text{-}eq}(X)_t \leq C_{\max} \qquad \forall\ t$$

$$(b)\ \alpha_{\min}\cdot GNP(X)_{t-1,r} \leq GNP(X)_{t,r} \leq \alpha_{\max}\cdot GNP(X)_{t-1,r} \qquad \forall\ t,r \tag{3.2}$$

$$(c)\ GNP(X)_{t,r} = ci_{t,r}^{-1}\cdot x_{t,r} \qquad \forall\ t,r$$

$$(d)\ ci_{t,r}^{-1} = \beta_r \cdot ci_{t-1,r}^{-1} \qquad \forall\ t,r$$

$$with\ x_{i,r} \geq 0 \qquad \forall\ i,r$$

, where W(**X**) is the welfare function, $GNP(\mathbf{X})_{t,r}$ (in \$) the Gross National Product in region r in year t. The parameters α_{min} and α_{max} restrict the speed of GNP growth, and $ci_{t,r}$ (in tC/\$) is the carbon intensity of the economy of region r. The carbon intensity is assumed to improve each year by constant rate β_r.

Using an iso-elastic utility function, where utility is dependent on consumption (here income per capita) and elasticities, utility of a person in region r in year t can now be modelled as follows:

$$U_{t,r}(x_{t,r}) = \frac{\left(\frac{GNP(x_{t,r})_{t,r}}{pop_{t,r}}\right)^{1-e}}{1-e} \tag{3.3}$$

, where the e value (>1) is the elasticity of marginal utility.
The total welfare of future generations is the sum of all individual utilities.

$$W(X) = \sum_r \sum_t pop_{t,r}\cdot U_{t,r}(x_{t,r}) \tag{3.4}$$

We will now first discuss an allocation for a base case and thereafter present results for different future population projections.

3.3.2 Base Case

We will now formulate a base case in which the CO_2-equivalent concentration is restricted to below 530 ppmv (the concentration level in 2100 of the Accelerated Policies scenario), while non-CO_2-emissions and land use changes are assumed to follow the Accelerated Policies scenario (Table 3.1). In the base case we assume that population growth follows a medium projection (UN, 1992). The annual GNP growth is restricted to between 0 and 6%, based on economic growth rate assumptions used by the IPCC (1991), while the GNP data of 1990 are based on WRI (1990/1991), The Economist (1990) and IMF (1992) and are given in 1987 dollars. The carbon intensity improvement rate ($ß_r$) is estimated using the data from the Accelerated Policies scenario (IPCC, 1991) and is assumed to be constant until 2100 for all regions. Estimates of the elasticity of marginal utility are not known and therefore an e value of 3 is rather arbitrary, although results in Janssen (1992) show only a relatively small sensitivity by varying the e value.

Maximizing welfare leads to a large decrease of emissions in industrialized regions, which already had a high level of welfare (Table 3.2). The developing regions are allowed to increase the emissions substantially until 2025, although not exceeding the Business-as-Usual level. Because of the allowed increase in the first 35 years, the GNP per capita in developing regions also increases sharply, which causes a more equal distribution of incomes. The GNP per capita in industrialized regions also increases, although this increase is realized at the end of the next century after a small decline at the beginning. The emissions in FCPC countries are reduced more slowly than in OECD countries because the welfare per capita in developing regions increases to the FCPC level and therefore welfare in FCPC also rises sharply after 2075.

Compared with the Accelerated Policies scenario, more emissions are allocated in developing regions and fewer in industrialized regions. However, because many of the emissions are allocated in regions and periods where carbon intensity is high, the GNP per capita values in the Welfare Maximization case are lower by 2100 than in the Accelerated Policies scenario. Note that the gap between OECD regions and non-OECD regions remains for the next 110 years, also when utility is maximized.

Table 3.1: Parameters values in the base case

Parameters	EC	rOECD	FCPC	DEV
ci_i^{-1} ($/tC)	4731	4026	955	1365
$ß_i$	1.025	1.027	1.032	1.034
α_{min}	1.00			
α_{max}	1.06			
C_{max} (ppmv)	530			
e - value	3			
Land Use Changes	Accelerated Policies scenario			
Non CO_2 gases	Accelerated Policies scenario			
Population Growth	Medium Projection			

3.3.3 The Influence of Population Growth

We now examine the influence of population growth on the allocation of regional fossil CO_2-emissions. Using low and high population projections of the UN (1992) results in an allocation of CO_2 that only changes slightly (see Table 3.3). This is because the emission reductions in industrialized regions are restricted by the lower limit on GNP growth. The increase of emissions in developing countries is restricted by the upper limit on GNP growth and the maximum CO_2-equivalent concentration level, and therefore only some small differences in the time period occur. When high population projections are used, emissions of developing regions are allocated mainly during the second half of the next century.

However, the GNP per capita values differ enormously in the two cases. Low population growth leads to significantly higher income levels compared with high population growth. Moreover the income levels in OECD regions decline in the high growth case, while in the low growth case the income levels in the developing regions increase beyond the present income level in OECD countries.

These results indicate the small influence of population growth on the allocation of emission reductions. However, reducing population growth will lead to significantly higher income levels of a world community striving for a more equal distribution of welfare and resources in a sustainable world.

Table 3.2: Fossil CO_2-emissions and GNP per capita values (1987$) in four world regions: EC, rest of the OECD, former centrally planned countries (FCPC) and developing regions (DEV)

Case	1990	2000	2025	2050	2075	2100
Maximum Welfare						
CO_2-Emissions (in GtC)						
EC	0.8	0.7	0.4	0.2	0.1	0.1
rOECD	2.0	1.6	0.8	0.4	0.2	0.1
FCPC	1.5	1.1	0.5	0.3	0.2	0.2
DEV	1.7	2.4	4.4	2.7	2.1	1.8
World	**6.0**	**5.7**	**6.1**	**3.6**	**2.6**	**2.2**
GNP per Capita (in 1000 $/cap)						
EC	11.8	11.8	11.9	13.1	13.8	18.6
rOECD	16.3	15.1	13.8	13.7	13.8	17.9
FCPC	3.4	3.2	3.0	3.9	6.7	12.4
DEV	0.6	0.9	2.8	3.1	4.9	9.7
World	**3.1**	**2.9**	**3.9**	**4.1**	**5.8**	**10.5**
Accelerated Policies						
CO_2-Emissions (in GtC)						
EC	0.8	0.8	0.6	0.4	0.3	0.3
rOECD	2.0	1.7	1.3	0.8	0.7	0.6
FCPC	1.5	1.6	1.1	0.7	0.6	0.6
DEV	1.7	1.7	2.6	1.6	1.5	1.4
World	**6.0**	**5.8**	**5.6**	**3.5**	**3.1**	**2.9**
GNP per Capita (in 1000 $/cap)						
EC	11.8	13.3	19.8	24.9	41.4	71.9
rOECD	16.3	16.1	22.1	26.0	43.3	82.0
FCPC	3.4	4.7	6.8	8.6	16.6	34.0
DEV	0.6	0.6	1.6	1.8	3.5	7.5
World	**3.1**	**3.0**	**4.1**	**4.3**	**7.3**	**14.3**

Table 3.3: Fossil CO_2-emissions and GNP per capita values (1987$) in four world regions: EC, rest of the OECD, former centrally planned countries (FCPC) and developing regions (DEV)

Case	1990	2000	2025	2050	2075	2100
Low Population Growth						
CO_2-Emissions (in GtC)						
EC	0.8	0.7	0.4	0.2	0.1	0.1
rOECD	2.0	1.6	0.8	0.4	0.3	0.2
FCPC	1.5	1.1	0.5	0.3	0.2	0.1
DEV	1.7	2.4	4.4	3.2	2.0	1.8
World	**6.0**	**5.7**	**6.0**	**4.0**	**2.5**	**2.1**
GNP per Capita (in 1000 $/cap)						
EC	11.8	11.7	12.1	14.6	18.4	30.7
rOECD	16.3	15.5	14.9	16.7	24.0	39.1
FCPC	3.4	3.4	3.6	4.2	6.8	9.8
DEV	0.6	0.9	3.1	4.9	7.6	18.9
World	**3.1**	**3.0**	**4.4**	**5.9**	**8.9**	**20.0**
High Population Growth						
CO_2-Emissions (in GtC)						
EC	0.8	0.7	0.4	0.2	0.1	0.1
rOECD	2.0	1.6	0.8	0.4	0.2	0.1
FCPC	1.5	1.1	0.5	0.3	0.2	0.1
DEV	1.7	2.4	3.3	3.6	2.6	1.8
World	**6.0**	**5.7**	**5.0**	**4.4**	**3.1**	**2.1**
GNP per Capita (in 1000 $/cap)						
EC	11.8	11.4	10.6	10.4	9.7	8.5
rOECD	16.3	14.9	12.0	10.7	9.4	9.0
FCPC	3.4	3.2	2.9	3.0	4.9	4.9
DEV	0.6	0.9	1.9	3.4	4.3	5.7
World	**3.1**	**2.9**	**3.0**	**4.1**	**4.9**	**5.9**

4 Conclusions

To allocate the responsibility for future reductions of carbon dioxide among world regions, we developed two methods. The first one allocates permitted emission budgets to regions and is based on equity between the developed and the developing world, taking into account the inequities between the historical regional CO_2-emissions. The second one allocates the CO_2-emissions to regions in the time period 1990 - 2100 and is based on optimization of a socio-economic impact objective function, restricted by a maximum CO_2-equivalent concentration level.

In the first method we described the inequity between historical emissions of developed and developing regions via the concept of emission debt. The emission debt concept tries to quantify the fact that some regions have emitted more CO_2 than they were allowed to based on equity rules. We assume an equal emission budget per year, meaning all persons living between 1800 and 2100 have an equal yearly emission quotum irrespective of the generation one belongs to or the country one lives in. We used two approaches to estimate the equal emission quota.

The starting point of the intergenerational approach is the principle of total equity between regions over the whole period. Taking a target level, an emission scenario from 1800 until 2100, based on population levels, is used to estimate, iterative with IMAGE, the allowed emission quotum per capita per year. This approach leads to lower yearly emission quota (0.37 - 1.27 tC) than the budget approach (0.49 - 1.41 tC), in which a total carbon budget, containing historical emissions and future emission projections, is divided, as based on population levels.

Although the budget approach does not reflect total equity over the whole period, the advantage with respect to the intergenerational approach is the allocation of the remaining budget in regional emission rights. This approach leads to lower yearly emission permitted per capita for industrialized regions (-1.7, 1.9 tC) than for developing regions (0.1, 2.1 tC). This initial allocation may be used for a concept of tradable emission rights. The emission debt concept is based here on a per capita equity rule, but we recognize the need for a more elaborate approach which reflects other differences among regions as well. An extension of the budget approach in which fossil CO_2-emission rights are allocated by involving more indicators will be presented in the near future.

The emission debt concept may be a helpful tool to improve the understanding of the regional inequity and the problem of allocating future emission rights. However, it does not account for the socio-economic consequences of reductions and the pathway of future emissions. Therefore we formulated the allocation problem of carbon emissions by fossil fuel combustion as a constrained nonlinear optimization problem, where the concentration restriction is dependent on simulation runs with IMAGE and where the objective function estimates the socio-economic consequences of response strategies. The optimization algorithm developed is successful in finding a suboptimal solution of this problem.

Optimization results indicate that, given our model assumptions, large reductions have to be realized by industrialized regions to maximize welfare of future generations. In this optimization problem the maximum CO_2-equivalent concentration level is restricted to

530 ppmv and the yearly GNP growth is restricted to between 0 and 6%. The level of welfare in developing regions will, however, not reach the present level of OECD regions in the next 110 years.
With respect to the optimization method, the next step will be the development of a meta version of an energy/economy simulation model and a dynamic 'cost of effects' model. Then we can perform a comprehensive cost/benefit analysis where an optimal strategy in terms of economic and technical measures to reduce anthropogenic greenhouse gas emissions can be derived by using simulation models for climate change and the socio-economic activities.

Effective, preventive and adaptive response to climate change requires a concerted global effort. A successful global response to climate change can be based on (intergenerational and interregional) equity, environmental feasibility and economic efficiency. Results of both the emission debt concept and the optimization approach indicate that industrialized regions have to take the main responsibility in reducing CO_2-emissions and that reducing population growth increases average welfare and emission rights per capita significant, given the CO_2-equivalent concentration constraints.

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Appendix 1 : IMAGE (an Integrated Model to Asess the Greenhouse Effect)

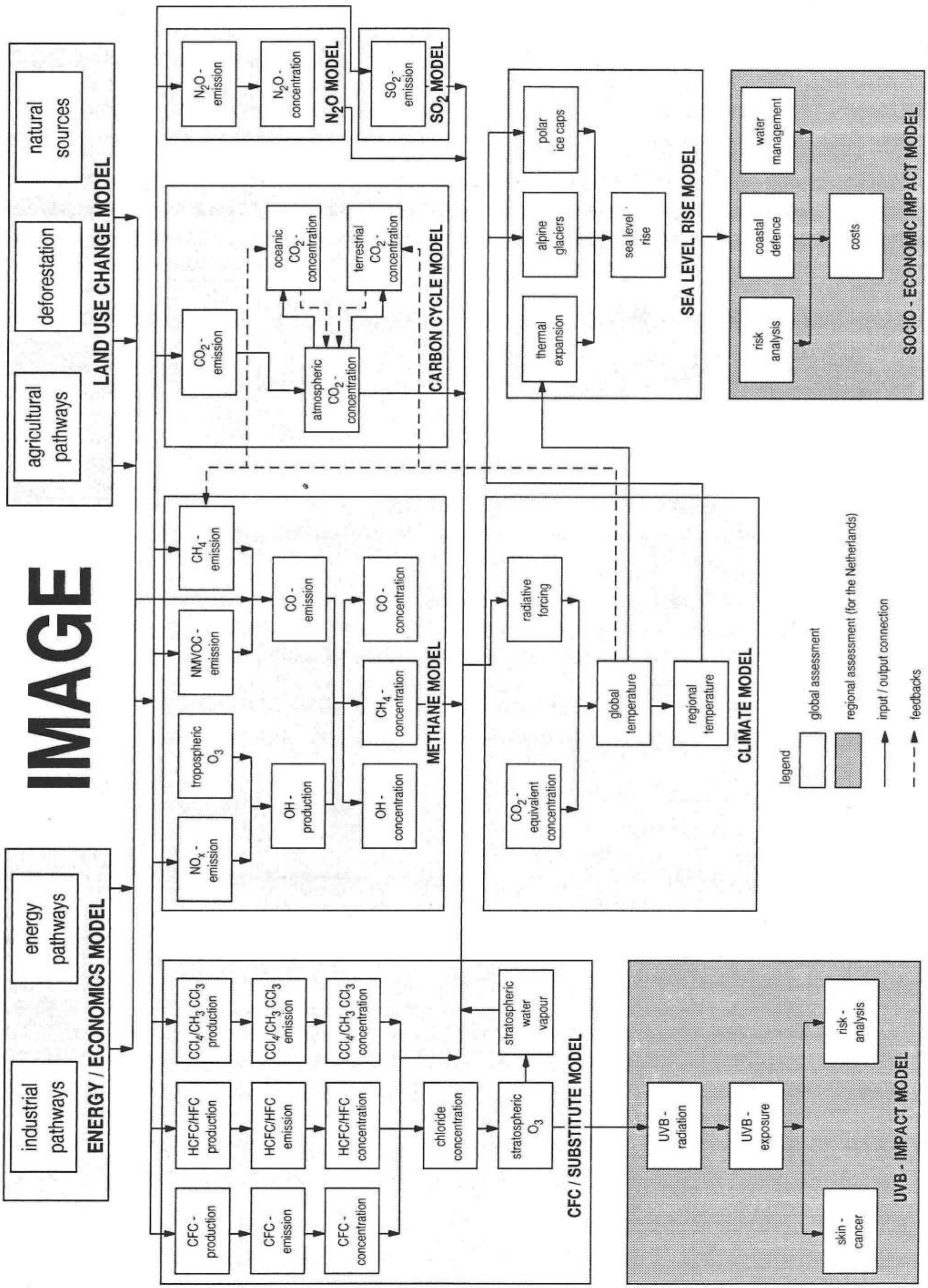

Figure A1: Structure of the Integrated Model for the Assessment of the greenhouse Effect (IMAGE)

Appendix 2 : Scenarios

Table 1: CO_2-emissions, CO_2-concentration and CO_2-equivalent concentration for the IPCC scenarios and the Low-Risk scenario.

Scenario	CO_2 1990 GtC (tC/cap.yr) Ind.[1] world	Dev.[2] world	CO_2 2025 GtC (tC/cap.yr) Ind. world	Dev. world	CO_2-conc. (ppmv) 2100	CO_2-equiv. conc. (ppmv) 2100
Business-as-Usual scenario	4.4 (3.1)	1.6 (0.4)	6.7 (4.7)	3.4 (0.5)	755	1240
Low Emission scenario	4.4 (3.1)	1.6 (0.4)	4.4 (3.1)	2.4 (0.3)	525	780
Control Policies scenario	4.4 (3.1)	1.6 (0.4)	4.4 (3.1)	2.3 (0.3)	464	595
Accelerated Policies scenario	4.4 (3.1)	1.6 (0.4)	3.5 (2.5)	2.1 (0.3)	420	530
Low-Risk scenario	4.4 (3.1)	1.6 (0.4)	1.7 (1.2)	1.0 (0.1)	398	475

[1] Ind. = Industrialized
[2] Dev. = Developing

Table 2: Description of the IPCC-scenarios (IPCC, 1991)

Scenario	Business-As-Usual scenario	Low Emission scenario	Control Policies scenario	Accelerated Policies scenario
Energy Supply	Coal-intensive	Natural Gas-intensive	Non-Fossil-intensive	Early Non-Fossil-intensive
Energy Demand	Moderate Efficiency	High Efficiency	High Efficiency	High Efficiency
Control Technology	Modest Controls	Stringent Controls	Stringent Controls	Stringent Controls
CFCs	Protocol/Low Compliance	Protocol/Full Compliance	Phase Out	Phase Out
Deforestation	Moderate	Reforestation	Reforestation	Reforestation
Agriculture	Current Factors	Current Factors	Declining Factors	Declining Factors

Appendix 3 : CO_2-equivalent Concentration

The CO_2-equivalent concentration can be expressed as equation A.1 (Rotmans, 1990).

$$pCO_{2eq} = pCO_2in \cdot e^{[\frac{Ln(2)}{\Delta Q_{2xCO_2}} \cdot \Delta Q]} \qquad (A.1)$$

, where

pCO_2in = pre-industrial CO_2-concentration, in 1900 (ppmv)

pCO_{2eq} = atmospheric CO_2-equivalent concentration (ppmv)

ΔQ = total radiative forcing, caused by changes in concentrations of all trace gases (W/m^2)

ΔQ_{2xCO_2} = radiative forcing for a doubled CO_2-concentration (equal to 4.3 W/m^2 according to the IPCC (1990)).

Changes in the concentration of radiative active trace gases result in corresponding changes in radiative forcing of the climate system. According to Ramanathan *et al.* (1979) the following relation approximately holds for the change in the radiative forcing by CO_2-emissions.

$$\Delta Q_{CO_2} = \left(\frac{\Delta Q_{2xCO_2}}{Ln(2)}\right) \cdot Ln\left(\frac{pCO_2}{pCO_2in}\right) \qquad (A.2)$$

, where

ΔQ_{CO_2} = change in radiative forcing by CO_2 (W/m^2)

pCO_2 = atmospheric CO_2-concentration (ppmv)

Using above equation and the fact that ΔQ is the total change in radiative forcing, defined as the sum of changes in radiative forcing by all trace gases ($=\Delta Q_{CO_2}+\Delta Q_{nonCO_2}$), the CO_2-equivalent concentration can be rewritten as follows:

$$pCO_{2eq} = pCO_2in \cdot e^{[\frac{Ln(2)}{\Delta Q_{2xCO_2}} \cdot (\Delta Q_{nonCO_2} + \frac{\Delta Q_{2xCO_2}}{Ln(2)} \cdot Ln(\frac{pCO_2}{pCO_2in}))]} \qquad (A.3)$$

The atmospheric CO_2-concentration (A.3) is determined by the fossil fuel combustion, uptake of CO_2 by the oceans, flux of CO_2 from the terrestrial biota and the net ecosystem production flux, and can be modelled according to the following equation (Rotmans, 1990).

$$pCO_2(t)=pCO_2(t-1)+\int_{t-1}^{t} atmcf\cdot(FSEM(\tau)+OCEA(\tau)-TNEP(\tau)+THDIST(\tau))d\tau \qquad (A.4)$$

, where

$pCO_2(t)$	= atmospheric CO_2-concentration at time t (ppmv)
atmcf	= factor that converts emissions of CO_2 into concentrations (ppmv/GtC)
FSEM(t)	= fossil fuel combustion flux at time t (GtC a-1)
OCEA(t)	= flux from oceanic mixed layers to the atmosphere at time t(GtC a-1)
TNEP(t)	= carbon flux by total net ecosystem production at time t(GtC a-1)
THDIST(t)	= total carbon flux of CO_2 due to human disturbance at time t (GtC a-1)

Using equation A.2 and A.3, the CO_2-equivalent concentration can be formulated as in A.5. The variables derived from calculations of IMAGE are: $\Delta Q(t)$, $\Delta Q_{CO_2}(t)$, OCEA(t), TNEP(t), THDIST(t). Model calculations show that the numerical (simulation results) and analytical CO_2-equivalent concentrations have a difference of less than 0.5%, when the variables derived from IMAGE are not changed.

$$pCO_{2\text{-}eq}(t) = u_t^1 \cdot u_t^2 + u_t^1 atmcf \sum_{y=1991}^{t} \sum_{r=1}^{R} FSEM(y) \quad \forall\ t \qquad (A.5)$$

, *where*

$$FSEM(\tau) = FSEM(t_{i-1}) + (FSEM(t_i) - FSEM(t_{i-1}))\cdot\frac{(\tau - t_{i-1})}{(t_i - t_{i-1})} \quad \forall\ \tau\in[t_{i-1},..,t_i] \quad \forall\ i$$

$$FSEM(t_i) = \sum_{r=1}^{R} x_{i,r} \quad \forall\ i$$

$$x_{i,r} \geq 0 \quad \forall\ i,r$$

$$u_t^1 = e^{\frac{\ln(2)}{\Delta Q_{2xco_2}}\left(\Delta Q(t) - \Delta Q_{co_2}(t)\right)} \quad \forall\ t$$

$$u_t^2 = pco_2(1990) + \sum_{y=1991}^{t} [atmcf\cdot(ocea(y) - tnep(y) + thdist(y))] \quad \forall\ t$$