Stabilization targets for atmospheric greenhouse gas concentrations: An assessment of impacts and emission mitigation pathways

Janina Onigkeit
Joseph Alcamo (Project leader)

Commissioned by the German Federal Environmental Agency

Center for Environmental Systems Research

University of Kassel, Germany

Wissenschaftliches Zentrum für Umweltsystemforschung

Universität Gesamthochschule Kassel

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Stabilization Targets for Atmospheric Greenhouse Gas Concentrations: An Assessment of Impacts and Emission Mitigation Pathways

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Janina Onigkeit
Joseph Alcamo (Project leader)

and
Frank Kaspar
Thomas Rösch

Center for Environmental Systems Research
(Report No. P0002)
University of Kassel

Director
Prof. Dr. Joseph Alcamo

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Abbreviations and Acronyms

AOSIS:	Alliance of Small Island States
CFCs:	Chlorofluorocarbons
EU:	European Union
e_{crit}:	Critical emission flux of sulfur dioxide
GCM:	General Circulation Model
GhG:	Greenhouse Gas
GWP:	Global Warming Potential
HCFCs:	Hydrochlorofluorocarbons
HFCs:	Hydrofluorocarbons
IMAGE:	*I*ntegrated *M*odel to *A*ssess the *G*reenhouse *E*ffect
IPCC:	Intergovernmental Panel on Climate Change
MPI:	Max Planck Institute
PBA:	Pollutant Burden Approach
PFCs:	Perfluorocarbons
UNFCCC:	United Nations Framework Convention on Climate Change
WaterGAP:	*Water*-*G*lobal *A*ssessment and *P*rognosis

Chemical Symbols

CO_2:	Carbon Dioxide
CH_4:	Methane
N_2O:	Nitrous Oxide
SF_6:	Sulfur Hexafluoride
SO_2:	Sulfur Dioxide

Summary

Background and Objectives

The European Union and other Parties to the United Nations Framework Convention on Climate Change (UNFCCC) have proposed a number of goals for the protection of the climate system in the course of the ongoing global climate negotiations. The main purpose of this study is to provide insight into some of the environmental consequences of these long term climate goals. The proposals included climate goals such as:

- a stabilization of the atmospheric CO_2 concentration at 550 ppm or lower,
- a limit on global temperature increase of 2°C compared to pre-industrial temperature,
- a limit of 20 cm to sea level rise compared to the level of 1990.

A number of models and new approaches were used or developed to do an extensive analysis of the consequences of these climate goals. This analysis covers the whole cause-effect chain of global climate change: (1) The global emissions pathways that are necessary to achieve these climate goals, (2) possible emissions control on the regional scale that is necessary to go along the prescribed global emissions pathways, (3) an evaluation of globally averaged impacts, and (4) an evaluation of impacts on the regional scale caused by these climate goals.

The basic instrument to do these analyses was the integrated model IMAGE 2.1 which enables the calculation of global and regional climate change impacts. This model was coupled with a global water model (WaterGAP) to compute the change in water availability caused by a stabilization of greenhouse gas concentrations at different levels. Additionally, the IMAGE model delivers the background data for the "safe emission corridor" software which was used to calculate emissions that are allowable on the short term to achieve the long term goals for temperature and sea level rise stated above.

A New Approach to Sulfur Emission Scenarios

In order to do these analyses it was necessary to develop two new scenario approaches covering aspects that are relevant for the analysis of climate protection goals and their impacts. The first approach addresses the problem of estimating future sulfur emissions that could have a significant effect on impact levels caused by climate change. To take these emissions into account we developed new scenarios for regional and global sulfur emissions, using the "Pollutant Burden" approach which was developed in this project. Using this approach we make an estimate about (1) the point in time when sulfur control measures begin in regions of the world where up to now no control of sulfur emissions takes place and (2) the tempo of sulfur emission reductions once they begin.

A New Approach to the Analysis of Burden Sharing

The second new scenario approach combines the question of stabilization targets with that of the participation of developing countries in greenhouse gas emission mitigation

measures. This approach is used to estimate the responsibilities of both developing countries and industrialized countries to reduce emissions under various "burden sharing" schemes. Using this approach, we evaluate the implications of different "rules" for deciding when developing countries begin mitigating emissions. This approach especially enables an estimate of necessary mitigation measures in industrialized as well as developing countries in order to achieve a certain stabilization target.

Within this study we focus on the implications of the two CO_2 concentration targets of 550 ppm and 450 ppm. Additionally, the allowable ranges of short term emissions to achieve the temperature and the sea level rise targets are described. The results of this study are summarized in the following paragraphs and in Table 1.

Global Emissions under Stabilization of Greenhouse Gases in the Atmosphere

To perform an impact analysis of stabilization scenarios it is necessary to consider the global emission and concentration pathways of all relevant greenhouse gases (GhG). From the six gases covered by the Kyoto Protocol the anthropogenic emissions of CO_2, N_2O and CH_4 together account for 90% of current total GhG emissions. From these gases, CO_2 emissions, mostly from the energy/industry sector, play the most important role (60%), followed by CH_4 and N_2O emissions which together cover 30% of all GhG emissions. The remaining 10% stem from the CFCs (about 9%) and from the HFCs, PFCs and SF_6 (about 1%). Within this study, emissions of the three gases CO_2, N_2O and CH_4 from energy/industry as well as from land use are covered.

CO_2 Emissions

Global allowable CO_2 emissions are computed in an inverse mode from the prescribed CO_2 concentration pathways of the IPCC model exercise described in Enting *et al.* (1994). In order to achieve a long term stabilization of the atmospheric CO_2 concentration at 550 ppm CO_2 emissions cannot be any higher than 148% of 1990 emissions in 2030. Towards 2100 emissions have to be decreased to 107% of the 1990 emissions level. However, a further emission mitigation might be necessary after 2100, since a stabilization at 550 ppm will not be reached before 2150. For the 450 ppm stabilization target a stricter emissions control is necessary from the very beginning: Emissions may reach a maximum of 128% of 1990 emissions in 2030 and then have to be reduced to 44% of 1990 emissions by 2100. In contrast to the 550 ppm stabilization target, a stabilization of the atmospheric CO_2 concentration at 450 ppm will be reached within the time frame of the scenario (1990-2100).

N_2O and CH_4 Emissions

For the analysis of stabilization of greenhouse gases, we assumed that global N_2O and CH_4 emissions from the energy/industry sector are mitigated proportionally to CO_2 mitigation. Because of the lack of information about feasible reductions of these gases from land use activities, we assumed that N_2O and CH_4 from land use activities was uncontrolled, and that their trend followed the Baseline A reference scenario from IMAGE 2.1. We recommend that future studies should examine the potential to mitigate global land use emissions of CH_4 and N_2O. Total global N_2O and CH_4 emissions (the next most important GhGs after CO_2 if we exclude water vapor and O_3) are computed to reach a maximum around 2030 and to slightly decrease afterwards under both the 450 ppm and the 550 ppm stabilization scenario. Nevertheless, in 2100 N_2O and CH_4 emissions stay significantly above their 1990 level for both stabilization scenarios. This is because CH_4 and N_2O emissions from land use (1) significantly contribute to total CH_4 and N_2O emissions over the whole scenario period and (2) are assumed not to be controlled in the stabilization scenarios. The consequence is that increasing N_2O and CH_4 land-use emissions compensate for the assumed reductions in emissions from the energy/industry sector. Land-use emissions of these gases make up 90% of total N_2O and CH_4 emissions in 2100 for the 450 ppm scenario. In the 550 ppm scenario CH_4 and N_2O land-use emissions contribute up to 80% of the total emissions of these gases. These numbers underline the importance of considering controls of N_2O and CH_4 emissions from the agricultural sector in future emission control strategies.

CO_2 Equivalent Emissions

The trend of global CO_2 equivalent emissions (CO_2, N_2O and CH_4), resulting from the prescribed CO_2 concentration pathways and the assumptions we made about non- CO_2 GhGs, resembles the global trend of CO_2 emissions. CO_2 equivalent emissions may increase up to 2030 and have to decrease towards 2100 for both stabilization scenarios. For the 450 ppm scenario, CO_2 equivalent emissions have to be reduced to a level of 66% of 1990 emissions. By contrast, for the 550 ppm scenario, the emissions must also be reduced after 2030 but may stay at 117% of their 1990 level. However, it is worthwhile mentioning that emission reductions are partly postponed to a later point in time because this scenario assumes that GhG concentrations will not be stabilized until 2150.

SO_2 Emissions

Sulfur dioxide emissions have the potential to partly compensate for the effects of greenhouse gases. In order to take this fact into account in the evaluation of regional impacts of climate change we developed the so-called ”Pollutant Burden” approach (PBA). The PBA provides future SO_2 emission scenarios for the 13 regions of the IMAGE model. The two basic assumptions of this approach are: (1) Developing regions will begin to reduce their SO_2 emissions when their ”pollutant burden” reaches the same magnitude as the pollutant burden of industrialized regions when they began to reduce their emissions. (2) Once emission reductions begin in a developing region they proceed in a tempo similar to that observed in industrialized regions. The obtained SO_2 emissions show a significantly different trend for industrialized regions and developing regions. Whereas the SO_2 emissions of most developing regions strongly increase up to 2030 and then start to level off or decrease, the SO_2 emissions of industrialized countries continue their decreasing trend and end at 4 to 10% of their 1990 emission levels in 2100. Hence, the often used reference case of constant SO_2 emissions after 1990 (e.g. Houghton *et al.*, 1997) tends to underestimate the SO_2 emissions in developing regions and to strongly overestimate the SO_2 emissions of industrialized regions. Computing region-specific trends of SO_2 emissions can therefore greatly improve the evaluation of regional impact levels of climate change.

Global and Regional Emission Mitigation

Mitigating Global Emissions

To achieve a stabilization of the atmospheric CO_2 concentration on the prescribed concentration pathways, global emissions may increase up to 2030. Nevertheless, these allowable emissions are much lower than reference emissions, and thus emission controls are necessary from the very beginning. To keep global emission reduction rates low over the long term (lower than 0.5% per year until 2100), emissions may not increase by more than 1% per year over the medium term (until 2030) for the 550 ppm concentration pathway. For the 450 ppm stabilization scenario the increase of emissions must stay below 1% per year until 2030 to achieve long term reductions between 1 and 1.5% per year.

Mitigating Regional Emission – Examples of Burden Sharing Scenarios

From the policy standpoint it is interesting to explore the implications on different regions of limiting global emissions. To do so, we developed a procedure to distribute allowable global emissions between non-Annex B and Annex B regions. This procedure is based on two principles: (1) Due to their historical contribution to climate change and their high level of per capita emissions Annex B countries must start with emissions reductions at once. (2) Non-Annex B countries have to stabilize emissions when they reach a certain income level (a so-called “graduation” criterion) and must start reducing emissions when their per capita emissions equal Annex B per capita emissions.

The overall picture we get from this approach is similar for both stabilization scenarios: Average Annex B per capita emissions start at a relatively high level and have to be reduced substantially below their 1990 emissions level until 2100, whereas non-Annex B per capita emissions start at a low level, may slightly increase over the mid term, and then must decrease again to their 1990 emissions level or even lower to achieve the 450 ppm target. However, even the relatively low per capita emissions of non-Annex B regions lead to high total emissions because of assumed future population growth. Hence, total emissions of non-Annex B more than double within the next forty years and may stay at this high level until 2100 for the 550 ppm stabilization target. For the 450 ppm target, non-Annex B emissions again can double up to 2030, but then must be halved after 2030 to reach a level slightly above 1990 emissions in 2100. Annex B regions must substantially reduce their total emissions until 2100 to a quarter or less of their 1990 emissions to achieve globally equal per capita emissions and a stabilization of atmospheric greenhouse gas concentrations at the same time.

Impacts of the Stabilization Scenarios

Impact Indicators

In order to get a comprehensive picture of the impact levels that might be expected for the two stabilization targets of 550 ppm and 450 ppm CO_2 in the atmosphere in comparison to a reference scenario, five impact categories were evaluated:

1. *Atmospheric temperature change* is a direct response to the build-up of GhG concentrations in the atmosphere, and is often used as an indicator in formulating climate protection targets.
2. *Sea level rise* is an indirect indicator of the build-up of GhG concentrations, and stems from increasing ocean temperatures and melting of ice masses. Sea level rise could irreversibly endanger countries with low lying coastal areas and small island states.
3. The *change in potential crop productivity* is an indirect indicator of the possible impacts of climate change on the world´s agriculture system.
4. The *change in potential natural vegetation* reflects impacts on natural ecosystems.
5. The *change in water availability* could especially affect water supply in agricultural but also in industrial systems.

Temperature Change

For the 550 ppm stabilization scenario, a global mean temperature change of 1.7°C was computed between 1990 and 2100. This is equal to an increase of about 2.2°C compared to pre-industrial times. Even a stricter stabilization target of 450 ppm CO_2 in the atmosphere results in an temperature change of 1.7°C in 2100 compared to pre-industrial times.

For both stabilization scenarios, the global mean temperature rapidly increases between 1990 and 2030, exceeding a rate of 0.1°C per decade in the first half of the 21st century. This rate of change is sometimes suggested as an upper limit to which natural ecosystems can adapt to (Rijsberman and Swart, 1990). Only under the 450 ppm scenario the rate of temperature increase will fall below this value in the second half of the 21st century.

Sea Level Rise

Between 1990 and 2100, sea level rises 29 cm under the 450 ppm scenario and 33 cm under the 550 ppm scenario. Although the rate of temperature increase slows down towards the end of 21st century, the rate of sea level rise continues to accelerate because of the lag time in the warming of the ocean and the warming of the atmosphere. Average sea level is computed to increase by a further factor of three and four between 2100 and 2500 for the 450 ppm and 550 ppm scenarios, respectively.

Crop Productivity

As an indicator of risk to global and regional food production we use the percentage of current crop growing area that is affected by decreasing potential yield. In this analysis we only take into account the possible effect of changing temperature and precipitation on potential crop yield, and we neglect the possible adaptation of the agricultural system to climate change.

The main outcome of the analysis is that climate change may appreciably affect the potential yield of all types of crops examined (temperate cereals, tropical cereals and maize). For the 550 ppm scenario and temperate cereals, 15% of the current global crop area is affected by 2030, and 20% by 2100. For tropical cereals and maize we get similar patterns: 11% and 25% of current areas are affected by 2100, and more than half of this level is already reached by 2030. The impact levels of the 450 ppm scenario lie only 2-5% below the impact levels of the 550 ppm scenario.

On the regional scale, the percentage of area affected by decreasing crop yield varies widely. The largest impacts were computed in Canada, the USA and India, whereas Eastern Europe and the region of the Former Soviet Union show very low impact levels. This is valid for both stabilization scenarios and all three crop classes. Hence for an evaluation of impacts of different stabilization targets it is much more reasonable to consider regional effects. However, for this purpose the results of more than one climate model should be used because of the uncertainties associated with estimates of changes in precipitation.

Threat to Natural Vegetation

Even if climate protection measures lead to long term stabilization of atmospheric concentrations of greenhouse gases, considerable areas of natural vegetation might not be able to adapt to changing climate conditions. Under the 550 ppm scenario, we compute that climate change up to 2100 could change the potential vegetation on 28% of the existing area with natural vegetation. Under the 450 ppm scenario, 23% of this area could have changed vegetation.

Also under the 550 ppm scenario, we compute that climate change up to 2100 could change the potential natural vegetation in 23% of the area of current nature reserves. Under the 450 ppm scenario this figure is 21%.

Water Availability

Using the global water model WaterGAP we performed a first analysis to evaluate the impacts of climate change on the water availability in a number of watersheds. According to this evaluation, the climate change corresponding to the two stabilization targets could increase water availability in some watersheds, and decrease it in others. In some places, for example the Guadalquivir in Spain, climate change will increase the pressure on water resources in areas that are already water-short. For other places, like for example the Zambezi in Africa or the Rhine in Western Europe, we computed an increasing water availability for the two stabilization scenarios as well as for the Kyoto reference scenario.

Short Term Emission Mitigation and Long Term Climate Protection Goals

The so-called "Safe Landing Approach" was applied to estimate which short term emissions (until 2010) are allowed to achieve the long-term climate targets proposed by the EU and the AOSIS states. For this purpose an emissions corridor is computed for the period 1990 to 2010 which allows to accomplish climate targets formulated for the long-term (until 2100). In other words: If the global emissions stay within this emissions corridor until 2010, there will be at least one global emission pathway that allows to realize the selected targets for climate protection.

Using the ”Safe Landing Approach” we computed the emission corridors between 1990 and 2010 that comply with the long term climate goals proposed by the AOSIS countries (a maximum of 20 cm sea level rise and 1.5°C temperature increase compared to 1990, (UNFCCC, 1997a)) and the EU (1.5°C temperature increase compared to 1990, (UNFCCC, 1997b)). Additionally, we assumed that the rate of temperature change may not exceed 0.15°C per decade and that the necessary rate of global emission reductions should not exceed 2% per year over the time period 1990-2100. For the climate goal of the EU we also limited sea level rise to 30 cm between 1990 and 2100.

The climate goals of the AOSIS proposal lead to a very low and narrow emission corridor between 1990 and 2010. To fall within the corridor, emissions in Annex B countries must be stringently reduced by 2010 relative to 1990 assuming that non-Annex B countries do not control their emissions.

The climate goal of the EU proposal leads to a wider corridor for allowable emissions than the AOSIS proposal. Nevertheless to reach the middle of the corridor, Annex B emissions must be significantly reduced, and to reach the top of the corridor only small increases in Annex B emissions are allowed.

Global emissions resulting from the commitments of the Kyoto protocol lie outside of the emission corridor of the AOSIS proposal but inside the ”EU emission corridor” in 2010. But as they lie near the top of this corridor, a further increase in global emissions is not allowed after 2010 if the EU climate goal is to be achieved.

Overall Conclusions

Some general conclusions of this analysis are:

1. To achieve stabilization of CO_2 in the atmosphere at 450 ppm and 550 ppm, it will be necessary to significantly control emissions on the global and regional scale.

2. Even if the atmospheric GhG concentrations are stabilized over the long term, there will be a significant increase of concentrations especially in the coming decades. This will lead to a change of climate and possible climate impacts within a relative short period of time (before 2050).

3. Therefore, under the described stabilization scenarios it is important to not only mitigate GhG emissions, but also to plan measures for adapting to the global and regional climate change.

Table 1: Overview of global emissions and global impacts of the 450 ppm and 550 ppm stabilization scenarios and the Kyoto reference scenario.

	Scenario				
	450 ppm (SO$_2$: const. 1990)	**550ppm (SO$_2$: const. 1990)**	**550ppm (SO$_2$: PB-95%)[1]**	**550ppm (SO$_2$: PB-5%)[1]**	**Kyoto Scenario[2] (SO$_2$: const. 1990)**
Emissions					
CO_2 in 2100 [Gt C/yr]	3.1	7.6	7.6	7.6	20.2
CO_2 equivalent in 2100[3] [Gt C/yr]	6.5	11.5	11.5	11.5	26.2
Cumulative CO_2 1990-2100 [Gt C]	723	975	975	975	1537
Cumulative CO_2 equivalent[3] 1990-2100 [Gt C]	1108	1393	1393	1393	2068
Impacts					
Temperature change 1990-2100 [°C]	1.3	1.7	1.4	1.8	2.7
Sea level rise 1990-2100 [cm]	29	33	n.d.	n.d.	41
Sea level rise 1990-2500 [cm]	103	122	n.d.	n.d.	-
Area of current crop growing area with decreasing potential yield - Temperate cereals in 2100 [%]	18	20	17	21	22
Area of current crop growing area with decreasing potential yield - Maize in 2100 [%]	21	25	21	26	31
Area of current crop growing area with decreasing potential yield - Tropical Cereals in 2100 [%]	9	11	9	12	11
Area with current potential natural vegetation under risk in 2100 [%]	22	28	25	29	39
Area of nature reserves with potential natural vegetation under risk in 2100 [%]	21	23	23	28	39

n.d.: not determined

[1] "PB-95% SO$_2$" is the 95 percentile SO$_2$ emissions scenario computed with the "Pollutant Burden Approach", and "PB-5% SO$_2$" is the 5 percentile emissions scenario using the same approach.
[2] For the "Kyoto scenario" we assume a 5.2% reduction of 1990 Annex B GhG emissions until 2010. After 2010 GhG emissions of Annex B remain constant. Non-Annex B emissions follow Baseline A assumptions throughout the whole scenario period.
[3] CO_2 equivalent emissions include the greenhouse gases CO_2, CH_4 and N_2O from the energy/industry sector and land-use sector.

1. Introduction

The climate summit in Kyoto in December 1997 emphasized short term emission mitigation, while the climate summit in Buenos Aires in November 1998 focused on the operationalization of the Climate Protocol adopted in Kyoto. But an important question that was left open by both summits was the issue of defining a long term climate goal as it is stated in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC, 1992) (hereafter: the Climate Convention): "... *stabilization of greenhouse gas concentrations* in the atmosphere at a level that would *prevent dangerous anthropogenic interference* with the climate system. Such a level should be *achieved within a time-frame* sufficient *to allow ecosystems to adapt naturally* to climate change, to ensure that *food production is not threatened*, and to *enable economic development* to proceed in a sustainable manner." (Parenthesis added.)

The objective of the Climate Convention was already adopted in 1992. Only two groups of Parties, namely the European Union (EU) and the Alliance of Small Island States (AOSIS), proposed to make Article 2 more specific (FCCC/AGBM/1997/MISC.1/Add.2). The EU stated "...that global average temperatures should not exceed 2°C above pre-industrial level and that therefore concentration levels lower than 550 ppm CO_2 should guide global limitation and reduction efforts" (UNFCCC, 1997b). The AOSIS formulated the same limitation for global average temperature change and added "that global mean sea level rise ...should not exceed 20 cm above 1990 levels" (UNFCCC, 1997a). This small number of concrete proposals reflects the difficulty in deciding on a long term climate goal with all its consequences. Depending on the desired degree of climate protection, weak or strong reduction measures will be necessary. But even in the case of taking climate protection measures a change of or harm to some systems will have likely to be accepted. A further reason for the difficulties in setting long term climate protection targets may be that climate change impacts are not yet visible. However, Working Group II of the IPCC has pointed out that impacts are likely but they will occur in the future and they will add an important new stress to natural and socioeconomic systems (Watson *et al.*, 1996).

In this situation integrated models such as the IMAGE model provide climate policy makers with the long-term perspective they need to develop policies to lessen long-term impacts. The IMAGE model was designed to simulate the dynamics of the society-biosphere-climate system (Alcamo *et al.*, 1998a) and can provide an overview of the cause-effect chain of the climate change issue. Calculations with the IMAGE model range from the grid (0.5° x 0.5° latitude-longitude) to world regional level, depending on the type of calculations, with a time horizon from 1970 to 2100. Using the IMAGE model to analyze GhG (Greenhouse Gas) emission- or CO_2 stabilization scenarios provides a comprehensive picture of possible consequences of selected long term climate targets.

The aim of this report is to provide a comprehensive evaluation of the consequences of long term climate goals that are under discussion in the ongoing climate negotiation process. Comprehensive is meant here to cover the whole cause-effect chain starting from GhG emissions via climate change to the impacts of climate change. However, it is not meant as a comprehensive evaluation of all impacts that could occur.

In this report we pursue two approaches to evaluate the consequences of different climate targets:

1. Starting from two CO_2 concentration targets (550 ppm and 450 ppm) we will present the maximum allowable global emissions for achieving these targets in comparison to emissions of a reference scenario. As sulfur dioxide (SO_2) emissions are assumed to have a compensating effect on climate change, an approach was developed to describe the time path of regional and global sulfur emissions.
2. In a second analysis we use the so-called "Safe Landing” approach to compute a range of allowable emissions, in contrast to the single emission pathways we compute with the first approach. Using this approach we can evaluate long term climate targets such as the 2° C target proposed by the EU and AOSIS.

A brief description of the IMAGE model is given in chapter 2 and the assumed and computed concentration and emission pathways are described in chapter 3. In chapter 4 the necessary global emission mitigation including a possible regional distribution can be found. The impact indicators and impact levels for the chosen stabilization scenarios are described in chapter 5. Results of the analysis of long term climate goals proposed by the EU and the AOSIS using the ”Safe Landing” approach can be found in chapter 6. Some final conclusions are drawn in chapter 7.

2. The IMAGE Model: Instrument for Analysis

In this chapter we briefly describe the IMAGE 2.1 model, the instrument used for most of the climate impact analysis in this project.

2.1 Overview of the IMAGE Model

The IMAGE 2.1 model is an integrated global change model (Alcamo, *et al.* 1994a and Alcamo *et al.*, 1998a) which provides comprehensive, geographically-detailed, and quantitative information about trends in greenhouse gas emissions and their impact on climate, the biosphere, and society. The main inputs to the model, and the driving forces of the scenarios in this report as well, are changes in population, economy, and technology. Based on assumptions about these driving forces, IMAGE 2.1 computes future changes in the consumption of energy, food, and timber. This consumption leads to greenhouse gas emissions from energy and industry, shifts in land use and land cover, and changes in the fluxes of gases from the terrestrial environment. The emissions and fluxes of gases lead to changes in the atmospheric composition of various gases, as well as changes in the flux of heat and moisture between the terrestrial, oceanic and atmospheric environments. Eventually these fluxes affect regional climate, and these changes in regional climate then feed back to the terrestrial and oceanic environments in different ways, for example, by changing the productivity of crops and the required amount of future agricultural land.

The model is constructed from 13 individual global submodels organized into three fully linked subsystems: Energy-Industry, Terrestrial Environment, and Atmosphere-Ocean (Figure 1). The *Energy-Industry* models compute the emissions of greenhouse and other gases from five sectors in 13 world regions (Figure 2) based on estimates of industrial production and energy consumption. The *Terrestrial Environment* models simulate changes in global land use and cover on a grid-scale taking into account shifts in the demand and potential productivity of land. These models also compute the subsequent fluxes of gases between the terrestrial environment and atmosphere. The *Atmosphere-Ocean* models calculate the changes in atmospheric composition of greenhouse and other gases, changes in the heat and moisture balance of the earth, and subsequent shifts in temperature and precipitation patterns. Each submodel has been tested either with data from 1970 to 1990, or long-term averages, depending on suitability and availability of data. An overview of model development and testing is given in Alcamo, *et al.* (1994b). Details of development and testing of the Energy-Industry subsystem are given in de Vries, *et al.* (1994); for the Terrestrial Environment subsystem in Klein Goldewijk, *et al.* (1994), Kreileman and Bouwman (1994), Leemans and van den Born (1994), and Zuidema, *et al.* (1994); and for the Atmosphere-Ocean subsystem in de Haan, *et al.* (1994) and Krol and van der Woerd (1994).

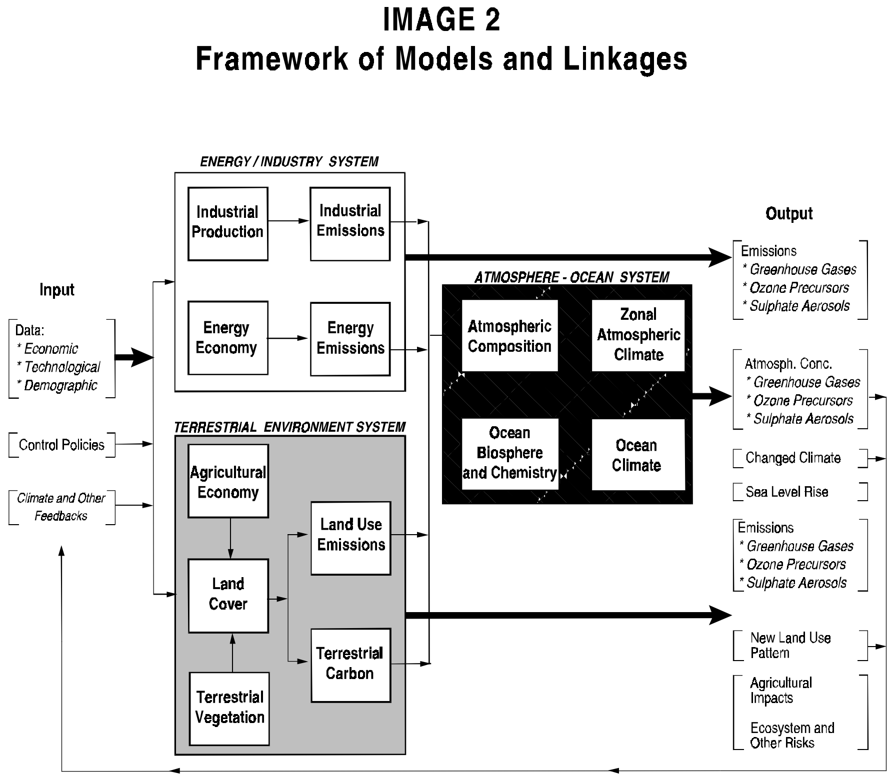

Figure 1: Schematic diagram of the IMAGE 2 model.

2.2 Reference Scenario for the Analysis

As a starting point for evaluating climate policies it is necessary to have a benchmark scenario that specifies the consequences of no policy action. In this paper we use a modified intermediate of three baseline scenarios developed with the IMAGE 2 model. The original scenario is called *Baseline A*, and is described in detail in Alcamo (1998b). Assumptions about the key driving forces in Baseline A come from the intermediate emissions scenario of IPCC, IS92a (Leggett, *et al.*, 1992). In this scenario world population grows to 11.3 billion in 2100 and GDP grows at a worldwide average of 2.3 % per year from 1990 to 2100. Assumptions for particular regions are quite distinct, although most industrialized regions level off in population and slow in economic growth in the coming decades, while most developing countries are assumed to sharply increase in both population and income until the second half of the 21st century. The modified scenario includes the commitments of the Kyoto Protocol in which Annex B countries[1] agreed to reduce a "basket" of gases by 5.2 % in the period 2008 to 2012, relative to their 1990 levels. For the time after 2010 we assumed no further reductions: Annex B emissions are held constant from 2010-2100 while non-Annex B emissions grow according to Baseline A emissions. This new reference scenario is called the "Kyoto Scenario".

[1] "Annex B countries" are parties to the Climate Convention that have agreed to emission control commitments as part of the Kyoto Protocol, and are listed in Appendix B of this protocol.

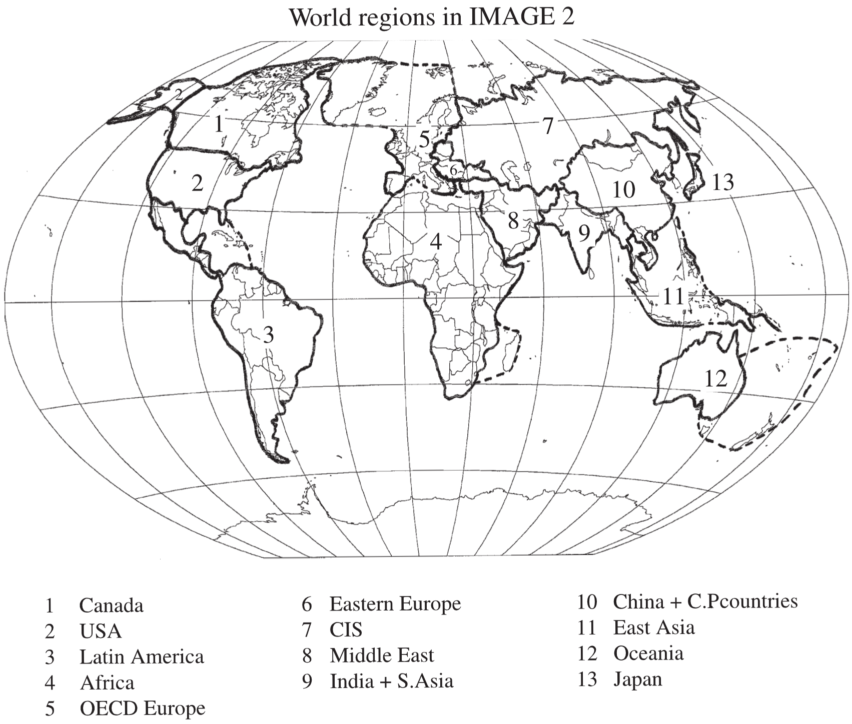

Figure 2: World regions in the IMAGE 2 model.

3. Stabilization of Atmospheric Greenhouse Gas Concentrations and Related Global Emissions

For the evaluation of allowable anthropogenic CO_2 emissions that comply with a stabilization target, the IMAGE model was used in "reverse mode" in that a global CO_2 concentration pathway is prescribed and CO_2 emissions are back-calculated from this concentration pathway. For an impact analysis however, we have to make additional assumptions about the emission pathways of all non- CO_2 greenhouse gases. These assumptions as well as the CO_2 concentration pathways are described in this chapter.

3.1 CO_2 Concentration Pathways

According to an EU proposal to the climate negotiations, CO_2 concentration levels lower than 550 ppm should guide global climate protection efforts. To evaluate the consequences of this proposal we performed an in depth analysis of the 550 ppm target and of a lower target of 450 ppm CO_2 in the atmosphere. In addition to the long-term concentration target, a pathway to reach this target must be specified for this analysis. For both targets we use the pathways prescribed in the IPCC exercise described in Enting *et al.* (1994). These pathways were designed for a model comparison exercise which included the IMAGE model. The targets of 450 ppm and 550 ppm will be reached in 2100 and 2150, respectively, as defined by the IPCC. The CO_2 concentration pathways are shown in Figure 3.

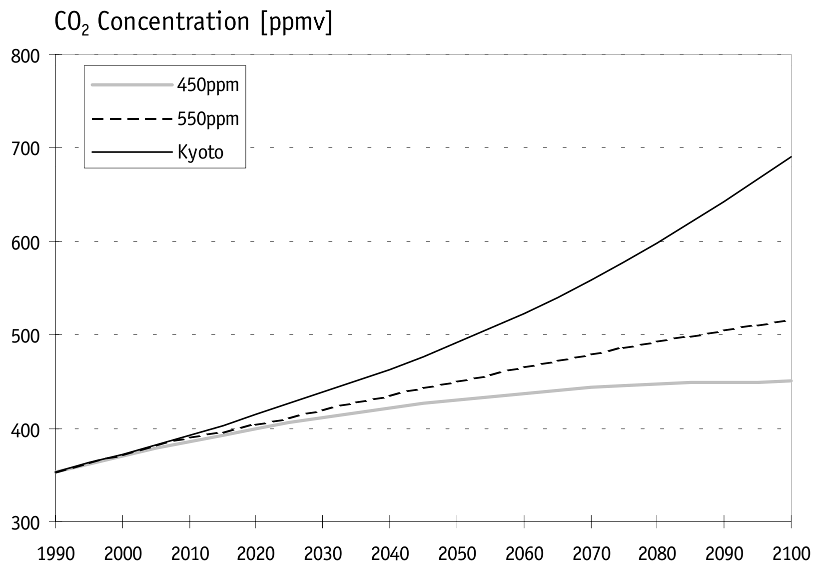

Figure 3: Atmospheric CO_2 concentration of the 450 ppm scenario, 550 ppm scenario and the "Kyoto" reference scenario.

The CO_2 concentration pathway of the Kyoto scenario illustrates the gap between the achievements of the Kyoto Protocol (if no further commitments would be agreed on) and two possible stabilization targets. The Kyoto scenario reaches 690 ppm in 2100 with a strongly rising tendency compared to 517 ppm and 450 ppm for both stabilization scenarios in 2100.

3.2 Emissions from Energy/Industry and Land Use

The Kyoto Protocol covers six gases that originate from very different sectors, namely energy, industry and agriculture. All these gases have to be taken into account for an impact analysis. We will analyze and give detailed information about the three main gases CO_2, CH_4 and N_2O. The other gases of the Kyoto Protocol (HFCs and PFCs) and the CFCs and HCFCs (their phasing out is governed by the Montreal Protocol on Substances that deplete the Ozone Layer) will also be taken into account. The same is valid for the atmospheric content of ozone and water vapor, which also contribute to the warming of the atmosphere.

The total of all anthropogenic greenhouse gas emissions is estimated to be currently 11.9 Gt C per year in CO_2 equivalent emissions[2] (Table 2). CO_2, CH_4 and N_2O together account for 90% of these emissions (Prather *et al.* 1995); the remaining 10% are covered by the CFCs (about 9%, depending on the GWPs used for these gases) and the HFCs, PFCs, and SF_6 (1%).

Table 2: Estimated global anthropogenic emissions of greenhouse gases in CO_2-equivalents (Gt C per year) for the time 1980 to 1990.

	Total emissions	**Energy/Industry**	**Land-use**
CO_2 [1)]	7.1	5.5	1.6
CH_4 [1)]	2.1	0.54	1.56
N_2O [1)]	1.5	0.35	1.16
CFCs [2)]	1.07 (1.47) [3)]	1.07 (1.47) [3)]	0
HFCs, PFCs, SF_6 [4)]	0.13	0.13	0
Total	**11.9 (12.3)** [3)]	**7.59 (7.99)** [3)]	**4.32**

1) Emissions data from IPCC (Prather *et al.,* 1995).
2) Emissions data from Pepper *et al.*, 1992, and GWPs from Schimel *et al.*(1996). GWPs includes an upper estimate of cooling effect of CFCs.
3) Same as 2) but GWPs include only direct effects of CFCs on radiative forcing.
4) Emissions in CO_2-equivalents from Olivier *et al.* (1996).

Looking at the sectoral distribution of current emissions, one can see that CO_2 emissions from the energy/industry system alone account for 5.5 Gt C per year or 46%. CO_2, CH_4 and N_2O emissions from the land-use sector together contribute about 36% or 4.3 Gt C per year in CO_2 equivalent emissions. Their assessment, however, is much more uncertain compared to that of the emissions from the energy/industry sector.

A notable point is that currently about 76% of CH_4 and N_2O stem from so-called land-

[2] Global warming potential (GWP) from Schimel et al. (1996): GWP N_2O: 310 kg CO_2/kg N_2O and GWP CH_4: 21.0 kg CO_2/kg CH_4

use emissions (see also Figure 4). Alcamo and Swart (1998c) found that the main sources of land-use emissions show increasing global trends up to the middle or even end of the 21st century in the 20 land-use emission scenarios they analyzed. The only exception are CO_2 emissions from deforestation that decrease towards the end of the 21st century due to an assumed slowing of agricultural land expansion or depletion of forested area. This high proportion of current land-use emissions as well as the future trends illustrate the important role that these emissions could play for the development of greenhouse gas concentrations in the atmosphere.

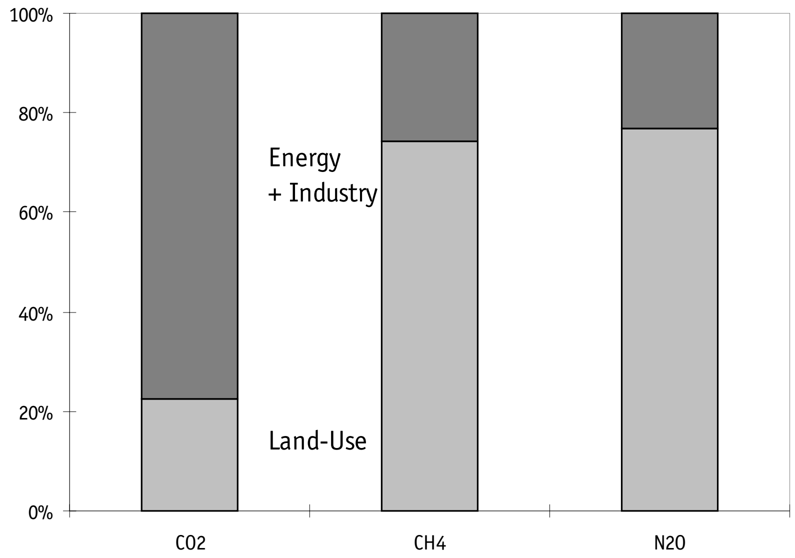

Figure 4: Percentage of global CO_2, CH_4, and N_2O emissions from "land-use" and "energy and industry" sources in the 1990's. Based on emissions data from IPCC (Prather *et al.*, 1995).

In the following chapters we will present the global emission pathways from 1990 to 2100 for CO_2, N_2O, and CH_4 under the two stabilization scenarios of 550 ppm and 450 ppm CO_2 in the atmosphere and the Kyoto reference scenario as they were computed by the IMAGE model. We will distinguish between emissions from the energy/industry sector and emissions from the land-use sector, as the latter will probably be of increasing importance due to an increasing demand for agricultural products in the future.

3.2.1 Carbon Dioxide Emissions

To compute the maximum allowable global energy/industry-related CO_2 emissions that would stabilize atmospheric CO_2 concentrations, the IMAGE model was used in reverse mode, i.e. CO_2 concentration pathways were specified, and then the model was run "backwards" to compute allowable emissions considering the biospheric and oceanic CO_2 uptake. But before doing that we had to estimate the CO_2 land-use emissions. These were taken from the IMAGE Baseline A scenario. In this scenario, CO_2 land-use emissions stem from deforestation measures mostly in Africa and Asia where an increasing demand for agricultural products leads to an extensive conversion of natural vegetation to agricultural land. The CO_2 land-use emissions are shown in Figure 5.

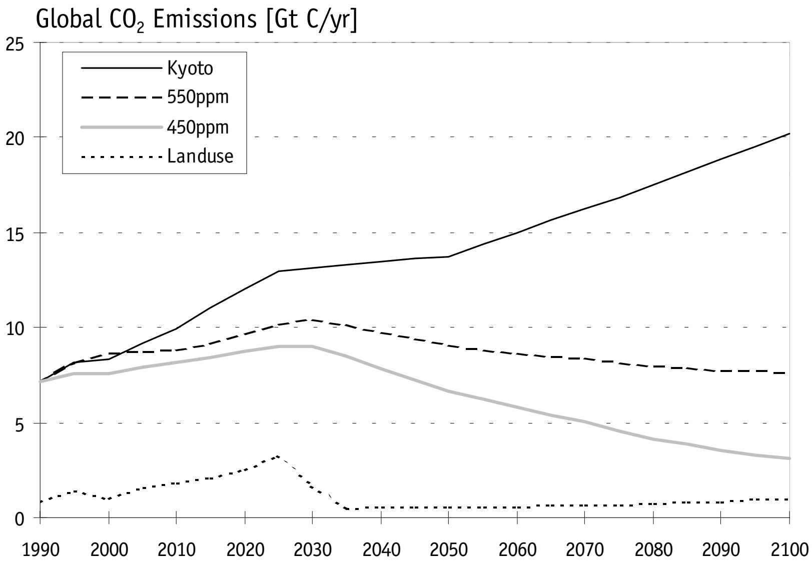

Figure 5: Global CO_2 emissions complying with two stabilization scenarios and the Kyoto reference scenario. The upper lines include energy/industry- and land use-related emissions. The additional short dashed line shows land use-related emissions only.

Following the prescribed concentration pathways, the global CO_2 emissions of both stabilization scenarios may increase up to the year 2030 and must be reduced afterwards. These emission pathways mainly result from (1) the allowable rate of change of the atmospheric CO_2 concentration which is high in the beginning due to the historic trend and slows down towards the end of the simulation period, and (2) the extensive conversion of forested areas to agricultural land (especially in Africa) which leads to a decreasing CO_2 uptake by the global biosphere after 2030 and thus requires additional reduction efforts to stay on the prescribed concentration pathways. Since the concentration pathway of the 450 ppm scenario is lower than that of the 550 ppm scenario throughout the whole scenario period (see chapter 3.1), the yearly amount of anthropogenic CO_2 that may be added to the atmosphere under the 450 ppm scenario is also much lower compared to the 550 ppm scenario. The shapes of the emission curves of the two stabilization scenarios, however, resemble each other since the change of land-use patterns is similar under both scenarios: A maximum of CO_2 emissions is allowed around the year 2030 and emissions must decrease after 2030 to compensate for the lower biospheric CO_2 uptake.

Starting from 7.1 Gt C per year in 1990 the total global CO_2 emissions for all scenarios increase until year 2030. For the 450 ppm stabilization scenario they reach 9.1 Gt C in 2030 (128% of 1990 emissions) and then sharply decrease to 3.1 Gt C in 2100 (44% of 1990 emissions). For the 550 ppm scenario, emissions may increase to 10.5 Gt C in 2030 (or 148% of 1990 emissions) and must then be reduced to 7.6 Gt C or 107% of 1990 emissions in 2100. Hence, for the 550 ppm target global CO_2 emissions may stay slightly above the 1990 level. But what should be remembered is that a stabilization of the CO_2

concentration at 550 ppm is not yet reached in 2100. Thus, continued emission mitigation will be necessary after 2100 whereas for the 450 ppm scenario the stabilization goal is already reached in 2100.

CO_2 land-use emissions, mainly originating from deforestation, start at about 1.0 Gt C in 1990 and then increase up to 3.3 Gt C in 2025. After 2030 emissions sharply decline to about 1.0 Gt C in 2035 where it remains until 2100. The increasing deforestation reflects the growing demand for agricultural land in developing regions like Africa and India. After 2030 forested areas in developing countries are assumed to be depleted and therefore CO_2 land-use emissions only play a minor role in the second half of the 21st century.

3.2.2 Nitrous Oxide Emissions

For the calculation of global N_2O emissions prescribed concentration pathways are not available. Therefore, we used the Baseline A emissions of the IMAGE model and made a number of assumptions for N_2O emission mitigation. For global energy- and industry-related N_2O emissions of the stabilization scenarios we assumed that they were mitigated proportionally to CO_2 emissions. N_2O land-use emissions, however, follow IMAGE Baseline A, since for these emissions information about feasible reduction measures are not yet available. N_2O land-use emissions originate from the five main sources included in the IMAGE model: Fertilizer use, animal waste, biomass burning, agricultural waste burning and enhanced N_2O release from soils after deforestation. From these sources the use of nitrogen fertilizers contributes most to N_2O emissions with an increasing tendency of emissions towards 2100. Total emissions (energy/industry plus land-use emissions) and land-use emissions alone are shown in Figure 6.

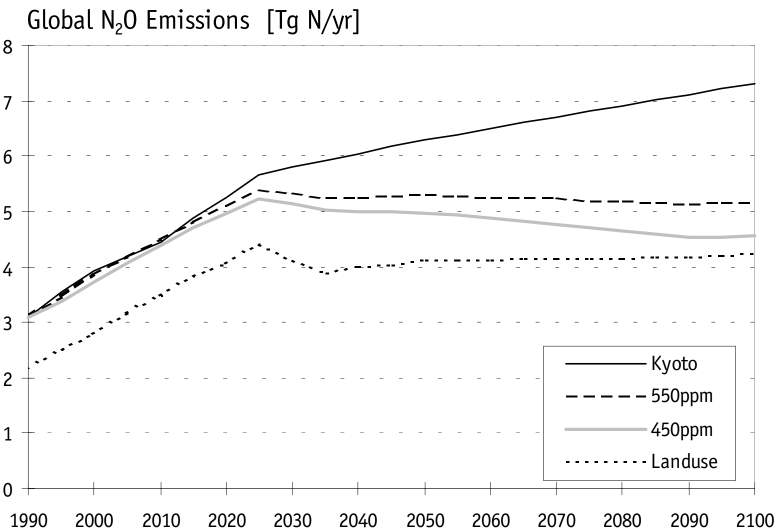

Figure 6: Global anthropogenic N_2O emissions from energy/industry and land-use. The additional short dashed line shows the contribution of N_2O land-use-related emissions.

Total global N_2O emissions increase from 3.1 Tg N in 1990 to a maximum of 5.2 and 5.4 Tg N (or 168% and 174% of 1990 emissions) in 2025 for the 450 ppm and 550 ppm scenario, respectively. For the Kyoto scenario N_2O emissions will reach 5.7 Tg N (or 184% of 1990 emissions) in 2025 and more than double to 7.3 Tg N (or 235% of 1990 emissions) in 2100. In contrast to the Kyoto scenario, the N_2O emissions of the two stabilization scenarios slightly decrease after 2025 as emissions from the energy/industry as well as land-use emissions, caused by deforestation measures, are to be reduced at this point in time. Thus, N_2O emissions reach 4.6 and 5.2 Tg N (148% and 168% of 1990 emissions) in 2100 for the 450 ppm and 550 ppm scenario, respectively.

N_2O land-use emissions in IMAGE account for 2.2 Tg N or 71 % to total N_2O emissions in 1990. Due to the assumption that no emission control measures are implemented for land-use-related emissions in the stabilization scenarios, their relative contribution to total emissions of these scenarios noticeably increases up to 2100. They make up 93 and 82% of total N_2O emissions in 2100 for the 450 ppm and 550 ppm scenario, respectively. This contribution might be regarded as unrealistically high since it is expected that in the agricultural sector greenhouse gas emissions will also be reduced. But even in the Kyoto scenario, for which we assume that greenhouse gas emissions from the agricultural sector of industrialized regions are slightly reduced, N_2O emissions from agriculture contribute 58% to total N_2O emissions.

3.2.3 Methane Emissions

As for N_2O there is no pathway defined for atmospheric CH_4 concentrations between 1990 and 2100. Therefore, we used the CH_4 emissions of the IMAGE Baseline A scenario and assumed that global CH_4 emissions originating from the energy/industry sector were mitigated proportionally to CO_2 emissions, whereas future land-use-related CH_4 emissions follow IMAGE Baseline A. In this scenario, CH_4 land-use emissions come from seven different sources from which rice cultivation and enteric fermentation contribute the most to global CH_4 emissions. Especially CH_4 emissions from enteric fermentation increase in importance due to an assumed increase of meat consumption in many regions of the world. In Figure 7 global CH_4 emissions from the land-use sector as well as total emissions originating from the energy/industry sector and the land-use sector are shown for the two stabilization scenarios and the Kyoto reference scenario.

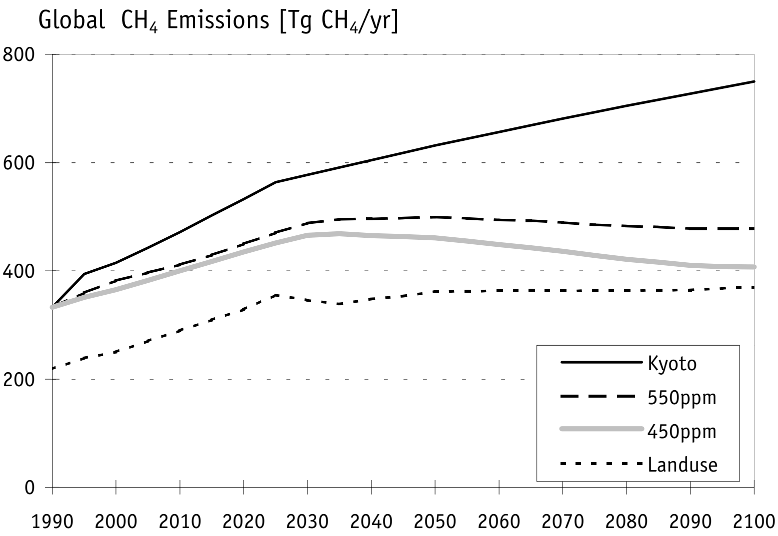

Figure 7: Global anthropogenic CH_4 emissions from the energy/industry and land use sector. The additional short dashed line shows CH_4 land-use emissions only.

Total anthropogenic CH_4 emissions increase from 333 Tg CH_4 in 1990 to a maximum of about 465 and 488 Tg CH_4 per year in the 2030's under the 450 ppm and 550 ppm stabilization scenario, respectively. This equals 140% of 1990 emissions for the 450 ppm scenario and 147% of 1990 emissions for the 550 ppm scenario. Although CH_4 emissions slightly decrease after 2030, in 2100 they still remain at 121% of 1990 emissions (407 Tg CH_4 per year) for the 450 ppm scenario and at 143% of 1990 emissions (477 Tg CH_4 per year) for the 550 ppm scenario. However, the CH_4 emissions of the Kyoto scenario more than double to 750 Tg CH_4 per year (or 227% of 1990 emissions) in 2100.

For the unmitigated CH_4 land-use emissions we find a trend comparable to that of N_2O emissions: They contribute 65% to total emissions in 1990 and up to 77% and 90% in 2100 under the 550 ppm and 450 ppm scenario, respectively. For the Kyoto scenario, for which land-use emissions are slightly reduced in industrialized regions, CH_4 emissions contribute 49% to total emissions. Hence, for CH_4 emissions from the agricultural sector the same is valid as for N_2O emissions from this sector: They contribute significantly to total emissions of these greenhouse gases.

3.2.4 Sulfur Dioxide Emissions: The Pollutant Burden Approach

Within the ongoing process of developing new greenhouse gas emission scenarios, the IPCC will also take into account sulfur emission scenarios since sulfate particles in the atmosphere (mostly originating from SO_2 emissions) may counteract the greenhouse effect. Sulfur is removed from the atmosphere relatively fast by wet or dry deposition. Its cooling effect is therefore, in contrast to the warming effect of greenhouse gases, spatially and temporally limited. Hence, SO_2 emission scenarios should be developed on a regional scale rather than on a global scale.

Grübler (1998) concluded from his review of existing scenarios that future sulfur emission trends will be spatially very heterogeneous with a decline in OECD countries and partly rapid increases in Asia. This heterogeneity in future trends is a further reason why sulfur emissions should not be modeled on a global scale only.

In order to generate regionally consistent SO_2 emission scenarios we have developed the new ”pollutant burden” approach. This approach was used to generate SO_2 emission scenarios for the 13 world regions of the IMAGE model up to 2100. We make a distinction between regions that have already established sulfur reduction measures (referred to as industrial regions) and regions that do not yet control their sulfur emissions (developing regions). For the latter regions, in particular, many scenarios assume a strong increase of sulfur emissions in the coming decades (Grübler, 1998). A crucial question for the evaluation of the impacts of sulfur emissions on climate change is therefore: When do the developing countries begin to control their sulfur emissions?

Starting from this question, the following three basic assumptions of the Pollutant Burden Approach were developed: (1) *The point in time when emission reductions begin in the developing regions*: Developing regions will begin to reduce SO_2 emissions when their “pollutant burden” reaches the same magnitude as the pollutant burden of industrialized regions at the time when they began to reduce their emissions, (2) *The speed of emission reductions in the developing regions*: Once emission reductions begin in developing regions, they proceed at a speed similar to that observed in industrialized regions. (3*) The continuation of SO_2 reduction measures in industrialized regions:* The industrialized regions will continue or even increase their reduction efforts in the future.

SO_2 Emission Scenarios for Developing Regions

To develop regional sulfur emission scenarios with the Pollutant Burden Approach we first had to answer the following four questions:

1. What is an appropriate measure to estimate the environmental pollution (pollutant burden) caused by sulfur emissions?
2. What is the critical threshold of pollutant burden when political measures commence?
3. What is the lag time between the beginning of policy action and the beginning of emission reductions in developing regions?
4. What is the rate of SO_2 emission reductions once reductions begin?

1. Indicator of Pollutant Burden

As an indicator of pollutant burden caused by sulfur emissions we use the annual rate of SO_2 emissions per unit area. More direct measures such as SO_2 deposition or SO_2 air concentration could not be used because models for calculating deposition and concentration indicators are only available for some regions of the world, such as for example, Europe and Asia, but are not readily developed for the remaining regions of the world. By contrast, estimates are available for the temporal trend and current gridded pattern of SO_2 emissions for the entire world. Combining these two data sets, namely regional scenarios for future SO_2 emissions and current emissions on a grid basis, we calculated the SO_2 emission rate per unit area by distributing regional emissions over the regional area using the emission patterns from the gridded data set.

For the Pollutant Burden approach the GEIA data base (Benkovitz *et al.*, 1997) provided the necessary gridded SO_2 fluxes (1° x 1° data for the year 1985) that were needed to scale down regional emissions provided by the IMAGE model. From this first step, we obtain SO_2 emissions per unit area for every year between 1990 and 2100. For global consistency, this emission flux can be seen as a rough surrogate of pollutant burden.

2. Deriving a Critical Threshold for the Pollutant Burden

Developing regions are assumed to commence policy actions when the emission flux over a critical percentage of their land area exceeds a critical level of emission flux. In other words, we assume that high emission fluxes will be tolerated if they occur only on a small part of a region's area. But as soon as the extension of this area with a high emission flux exceeds a critical percentage of the regional area, policy actions will be initiated. The crucial point of this analysis is to find these two critical values: (a) the critical emissions flux e_{crit} and (b) the critical percentage of a region's area.

(a) The critical level of emission flux e_{crit} (the pollutant burden) was derived in three steps: In the first step, we selected a value for e_{crit} and calculated the percentage of a region's area where this value is exceeded by the regional emissions of one year. This procedure was repeated for several values of e_{crit} for the regional emissions of Asia and Europe between 1990 and 2100.

For the second step, we employed the critical load concept, since it is a widely accepted measure for the impact of SO_2 depositions on forest ecosystems. It was used to calculate the percentage of area where the critical loads are exceeded for the same emissions of Europe and Asia as under step one. These data were available from Posch *et al.* (1996) who used the RAINS Europe and the RAINS Asia model (Alcamo *et al.*, 1990 and Foell *et al.*, 1995) to carry out these calculations.

In the third and final step, we compared the areas where the different e_{crit} values were exceeded with those areas where the critical loads were exceeded (see Figure 8). We selected that emission flux as a critical flux that gave the best agreement between the area where this emission flux was exceeded and the area where the critical loads were exceeded for the same regional emissions. If we select an e_{crit} value of e.g. 1.5 g S/m² we find in Figure 8 that this emission flux is exceeded on 19% of the area of Europe and that the critical loads are exceeded on 21% of the area for the same regional emissions. We found that for Europe as well as for Asia e_{crit} values between 0.5 and 1.5 g S/m² gave the best agreement in exceedance areas.

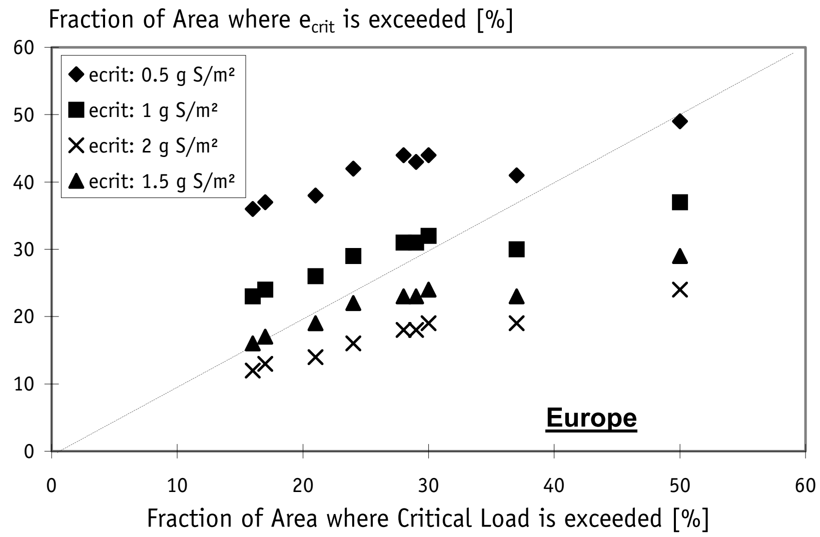

Figure 8: Estimation of the critical emission flux e_{crit} from critical loads for Europe.

(b) The critical area of a region that leads to the beginning of policy measures was derived from the time when the industrialized regions became aware of the problem of ecosystem damage caused by SO_2 emissions. From the regional emissions of this year and the e_{crit} value derived under (a) we calculated the critical areas for the industrialized regions. Since a number of industrialized countries already took policy measures to deal with the impacts of SO_2 emissions, we get a range of critical areas which can be used to determine the starting point of policy actions in developing countries.

3. Time Lag Between the Start of Policy Measures and the Beginning of SO_2 Emission Reductions

Between the time when policy makers become aware of the problems caused by SO_2 emissions and the commencement of emission reductions, there is often a lag time. This was noticed e.g. in Europe: At the Stockholm Conference on the Human Environment (1972), the problem of acidification of ecosystems was taken up in an international policy context for the first time. Thirteen years passed by before the First Sulfur Protocol came into force in 1985 with binding reduction commitments. This time is considered in the Pollutant Burden approach by introducing a lag time between the time when the critical area of a region is exceeded and the beginning of reduction measures.

4. Rate of Emission Reductions

Once emission reductions begin in a region, these reductions are assumed to follow a logistic trend over the long run. The rate of this logistic trend is estimated from current trends in industrialized regions.

SO_2 Emission Scenarios for Industrialized Regions

Somewhat different assumptions are required about the start time and speed of emission reductions in industrialized regions because they have already begun reducing emissions.

Their current policies to reduce emissions were assumed to continue over the long run by extrapolating their reduction trend with a logistic function.

Since all parameters in this analysis (the critical pollutant burden, the critical area, the lag time and the rate of emission reductions) are highly uncertain, we used probability distributions instead of discrete numbers to describe them. Moreover, in this analysis we also took into account the uncertainty of future population and economic growth, and its effect on estimated emissions. These input uncertainties were combined and propagated through the IMAGE Energy-Industry emissions model by using stochastic simulation. The result of this simulation are probability distributions for the long-term trends of SO_2 emissions in each of 13 world regions of the IMAGE model.

In Table 3 we present the estimates of the 95th percentile[3] (hereafter called "PB-95% SO_2" scenario) and the 5th percentile ("PB-5% SO_2" scenario) for these 13 regions for selected years. In Figure 9 we show the mean, the 95th percentile, and the 5th percentile of global SO_2 emissions in comparison to the standard case of constant SO_2 emissions after 1990.

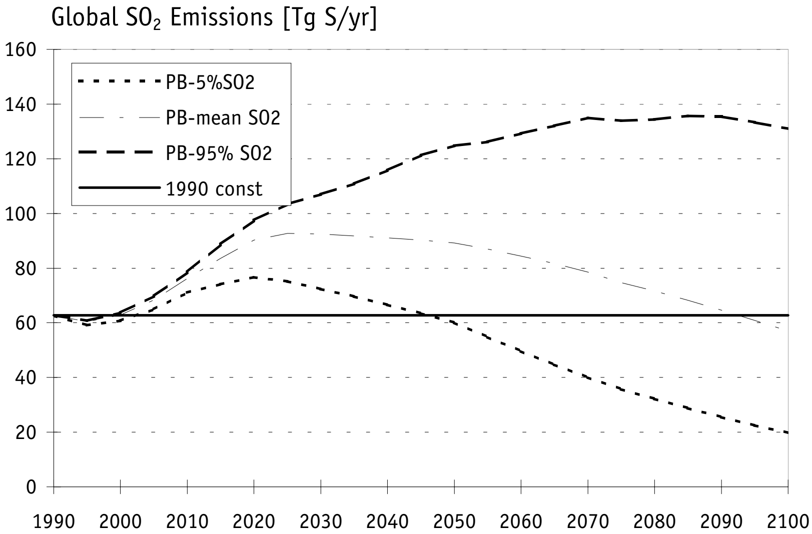

Figure 9: Global sulfur emission pathways resulting from the Pollutant Burden approach in comparison to the assumption that emissions remain constant at the 1990 level.

From Figure 9 it becomes obvious that the SO_2 emission trend, especially in the first half of the 21st century, is strongly underestimated by the assumption that emissions remain constant after 1990. Even the "PB-5% SO_2" scenario shows an increase from 62.7 Tg S per year in 1990 to 76.7 Tg S per year (or 122% of 1990 emissions) in 2020. This is important to note since such increasing SO_2 emissions may compensate somewhat for the increase in radiative forcing caused by increasing greenhouse gas emissions. This strong increase of

[3] Under the given assumptions 90% of the future SO_2 emission pathways lie between the 5 percentile and the 95 percentile. Only 10% of all emission pathways are above or below these values.

emissions continues for the ”PB-95% SO_2” scenario up to 131 Tg S in 2100. The ”PB-mean SO_2” and ”PB-5% SO_2” scenario, however, start to level off around 2020. They reach 19.8 Tg S and 57.0 Tg S in 2100 for the ”PB-5% SO_2” and the ”PB-mean SO_2” scenario, respectively.

On the regional scale, this approach results in a mean estimate of 13.8 Tg S per year of emissions for China plus Centrally Planned Asia (as compared to emissions of 11.6 Tg S per year in 1990), with a 90% confidence interval of 3.9 to 40.4 in 2100 (Figure 10a). The mean estimate levels off and begins to decline around 2020. For Western Europe, the mean estimate for 2100 is 0.4 Tg S per year (compared to 9.0 Tg S per year in 1990) (Figure 10b). The 90% confidence interval is very small for this region, as is the case for all regions with SO_2 reductions before 1990. This is due to the fact that the main uncertainty of this analysis, namely the point in time when emission reductions begin, is not relevant for these regions.

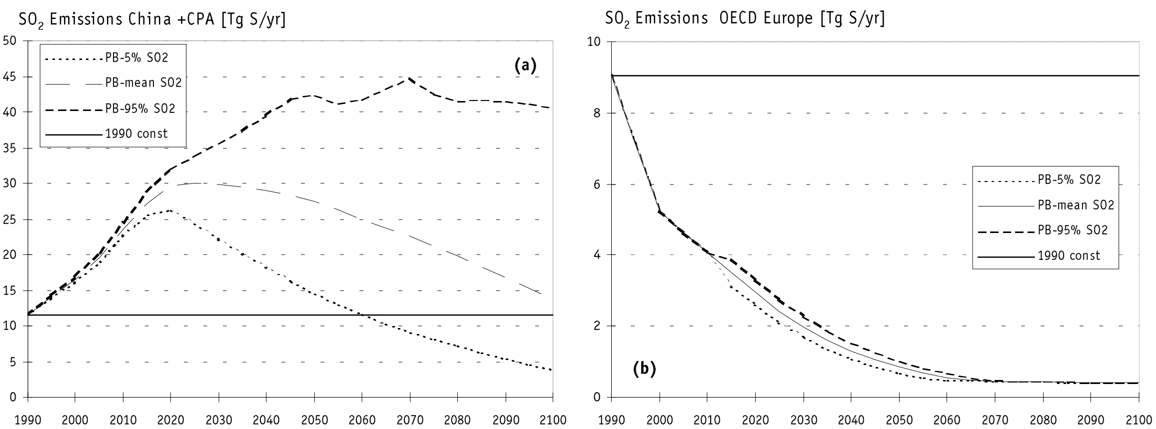

Figure 10: Regional sulfur emissions for (a) China plus Centrally Planned Asia and (b) Western Europe.

This approach has the advantage of explicitly taking into account one of the driving forces that stimulate policies (the burden of pollutants onto a country), as well as the change in these forces over time in developing regions. It also provides confidence intervals of future emissions which represent some of the uncertainties of making long-term estimates. The major disadvantage is that it assumes that all societies respond similarly to high levels of sulfur emissions.

*Table 3: R*egional sulfur emissions (in Tg S) of selected years under the ”PB-95% SO_2” and ”PB-5% SO_2” scenario resulting from the Pollutant Burden approach.

IMAGE region	**PB-5% SO_2 Scenario**				**PB-95% SO_2 Scenario**		
	1990	**2010**	**2050**	**2100**	**2010**	**2050**	**2100**
Canada	1.44	1.26	0.43	0.13	1.26	0.59	0.23
USA	10.88	7.51	1.68	0.56	7.51	2.63	0.58
Latin America	3.50	5.21	12.73	2.75	5.37	14.17	14.43
Africa	2.38	3.42	9.29	4.94	3.66	16.14	31.52
OECD Europe	9.04	4.07	0.68	0.40	4.07	1.02	0.42
Eastern Europe	5.27	3.06	0.68	0.52	3.06	1.03	0.69
CIS	10.60	7.55	4.08	1.38	11.15	12.32	9.58
Middle East	2.38	3.79	4.90	1.55	4.23	10.63	10.35
India & S. Asia	1.94	5.19	6.12	1.88	5.62	13.06	10.30
China & CP Asia	11.61	22.49	14.60	3.89	24.48	42.34	40.47
East Asia	2.33	5.26	4.14	1.62	5.67	9.17	11.16
Oceania	1.05	2.12	0.59	0.10	2.32	1.58	1.13
Japan	0.16	0.08	0.09	0.08	0.09	0.12	0.15
World	62.58	71.01	60.01	19.80	78.49	124.81	131.00

For the main purpose of this report, namely to estimate the climate change impacts of stabilization scenarios, we use only the ”PB-95% SO_2”and the ”PB-5% SO_2” estimate of regional sulfur emissions. We note here that the pollutant burden approach does not take into account the expected connection between future trends in greenhouse gas and SO_2 emissions. This is important because the stabilization scenarios imply global reductions of greenhouse gas emissions which will be at least partly initiated by reducing energy consumption and changing fuel mixes. Hence, greenhouse gas emission mitigation will probably also result in a reduction of sulfur emissions as a positive side effect. But unfortunately, up to now there is a lack of quantitative information of how strong this effect could be. The climate change impact results assuming different SO_2 emissions should therefore be seen as a sensitivity analysis. However, in the context of stabilization scenarios, the ”PB-5% SO_2” emission scenario seems to be much more likely than the ”PB-95% SO_2” emission scenario. In order to make the results of this study, however, comparable to other studies we use the SO_2 emission scenario with constant SO_2 emissions after 1990 as a standard case.

3.3 CO_2 Equivalent Concentrations and Resulting Emissions: Starting Point for the Analysis of Emission Mitigation and Climate Change Impacts

From the prescribed CO_2 concentration pathways and the assumptions we made for the emissions of non-CO_2 gases (CH_4 and N_2O) from the energy/industry and the land-use sector (see chapter 3.2), we obtain the CO_2 equivalent concentration pathways for the 450 ppm and the 550 ppm CO_2 stabilization target. The concentration pathways of these scenarios and of the Kyoto scenario are shown in Figure 11a.

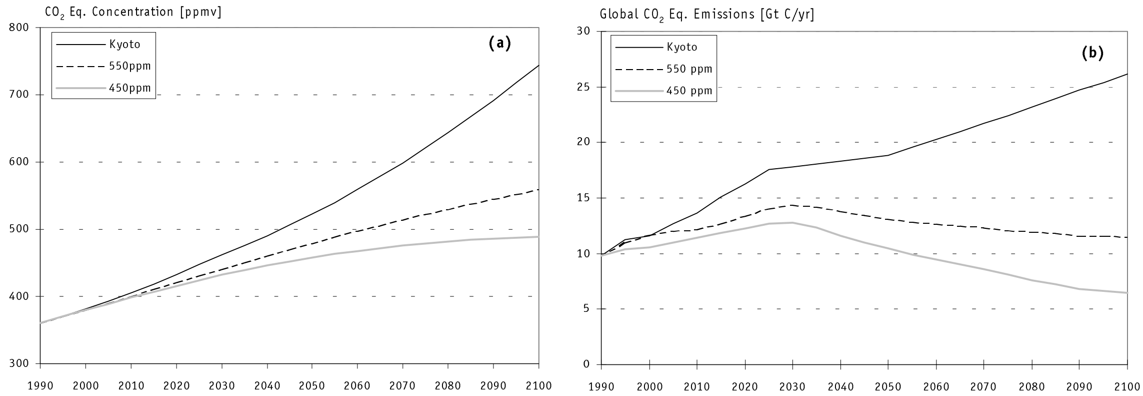

Figure 11: (a) Atmospheric CO_2 equivalent concentration of the 450 ppm and 550 ppm CO_2 stabilization targets and the Kyoto reference scenario. (b) Global CO_2 equivalent emission pathways complying with the CO_2 stabilization targets of 450 ppm and 550 ppm. The high scenario shows global CO_2 equivalent emissions resulting from the Kyoto Scenario.

Under the assumptions specified for non-CO_2 greenhouse gases, the 550 ppm and 450 ppm CO_2 stabilization scenarios lead to an atmospheric CO_2 equivalent concentration of 560 ppm and 490 ppm in the year 2100, respectively. For the ”Kyoto” scenario the CO_2 equivalent concentration increases up to 744 ppm in 2100. Thus, CH_4 and N_2O emissions add an additional 40 ppm for the 450 ppm scenario, 43 ppm for the 550 ppm scenario (517 ppm in 2100) and 54 ppm for the Kyoto scenario to the prescribed CO_2 concentration pathways. The trend for CO_2 equivalent concentrations, however, remains the same as for the CO_2 concentration pathways alone: The 450 ppm scenario stabilizes in 2100, the 550 ppm scenario still shows a slight increase and the Kyoto scenario a strong increase of CO_2 equivalent concentrations in 2100.

The global CO_2 equivalent emission pathways for both stabilization scenarios show an increasing tendency until 2030 (see Figure 11b). Between 2030 and 2100 emissions have to decrease to a level slightly above the 1990 level for the 550 ppm scenario (11.5 Gt C per year or 117% of 1990 emissions) and to about half the 1990 emissions for the 450 ppm scenario (6,5 Gt C per year or 66% of 1990 emissions). If climate negotiations brought about no further reduction targets than those agreed on in Kyoto, CO_2 equivalent emissions could rise to about 26.2 Gt C in 2100.

3.4 Summary and Conclusions

In order to perform an impact analysis of stabilization scenarios, it is necessary to consider the global emission and concentration pathways of all relevant GhGs. From the six gases covered by the Kyoto Protocol the anthropogenic emissions of CO_2, N_2O and CH_4 together account for 90% of current total GhG emissions. From these gases, CO_2 emissions, mostly from the energy/industry sector, play the most important role (60%), followed by CH_4 and N_2O emissions which together account for 30% of all GhG emissions. Within this study, emissions of the three gases CO_2, N_2O and CH_4 from energy/industry as well as from land use are covered.

CO_2 Emissions

Global allowable CO_2 emissions are computed in an inverse mode from the prescribed CO_2 concentration pathways of the IPCC model exercise described in Enting *et al.* (1994). In order to achieve a long term stabilization of the atmospheric CO_2 concentration at 550 ppm CO_2 emissions may increase to 148% of 1990 emissions in 2030. Towards 2100 emissions have to be decreased to 107% of the 1990 emissions level. However, a further emission mitigation might be necessary after 2100, since a stabilization at 550 ppm will not be reached before 2150. For the 450 ppm stabilization target, stricter emission reductions are necessary from the very beginning: Emissions may reach a maximum of 128% of 1990 emissions in 2030 and then have to be reduced to 44% of 1990 emissions. In contrast to the 550 ppm stabilization target, a stabilization of the atmospheric CO_2 concentration at 450 ppm will be reached within the time frame of the scenario (1990-2100).

N_2O and CH_4 Emissions

For global N_2O and CH_4 emissions from the energy/industry sector we assumed mitigation measures proportional to CO_2 mitigation, whereas emissions from the land-use sector follow the IMAGE Baseline A scenario. Total global N_2O and CH_4 emissions (the next most important GhGs after CO_2 if we exclude water vapor and O_3) are computed to reach a maximum around 2030 and to slightly decrease afterwards under both the 450 ppm and the 550 ppm stabilization scenario. Nevertheless, in 2100 N_2O and CH_4 emissions stay significantly above their 1990 level for both stabilization scenarios. This is because CH_4 and N_2O emissions from land use (1) significantly contribute to total CH_4 and N_2O emissions over the whole scenario period and (2) are assumed not to be reduced in the stabilization scenarios. The consequence is that <u>increasing</u> N_2O and CH_4 land-use emissions compensate for the assumed <u>reductions</u> in emissions from the energy/industry sector. Land-use emissions of these gases make up 90% of total N_2O and CH_4 emissions in 2100 for the 450 ppm scenario. In the 550 ppm scenario, CH_4 and N_2O land-use emissions contribute up to 80% of the total emissions of these gases. These numbers underline the importance of considering N_2O and CH_4 emissions from the agricultural sector in future emission control strategies.

CO_2 Equivalent Emissions

The trend of global CO_2 equivalent emissions (CO_2, N_2O and CH_4), resulting from the prescribed CO_2 concentration pathways and the assumptions we made about non- CO_2 GhGs, resembles the global trend of CO_2 emissions. CO_2 equivalent emissions may increase up to 2030 and have to decrease towards 2100 for both stabilization scenarios. For the 450 ppm scenario, CO_2 equivalent emissions have to be reduced to a level of 66% of

1990 emissions. By contrast, for the 550 ppm scenario, the emissions must also be reduced after 2030 but may stay at 117% of their 1990 level. However, it is worthwhile to mention that emission reductions are partly postponed to a later point in time because this scenario assumes that GhG concentrations will not be stabilized until 2150.

SO_2 Emissions

Sulfur dioxide emissions have the potential to partly compensate for the effects of greenhouse gases on the regional scale. In order to take this fact into account in the evaluation of regional impacts of climate change we developed the so-called ”Pollutant Burden” approach (PBA). The PBA provides future SO_2 emission scenarios for the 13 regions of the IMAGE model. The two basic assumptions of this approach are: (1) Developing regions will begin to reduce their SO_2 emissions when their ”pollutant burden” reaches the same magnitude as the pollutant burden of industrialized regions when they began to reduce their emissions. (2) Once emission reductions begin in a developing region they proceed in a speed similar to that observed in industrialized regions. The obtained SO_2 emissions show a significantly different trend for industrialized regions and developing regions. Whereas the SO_2 emissions of most developing regions strongly increase up to 2030 and then start to level off or decrease, the SO_2 emissions of industrialized countries continue their decreasing trend and end at 4 to 10% of their 1990 emission levels in 2100. Hence, the frequently used reference case of constant SO_2 emissions after 1990 (e.g. Houghton *et al.*, 1997) tends to underestimate the SO_2 emissions in developing regions and strongly overestimate the SO_2 emissions in industrialized regions. Computing region-specific trends of SO_2 emissions can therefore greatly improve the evaluation of regional impact levels of climate change.

4. Global and Regional Emission Mitigation

In the Kyoto Protocol the necessity for a reduction of not only CO_2 emissions but all anthropogenic greenhouse gas emissions has already been recognized. Article 3.1 calls for emission reductions of a total of six gases but makes no statement about the control of specific greenhouse gases from specific sources. Therefore the following analyses of emission mitigation, necessary to achieve a stabilization of GhG concentrations in the atmosphere, are based on total CO_2 equivalent emissions of CO_2, N_2O and CH_4 from the energy/industry sector as well as from land-use. We start with an analysis of emission reductions that are necessary on the global scale. In a second step we allocate global allowable emissions to Annex B and non-Annex B regions taking into account the principle of the Climate Convention that the climate system should be protected "...on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities" (UNFCCC, Article 3).

4.1 Global Emission Mitigation

To achieve a stabilization of atmospheric GhG concentrations on the prescribed concentration pathways global GhG emissions may increase up to the year 2030 as already shown in chapter 3.3 (Figure 11b). The rates of change calculated from these global emissions (see Figure 12), however, show that emission reduction measures have to be taken earlier: Emissions of the stabilization scenarios may increase significantly more slowly than emissions of the Kyoto reference scenario. The increase of emissions is reflected by a positive rate of change in Figure 12, which remains below 1% per year for the two stabilization scenarios. For the Kyoto scenario, global emissions increase at a rate of 1.5% per year and higher between 1990 and 2030. After 2030 emissions still increase, but at a lower rate of about 0.5% per year. In contrast, strong reduction efforts are necessary after 2030 for the two stabilization scenarios. Global emissions have to decline at a rate of 1 to 1.5% per year under the 450 ppm scenario and at a rate of about 0.5% per year under the 550 ppm scenario. This trend in emission reductions has to be continued until the end of the 21st century. Hence, in order to stabilize the atmospheric GhG concentration on the prescribed concentration pathways, emission control measures have to be taken throughout the entire simulation period.

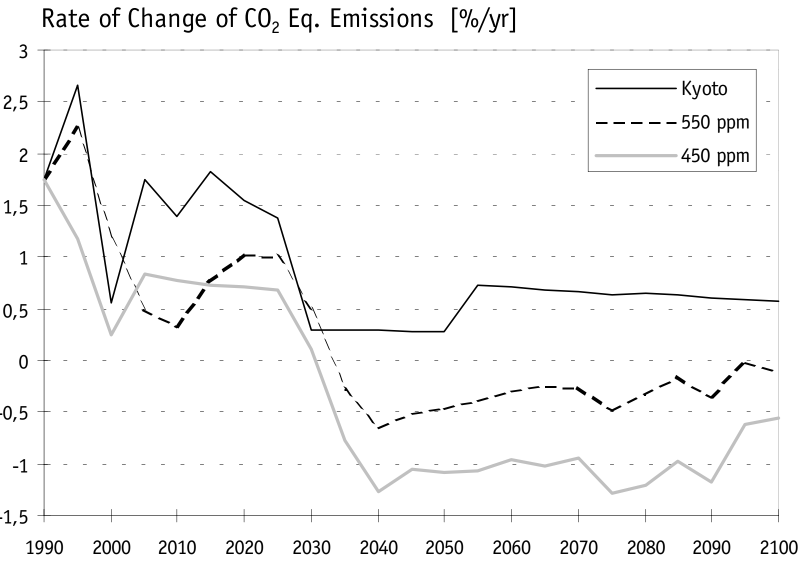

Figure 12: Rate of change of global anthropogenic equivalent CO_2 emissions necessary to achieve a CO_2 stabilization at 450 ppm and 550 ppm (compared to the Kyoto reference scenario).

4.2 From Global Emission Mitigation to Regional Emissions: Combining Burden Sharing and Climate Protection

The climate summits in Kyoto and Buenos Aires achieved some tentative first steps for international climate protection. An important question, however, that was left open by both summits was the issue of strategies that are necessary for long-term climate protection and their consequences on emission reduction commitments for both industrialized and developing countries. This question was later given high priority at the 6th International Workshop on "Using Global Models to Support Climate Negotiations", in Kassel, Germany (see Onigkeit *et al.*, 1998) and is addressed in this chapter. The purpose of this chapter is to present an approach that combines the question of stabilization targets with the question of allocation of GhG emissions. We use this approach to evaluate the implications of two different stabilization targets on the allocation of emission reductions in non-Annex B and Annex B countries. This allocation is based on two indicators that reflect considerations of capability and equity. Why is the allocation of emissions an issue for industrialized countries and developing countries? First of all, according to the Berlin Mandate and Kyoto Protocol, most industrialized countries are required to begin reducing their greenhouse gas emissions. Some have argued that this is justified because of their high level of per capita emissions and their historical contribution to climate change. On the other hand, results of our analyses of stabilization scenarios have shown that many climate targets require significant reductions in global emissions (see chapter 4.1) that would be virtually impossible for Annex B countries to achieve alone. One reason is that greenhouse gas emissions from developing countries are expected to increase substantially (Alcamo *et al.*, 1995). In response to this situation, we present here an approach that can help identify strategies for both long-term climate protection, and for sharing the burden of emission reductions between Annex B and non-Annex B parties. This approach is one of the first attempts to combine climate protection and burden sharing with indicators for equity and capability in a single analysis. In this paper we apply this approach to the two CO_2 stabilization targets of 450 ppm and 550 ppm, taking into account CO_2, CH_4 and N_2O emissions from the energy/industry sector as well as land-use emissions.

4.2.1 The Burden Sharing Concept

The main idea behind the proposed burden sharing scheme is that emissions of non-Annex B parties are allowed to increase without mitigation measures until these countries reach a specified income level (the so-called graduation criterion). Above this level, developing countries are expected to participate in international emission regimes. In principle, the graduation income level is set high enough so that developing countries will have a sufficiently high national income so that they can afford to control their emissions. The first step in participating in international regimes is to freeze emissions, and the second is to reduce emissions.

In the following paragraphs, we specify the rules for allocating global emissions between Annex B and non-Annex B countries. For this allocation, a baseline emissions pathway and an economic growth scenario are needed for each non-Annex B country or group of countries. A population scenario is required for both Annex B and non-Annex B countries since the allocation of emissions is carried out on a per capita basis.

Procedure for Setting Climate Protection Goals and Allocating Emissions

1. *Pathway of global emissions:* A stabilization target for the atmospheric CO_2 concentration is first specified; then the global emissions that comply with this stabilization target are computed. If the analysis is based on CO_2 equivalent emissions, additional assumptions must be made for non-CO_2 greenhouse gas emissions.
2. *Non-Annex B emissions up to and after the graduation income level.* Emissions from non-Annex B regions are not controlled until their income reaches the graduation income level. Up to this point they follow their baseline emission pathway. After the graduation level is reached, emissions are frozen until non-Annex B per capita emissions are equal to the average of Annex B emissions.
3. *Non-Annex B emissions equal Annex B emissions*: When the per capita emissions of the non-Annex B region converge with the average per capita emissions of Annex B countries, then they both follow the same per capita emissions pathway (see Figure 13). The non-Annex B party then joins an "Extended Annex B" group and must commence emission reductions.
4. *Annex B total emissions.* The emissions from Annex B are computed to be the global emissions from step 1 minus the total of all non-Annex B emissions. After this step, the total emissions of non-Annex B countries consist partly of baseline emissions (for those non-Annex B countries that did not yet meet the graduation criterion) and partly of

controlled non-Annex B emissions.

These calculations are performed iteratively for each of the non-Annex B countries and the average of all Annex B regions for each time step.

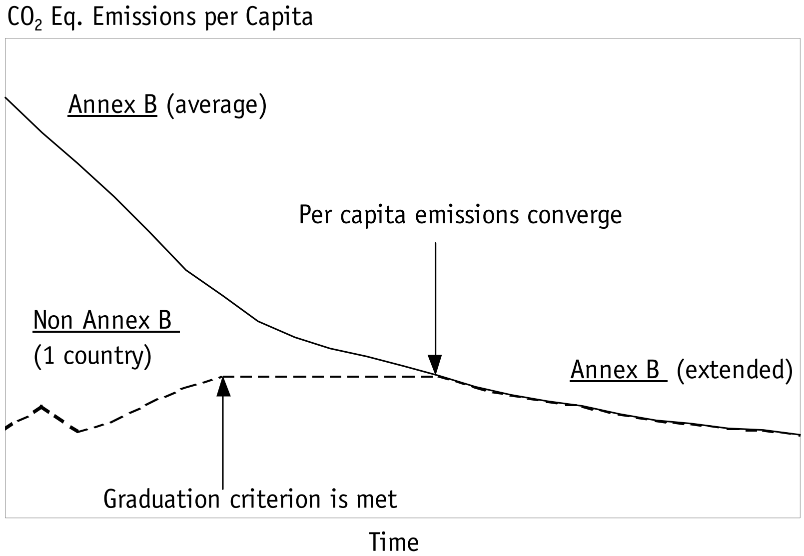

Figure 13: Illustration of the burden sharing concept: Presented is the per capita emissions pathway of one non-Annex B country and the averaged Annex B per capita emissions.

Some Characteristics of the Burden Sharing Approach

1. Allowable emissions of Annex B are derived by subtracting total emissions of non-Annex B from the total global emissions. Since the global emissions are prescribed by the stabilization target, the Annex B emissions only depend on the total amount of non-Annex B emissions. Therefore, the higher these emissions rise the lower are the allowable emissions for Annex B. Since, the distribution of emissions presented is based on per capita emissions, the total of non-Annex B emissions is proportional to the population of non-Annex B countries. Therefore, it is advantageous to Annex B countries that non-Annex B countries with large and fast growing populations join the Annex B group as early as possible.
2. If we assume that a non-Annex B country has to reach a high per capita income (high graduation criterion) before it must become active in a climate protection regime this non-Annex B party is likely to follow the baseline emissions pathway for a longer time compared to the case of a lower graduation criterion. The price this region has to pay is the need for more rapid reductions of per capita emissions after convergence (see *Figure 14*). The decision for a low criterion leads to earlier participation in emissions controls but to less stringent annual reduction rates in the longer term.
3. Selecting a stricter stabilization target (e.g. 450 ppm CO_2 in the atmosphere instead of 550 ppm) results in a lower global emissions pathway. In this case, stricter emission reductions are required for Annex B countries, since baseline emission profiles of non-

Annex B parties remain the same. The consequence for non-Annex B parties is that their per capita emissions sometimes converge with the per capita emissions of Annex B countries before they (the non-Annex B parties) reach the graduation income level. Hence, the "grace period" of constant per capita emissions is omitted and their first action must be a reduction of per capita emissions.

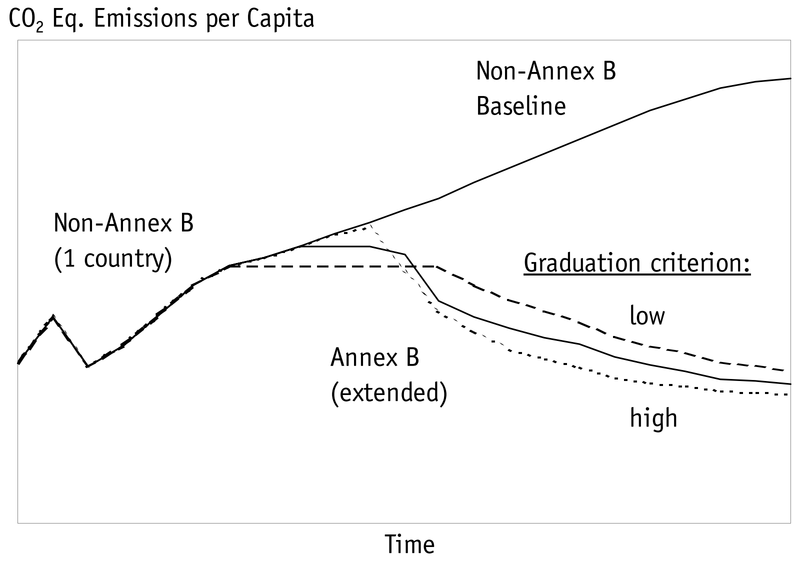

Figure 14: Illustration of the implications of different graduation criteria. A high graduation criterion stands for a high percentage of Annex B average GDP per capita in 1990 (e.g. 100%) and vice versa.

4.2.2 Application of the Burden Sharing Concept

The implications of the burden sharing rules for the distribution of global emissions between Annex B and non-Annex B was evaluated for two stabilization targets: (1) Stabilization of the atmospheric CO_2 concentration at 550 ppm, a target which is under discussion in the European Union and (2) a stricter target of 450 ppm. The following assumptions were made for this analysis:

1. The burden sharing analysis was performed for the six non-Annex B regions of the IMAGE 2.1 model (see Alcamo *et al.*, 1998a) whereas the seven Annex B regions of the model were aggregated to one region.
2. Population for both Annex B and non-Annex B regions increase according to the IPCC medium scenario IS92a (Alcamo *et al.*, 1998b).
3. Economic growth of the non-Annex B regions is based on IPCC scenario IS92a assumptions.
4. The baseline emissions of the non-Annex B regions originate from the Baseline A scenario of the IMAGE model. In this scenario population growth and economic growth assumptions of IS92a have been implemented (Alcamo *et al.*, 1998b). We included CO_2, CH_4 and N_2O emissions from both energy/industry and land use.

5. As a graduation criterion we use different percentages of the average per capita income of Annex B countries in 1990. Around this year the Annex B countries declared their intention to take action for climate protection (Earth Summit in Rio, 1992). It seems therefore appropriate to take the economic strength of Annex B countries in this year as a measure for the capability of non-Annex B countries to initiate emission controls.

4.2.3 Per Capita Emissions Resulting from the Burden Sharing Concept

The global emissions between 1990 and 2100 that are allowed to reach the specified stabilization targets (see chapter 3.3) were distributed year by year on a per capita basis between Annex B and non-Annex B regions following the specified rules (see Figure 15). We present the implications of two different graduation income level criteria for non-Annex B regions: They must freeze their per capita emissions when their per capita income equals (1) 10% and (2) 100% of the Annex B average per capita income in 1990.

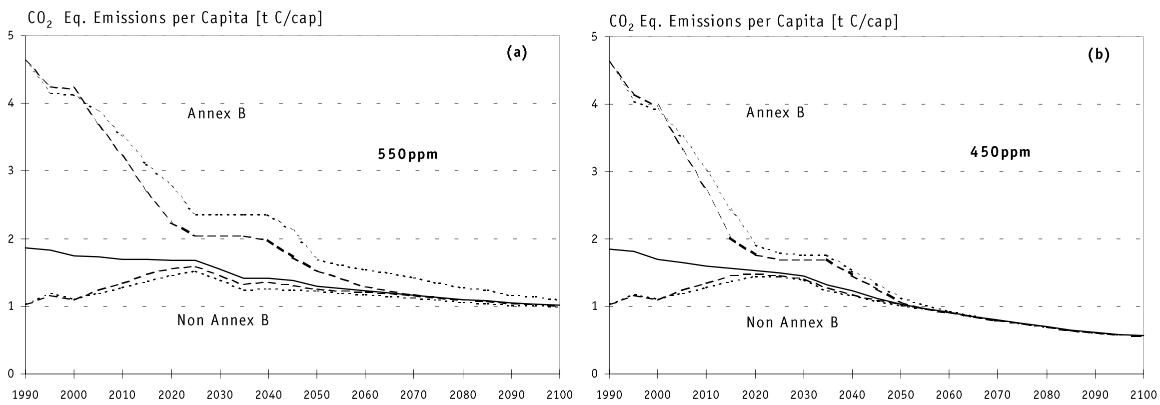

Figure 15: Application of the burden sharing concept to two CO_2 stabilization targets: (a) 550 ppm and (b) 450 ppm. Depicted are the pathways of average annual per capita emissions (CO_2 equivalent) of Annex B and non-Annex B regions. The short-dashed line shows results for the specified graduation criterion of 10% of Annex B average GDP/cap. The long-dashed line shows results for the higher criterion – 100% of Annex B average GDP/cap. The solid line gives the global annual average per capita emissions.

The average per capita emissions of Annex B start at an emissions level in 1990 that is more than twice the average of global per capita emissions (see Figure 15). According to the specified rules and the underlying assumptions for population growth and economic growth, Annex B per capita emissions have to decrease to 22% and 12% of their 1990 level until 2100 for the 550 ppm and 450 ppm stabilization scenarios, respectively (Figure 15). A reduction rate of 2% to 3% per year is needed between 1990 and 2030 for the 550 ppm and 450 ppm target, respectively. After 2030 reduction rates decline to about 0.75 and 1% per year because of an increasing participation of non-Annex B regions, but reductions must continue. The stringent reductions required for Annex B per capita emissions is caused by three factors: (1) the concentration targets, (2) the growing population and per capita emissions in non-Annex B countries, and (3) the growing population in Annex B regions.

The average of non-Annex B per capita emissions starts at a level half of the global average per capita emissions in 1990 and may therefore increase by about 50% up to 2025. After 2025 per capita emissions must decline to reach their 1990 level again by 2100 under the 550 ppm scenario (compare Figure 15). For the 450 ppm case, per capita emissions must sink substantially below this level by 2100 to 54% of their 1990 emissions. Hence, although Annex B per capita emissions are considerably reduced under both stabilization scenarios, the average of non-Annex B per capita emissions may never exceed the globally averaged per capita emissions which are decreasing to about half of their 1990 level or lower. It should, however, be kept in mind that the per capita emissions of some non-Annex B regions may in fact rise above the globally-averaged per capita emissions or even start above this level in 1990.

Varying the graduation criterion has a bigger impact on Annex B per capita emission reductions under the 550 ppm stabilization scenario than under the 450 ppm scenario. This is due to the slower reduction of Annex B per capita emissions between 1990 and 2020 in the 550 ppm scenario. In the 450 ppm scenario it makes no difference for many of the non-Annex B regions whether the graduation criterion is high or low because their emissions equal Annex B emissions before they meet the graduation criterion. They are, thus, not allowed to go through a stage of frozen per capita emissions but have to reduce emissions as their first action. It should be noted that for graduation criteria between 10% and 100%, emission pathways do not necessarily lie between the two presented profiles. Instead, these pathways will be equally influenced by the assumed GDP/cap growth rate for non-Annex B countries; these growth rates will determine when the different non-Annex B countries reach the graduation income level, and when they will freeze their emissions

4.2.4 Total Emissions of Annex B and Non-Annex B Regions

The total CO_2 equivalent emissions of Annex B and non-Annex B regions resulting from the application of the burden sharing concept are depicted in Figure 16.

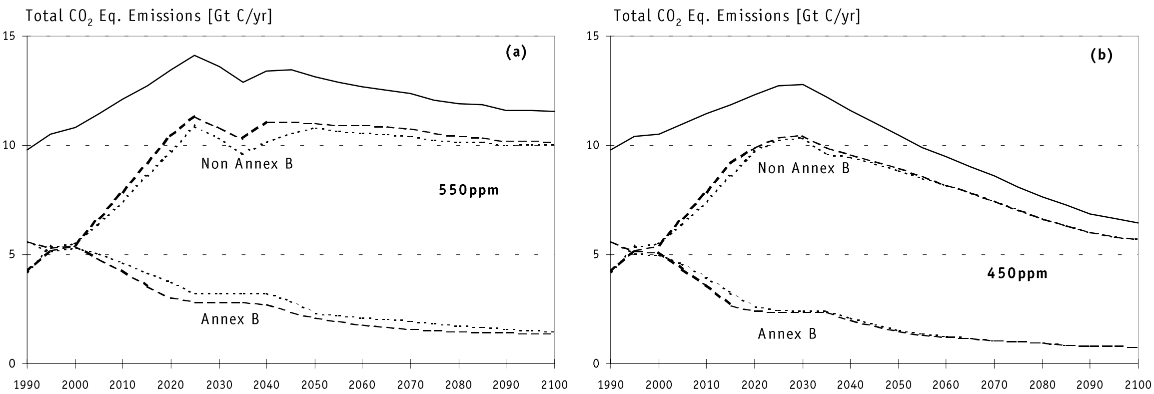

Figure 16: Total CO_2 equivalent emissions of Annex B and non-Annex B compared to allowable global emissions for the two stabilization targets of (a) 550 ppm and (b) 450 ppm CO_2. The short-dashed line represents a graduation criterion of 10% of Annex B average GDP/cap in 1990, and the long-dashed line a higher criterion of 100%.

From the per capita emissions obtained in chapter 4.2.3 and the assumptions of the IPCC IS92a population scenario, it follows that non-Annex B total CO_2 equivalent emissions are allowed to more than double up to 2030 for both stabilization scenarios (compare Figure 16). Afterwards, emissions slowly decrease for the 550 ppm scenario reaching 234% of 1990 emissions in 2100. For the 450 ppm scenario the picture looks somehow different: Non-Annex B emissions have to be sharply reduced reaching 136% of 1990 emissions in 2100.

From the emission pathway of the non-Annex B regions and the prescribed global emissions, it follows that Annex B total CO_2 equivalent emissions must be halved by 2030 under both stabilization scenarios. Further reductions to 25% and 14% of their 1990 emissions level are necessary up to 2100 under the 550 ppm and the 450 ppm scenarios, respectively (compare Figure 16). These reduction requirements might seem very high but, firstly, they are delayed over more than 100 years and, secondly, we did not consider the so-called Flexibility Mechanisms (e.g. the Clean Development Mechanisms) which are discussed to make emission reduction efforts of Annex B countries more cost effective.

A variation of the graduation criterion between 10% and 100% of the Annex B average 1990 per capita income makes a difference of about 0.1 Gt C and 0.4 Gt C equivalent total emissions per year for the 450 ppm and 550 ppm scenarios, respectively. The fact that all non-Annex B regions may only emit an additional 0.1 Gt C per year when the 100% criterion is chosen over the 10% criterion in the 450 ppm scenario reflects the relatively stronger efforts that have to be taken by both Annex B and non-Annex B countries under such strict stabilization target.

4.3 Summary and Conclusions

Mitigating Global Emissions

To achieve a stabilization of the atmospheric CO_2 concentration on the prescribed concentration pathways, global emissions may increase up to 2030. Nevertheless, emission controls are necessary from the very beginning. To obtain global emission reduction rates lower than 0.5% per year over the long term, emissions may not increase by more than 1% per year over the medium term for the 550 ppm concentration pathway. It should be mentioned, however, that for the 550 ppm scenario, a stabilization is not yet reached in 2100, and that therefore stronger reduction efforts might be necessary after 2100. For the 450 ppm stabilization scenario the increase of emissions must stay below 1% per year in the medium term in order to achieve long-term reductions between 1 and 1.5% per year.

Mitigating Regional Emission – Examples of Burden Sharing Scenarios

In order to obtain a first estimate of what these global reduction rates could mean for emission control measures in different regions, we developed a procedure to distribute allowable global emissions between non-Annex B and Annex B regions. This procedure is based on two principles: (1) Due to their historical contribution to climate change and their high level of per capita emissions, Annex B countries must start with emissions reductions at once. (2) Non-Annex B countries have to stabilize emissions when they reach a certain income level (a so-called "graduation" criterion) and must start reducing emissions when their per capita emissions equal Annex B per capita emissions.

The overall picture we get from this approach is similar for both stabilization scenarios: Average Annex B per capita emissions start at a relatively high level and have to be reduced substantially below their 1990 emissions level until 2100, whereas non-Annex B per capita emissions start at a low level, may slightly increase over the medium range, and then must decrease again to their 1990 emission levels or even lower to achieve the 450 ppm target. However, even the relatively low per capita emissions of non-Annex B regions lead to high total emissions because of assumed future population growth. Hence, total emissions of non-Annex B more than double within the next forty years and may stay at this high level until 2100 for the 550 ppm stabilization target. For the 450 ppm target, non-Annex B emissions again can double up to 2030, but then must be halved after 2030 to reach a level slightly above 1990 emissions in 2100. Annex B regions must substantially reduce their total emissions until 2100 to a quarter or less of their 1990 emissions to achieve globally equal per capita emissions and a stabilization of atmospheric greenhouse gas concentrations at the same time.

5. Impacts of Stabilization Targets

The main objective of global climate policy is to minimize ”dangerous” impacts of future climate change on natural as well as socioeconomic systems. Regarding the evaluation of climate change impacts, this objective raises two main questions: (1) What are reasonable indicators of dangerous climate change? And (2): What is non-dangerous climate change, or what is the maximum impact level of climate change that we are able or willing to tolerate? Article 2 of the Climate Convention names two impact categories: Natural ecosystems and food production. However, the wording of Article 2 is so general that a straightforward selection and quantification of impact indicators is rather difficult.

In the following chapter we first discuss a number of indicators to make the formulation of Article 2 of the UNFCCC more concrete. Secondly, we use these indicators to evaluate the impact levels of the two stabilization targets of 450 ppm and 550 ppm CO_2 in the atmosphere.

5.1 Selection of Impact Indicators for Climate Policy

An indicator should be a comprehensive estimate of a state of a system or process. In the ideal case, environmental indicators which were developed to serve as a basis for political decisions should fulfill a number of criteria:

1. they have to be sensitive to the environmental aspect that is evaluated, and a change in the indicator value should be clearly related to the aspect that is evaluated;
2. evaluation of indicators (monitoring) should be reproducible and the results of model simulations should be robust so that policy makers can have some confidence in them;
3. they should be as simple (transparent) as possible but at the same time try to cover the complexity of the topic according to the state of the art of scientific research;
4. they should be as aggregated as possible in order to limit the number of required indicators (Leemans and Hootsmans, 1998).

This set of criteria will be used to discuss the strengths and weaknesses of the indicators we selected for the evaluation of the two stabilization targets with the IMAGE model.

Climate change is a particularly complex issue since it could affect a large number of aspects of human life. Until now, policy makers have mostly used mean global temperature as a direct indicator of the severity of climate change. However, Article 2 of the Climate Convention refers to indirect impacts of climate change such as to the threat to food production and ecosystems; also IPCC considers indirect impacts of climate change such as human health and the threat to water resources important (Watson *et al.*, 1997). In our impact analysis, we therefore have to also consider this wide spectrum of possible direct as well as indirect impacts and thus indicators. At first sight, it appears reasonable to use mean global temperature change as an indicator since temperature change (in addition to the change in precipitation) is the major cause for many of the possible impacts, and is also a direct result of the atmospheric accumulation of greenhouse gases. However it is extremely difficult to establish a relationship between such an average global temperature change and the various indirect global impacts. We, therefore, recommend to use in addition to the average global temperature change a number of additional indicators that reflect these numerous indirect impacts.

Another aspect of complexity is the spatial resolution of impact occurrence. All regions of the world will probably be affected by climate change, but whereas some regions will suffer large negative impacts, others may even benefit from climate change. Also, the vulnerability to impacts from climate change will differ greatly. Both aspects of vulnerability, the sensitivity of a region to a changing climate, as well as the capacity to adapt to such changes (e.g. changing crop types, coastal protection etc.) will be important. In conclusion, the geographical extent of the impacts is, thus, highly important in selecting the appropriate indicators. This is of particular importance since policy makers represent the interests of their own countries and are thus predominantly concerned with the negative impacts on their particular country.

Another important factor to consider in selecting appropriate indicators is the temporal resolution of indicators. Although it is easy and concise to report the global temperature change between 1990 and 2100, such a measure cannot reflect the temporal dynamics of impact occurrence, and, thus, the possibility of an environmental and/or socioeconomic system to adapt to future changing climate conditions. It is therefore important to consider the rate of change in addition to the cumulative change.

For this study, we evaluate the consequences of two stabilization scenarios and one reference scenario on the following five different impact categories: temperature change, sea level rise, crop productivity, threat to natural vegetation and threat to water availability (see Table 4). The indicators that we use for each of these impact categories are also listed in Table 4 and are described in more detail below.

Table 4: Impact categories and indicators to be analyzed for the 550 ppm and the 450 ppm stabilization scenario and the Kyoto Scenario as a reference scenario.

Impact category	Indicator
Temperature change	• Mean annual temperature increase in 2100 compared to 1990 (global) • Rate of mean temperature change per decade (global)
Sea level rise	• Sea level rise in 2100 and 2500 compared to 1990 (global) • Rate of sea level rise per decade (global)
Crop productivity	• Percentage of 1990 area with decreasing potential productivity of temperate cereals (global and regional) • Percentage of 1990 area with decreasing potential productivity of maize (global and regional) • Percentage of 1990 area with decreasing potential productivity of tropical cereals (global and regional)
Threat to natural vegetation	• Percentage of 1990 area with potential natural vegetation under risk (global and regional) • Percentage of 1990 area of nature reserves under risk (global and regional)
Water availability	• Change in mean annual runoff (watershed)

5.1.1 Temperature Change

All values of temperature change indicators presented in this report are based on the climate sensitivity of the IMAGE 2.1 model, which is 2.37°C for a doubling of the atmospheric CO_2 concentration. This sensitivity lies within the range of sensitivities (1.5-4.5°C) given by the IPCC (Houghton *et al.*, 1996). If a higher climate sensitivity is assumed, the temperature change and also the impact level will probably be higher.

The global mean temperature change is a good approximation for the severity of climate change as it is one of the main causes (in addition to the change in precipitation) of the possible threats to all natural and socioeconomic systems which form the basis for the impact indicators formulated in Table 4. It fulfills most of the criteria mentioned under 5.1. Global mean temperature change is a direct effect of the greenhouse gas accumulation in the atmosphere. Simulation model results (e.g. results of General Circulation Models (GCM)) are quite robust for globally averaged impact levels such as temperature change (Alcamo *et al.*, 1998a). Further, it is a relatively simple indicator and thus easy to communicate. However, global mean temperature change does not cover one aspect of the climate change issue that is very important to policy makers: it does not give them any insight into impact levels in those regions which they represent in the climate negotiations.

The rate of temperature change (in °C per decade) emphasizes an additionally important aspect of climate change: It is strongly related to the ability of natural as well as socioeconomic systems to adapt to climate change. High rates of temperature change will probably cause high impact levels especially in natural systems. When high rates of temperature change are sustained over longer time periods, irreversible responses can probably not be excluded. In this study we use temperature change between 1990 and 2100 and the decadal rate of temperature change as indicators.

5.1.2 Sea Level Rise

A rising sea level is likely to cause serious damage to socioeconomic systems and ecosystems in low-lying coastal areas. It particularly endangers the existence of small island states and is thus an important indicator for the severity of climate change. The IMAGE 2.1 model computes sea-level rise by taking into account the thermal expansion of the oceans, the melting of glaciers, and changes in the ice caps on Greenland and Antarctica. Not only net sea level rise between 1990 and 2100, but also the rate of sea level rise is computed here, since the adaptation to a rising sea level requires the build-up of strong protective infrastructures which is time- and money-consuming.

5.1.3 Potential Crop Productivity

The threat to food supply is explicitly mentioned in Article 2 of the Climate Convention. In the IMAGE model the potential crop productivity is calculated using a modified version of the FAO crop suitability model (Leemans and van den Born, 1994) which simulates potential productivity under rain-fed conditions. Additionally, the IMAGE version of this model considers the enhanced photosynthesis rate of plants caused by an increasing atmospheric CO_2 concentration (CO_2 fertilization effect).

We present the impacts of climate change on the potential productivity of temperate cereals, tropical cereals and maize in those areas where these crops are currently grown. The percentage of 1990 area where the potential productivity of these crops is decreasing by more than 5% below the 1990 productivity is used as an impact indicator. The potential productivity of crops is calculated from climate and soil conditions of each 0.5° x 0.5° grid cell. In the IMAGE model, we also compute an actual productivity by correcting the potential productivity with two factors which consider management measures and fertilizer use. However, since these agricultural measures are scenario-dependent and different for each region of the world, we only present impacts on the potential productivity of crops that are solely caused by changing climate conditions (see criterion 1 for climate change indicators in chapter 5.1). Additionally, we don't take into account adaptation measures such as the shift of cropping zones or change of crop varieties. This methodology has the advantage that it allows a comparison of results for different world regions over time.

In addition to the global impacts of climate change on the potential productivity of crops, we also present results on the regional level. With respect to the evaluation of results on the regional scale, however, it should be noted that the regional distribution of impacts is much more uncertain than the results for the global scale, since especially the simulation of precipitation patterns is a large source of uncertainty. Hence, the results with a higher spatial resolution could vary widely depending on the climate model that is used to obtain climate data (e.g. Rosenzweig and Parry, 1994). But as the main purpose of this study is a comparison of the impact levels of two stabilization scenarios rather than a presentation of absolute changes in potential crop productivity for one climate scenario, it seems to be reasonable to present also regional results. In this study we present results from the IMAGE-AOS climate model scaled with a GCM simulation run of the Max Planck Institute (MPI) (Cubasch *et al.*, 1992) to obtain patterns for temperature and precipitation on a 0.5° x 0.5° grid level.

5.1.4 Threat to Natural Vegetation

Article 2 of the Climate Convention requires that a change in climate is limited to a level which allows ecosystems to adapt to this change. To assess the impact of climate change on natural vegetation we use as an indicator the percentage of the current area (1990) with natural vegetation where this vegetation is threatened by climate change. It shows where the currently existing vegetation must change to another type of vegetation or where it is not able to adapt due to changing climate conditions.

Based on the 1990 vegetation cover, the IMAGE model calculates the natural vegetation which can potentially grow in these areas due to a changing climate using the BIOME model (Prentice *et al.*, 1992). The expression ”potential” natural vegetation describes the vegetation type that could potentially exist in an area depending only on soil and climate conditions whereas, in reality it also depends on additional factors, such as, for example the future demand for agricultural area or wood products. But as these demands are mainly driven by scenarios for future population- and economic growth, we use potential natural vegetation instead of the actual one as an indicator.

The IMAGE model calculates the distribution of different, highly aggregated vegetation classes depending on climate and soil characteristics by prescribing a set of minimum climate conditions that must be satisfied to allow the existence of a vegetation class in a certain area. Additionally, the model takes into account that increasing CO_2 concentration could increase the water use efficiency of plants. This is realized by lowering the minimum for the water demand so that a vegetation class can also exist in drier regions.

The IMAGE model considers 13 different types of natural vegetation which are differentiated especially with respect to their turnover of carbon. These vegetation classes are calculated on a 0.5° by 0.5° grid cell basis. If the climate conditions of a grid cell change significantly enough that the 1990 natural vegetation cannot exist anymore in this grid cell, we call it a threat to natural vegetation.

In order to evaluate the possible impacts of climate change in areas that are assigned to protect a certain type of ecosystem, we also compute the threat to natural vegetation in current nature reserves. Thus we present (1) the percentage of area of the potential natural vegetation which might be threatened by changing climate conditions and (2) the percentage of current areas with nature reserves which might be threatened by climate change.

Results for both indicators are presented on the global and the regional scale. As especially the simulation of changing precipitation patterns is highly uncertain, the results on the regional scale are more uncertain compared to the global results. The regional results should therefore be interpreted more as a scenario comparison rather than seen as absolute impact levels.

5.1.5 Water Availability

Changing precipitation and temperature patterns will have a substantial influence on the global water household. Most climate scenarios compute a global average increase in precipitation. However, they also estimate a significant regional difference in the intensity and direction of change. These climate-related changes will result in significant changes in water availability in many watersheds. Hence, water shortage as well as flooding, as the opposite extreme, will probably play an important role in global change in the coming decades. In order to estimate the effects of climate change on future water availability, we coupled the WaterGap model (Döll *et al.*, 1998, and Alcamo *et al.*, 1997a) with the climate and vegetation model of the IMAGE model. The WaterGAP model (*Water* - *G*lobal *A*ssessment and *P*rognosis) computes water use and water availability in each of 1162 watersheds covering nearly the entire terrestrial surface of the world. Although the model has been calibrated and tested against existing data it nevertheless contains many limitations in its description of water availability. On the watershed scale water availability is defined as the sum of annual river runoff and groundwater recharge in all 0.5° x 0.5° grid cells of a watershed. This is, of course, just a rough approximation of water availability, since it does not take into account the spatial variability within the watershed nor the month to month or week to week hydrologic variations On the other hand, many rivers have reservoirs which store river water from month to month, so computing the water availability over an entire year can be a reasonable first indicator of the water situation in a watershed. As such it is suited for drawing insights about likely trends in the future. (Version 2.0 of WaterGAP has been completed since completion of this analysis. The new version takes into account both spatial variability of runoff and daily hydrologic variations).

With respect to the stabilization scenarios we will present time series (1995-2100) for the river runoff of a selected number of watersheds. Since we assume that countries or societies are adapted to mean conditions for water availability and that problems arise only when the water availability strongly differs from these mean conditions we present results for 10 percentile dry year conditions which means that only in one of ten years the precipitation will be lower.

According to Watson *et al.* (1997) 19 countries around the world are currently classified as ”water-stressed”. Most of these 19 countries are in Africa so that we choose two watersheds in different parts of Africa: the Senegal and the Zambezi rivers. Additionally, we evaluate the Murray-Darling in Australia and the Guadalquivir in Spain as watersheds that are extensively used for agriculture and that already have problems in water supply. The last river we evaluate is the Rhine, an important European river.

5.2 Impact Levels of Stabilization Scenarios

The impact levels of two stabilization scenarios (450 ppm and 550 ppm) and a medium reference scenario (Kyoto scenario) were evaluated. The Kyoto scenario assumes no further emission reductions than those agreed on in Kyoto (-5.2% for Annex B regions in

2010[1]). Since sulfur emissions are expected to have a noticeable compensating effect on global warming we also evaluate the implications of the "PB-95% SO_2"[2] and the "PB-5% SO_2" emissions scenario on the impact levels of the 550 ppm stabilization scenario. Hence, we analyze five scenarios in total:

1. The Kyoto reference scenario,
2. the 550 ppm stabilization scenario with constant SO_2 emissions after 1990,
3. the 450 ppm stabilization scenario with constant SO_2 emissions after 1990,
4. the 550 ppm stabilization scenario with SO_2 emissions of the "PB-95% SO_2" scenario,
5. the 550 ppm stabilization scenario with SO_2 emissions of the "PB-5% SO_2" scenario.

SO_2 emissions of the scenarios (4) and (5) significantly differ from region to region and are therefore especially important for a regional evaluation of climate change impacts.

5.2.1 Global Impacts

Temperature Change

The accumulation of CO_2 and other GhGs in the atmosphere brings about an average increase in surface air temperature of 2.7°C between 1990 and 2100 under the Kyoto scenario (see Figure 17). For the 450 ppm stabilization scenario the global average temperature increases up to 1.2°C in 2100, and for the 550 ppm stabilization scenario the temperature increase will be 1.7°C between 1990 and 2100 if sulfur emissions are assumed to be frozen after 1990. If we take into account early and strong sulfur control policies ("PB-5% SO_2" scenario) the temperature increase in 2100 is somewhat higher at 1.8°C. For this scenario global SO_2 emissions are assumed to be about one third of 1990 emissions in 2100. However, a doubling of SO_2 emissions in 2100 compared to their 1990 level ("PB-95% SO_2" scenario) leads to a much lower temperature increase of 1.4°C in 2100. It should, however, be stressed that such high SO_2 emissions are very likely to cause substantial environmental damages which are not considered in this study.

[1] For a description of the Kyoto scenario see also chapter 2.
[2] The "PB-95% SO_2" and the "PB-5% SO_2" emissions scenario are described in chapter 3.2.4.

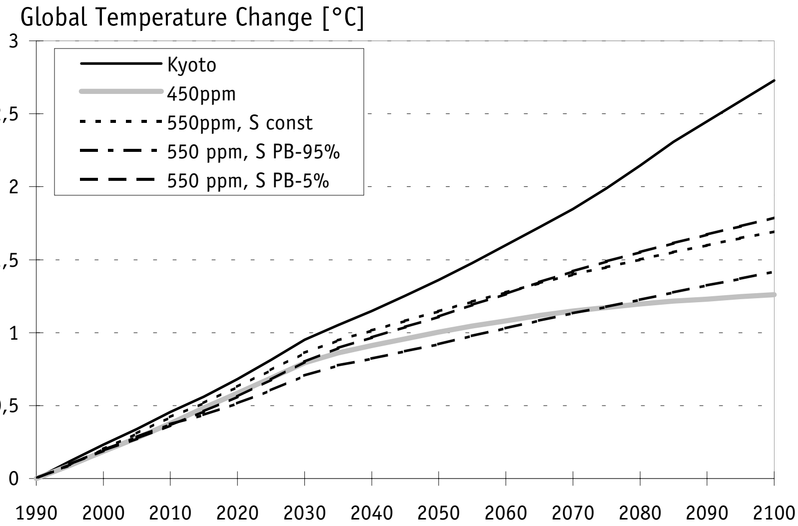

Figure 17: Global mean temperature change in 2100 compared to 1990.

For the Kyoto scenario, as well as for the two stabilization scenarios, the global mean temperature is still increasing in 2100, although the rate of increase is much smaller for the 450 ppm scenario in 2100 (0.03°C per decade) than for the 550 ppm scenario (0.09°C per decade). i.e., despite the stabilization of the atmospheric CO_2 concentration in 2100 in the 450 ppm scenario, we might expect a further increase in temperature because of the inertia of the climate system.

The rate of temperature change is an especially important indicator that reflects the ability of natural ecosystems to adapt to global warming. Rijsberman and Swart (1990) estimated that a global decadal rate of temperature change below 0.1°C might allow natural ecosystems to successfully adapt to climate change. However, as can be seen from Figure 18, this rate is exceeded by all five scenarios between 1990 and 2030. Their rate of temperature change lies above 0.15°C, which implies that even under the 450 ppm scenario considerable threats to natural ecosystems cannot be avoided in the coming decades. The rate of change of 0.1°C per decade or lower will be achieved by the 450 ppm scenario in the second half of the 21st century.

Under the 550 ppm scenario, assuming constant SO_2 emissions after 1990, the rate of temperature change will slow down to 0.1° per decade at the end of the 21st century whereas under the 550 ppm scenario combined with the high sulfur emissions of the "PB-95% SO2" scenario this rate will be achieved about 50 years early. Under both scenarios the rate of temperature change will not fall below the rate of 0.1° C per decade until 2100. It is noticeable, however, that the high SO_2 emissions of the "PB-95% SO2" scenario lead to a slower temperature increase than the 450 ppm scenario with constant SO_2 emissions between 1990 and 2030. This is mainly caused by the rapid increase of SO_2 emissions in China, where SO_2 emissions triple between 1990 and 2030 (see Figure 10a). But as already mentioned, these high SO_2 emissions will probably be accompanied by high negative effects on the environment and human health which are not covered within this study.

Assuming the lower SO_2 emissions of the "PB-5% SO_2" scenario for the 550 ppm scenario will lead to a faster increase of temperature at a rate of 0.15°C per decade and will only fall below this level late in the 21st century. The rate of change of 0.1°C per decade will be exceeded throughout the whole scenario period. The same is valid for the Kyoto reference scenario: Under this scenario the rate of 0.1°C per decade is exceeded by a factor of two and more between 1990 and 2100.

These high rates of temperature change for all scenarios, especially between 1990 and 2030 underline the importance of mitigating greenhouse gas emissions as early as possible.

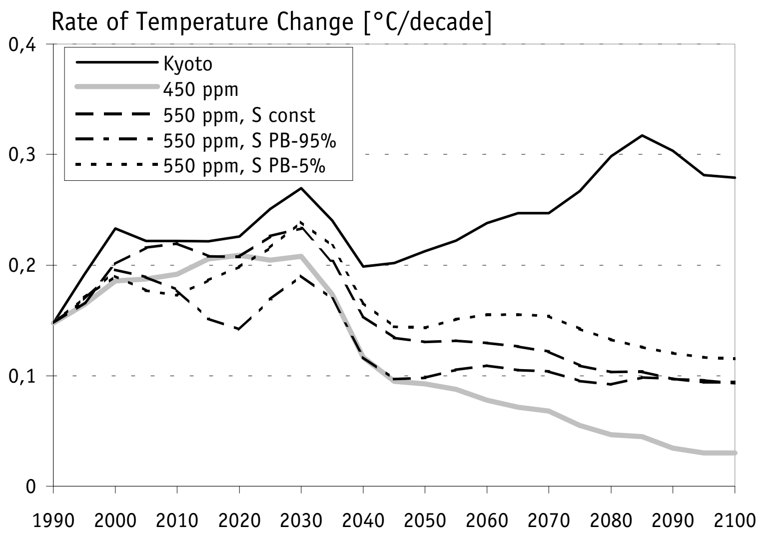

Figure 18: Mean global rate of temperature change per decade between 1990 and 2100.

Sea Level Rise up to 2100

One of the key impacts of climate change will be rising sea level, which could bring increased coastal flooding especially in developing countries not able to afford complete coastal protection. Because of the very slow deepwater mixing of the oceans, the sea level responds considerably more slowly than the atmosphere to the build up of GhGs and global warming. Hence, even for the stabilization scenarios, the global average sea level rise is about 29 and 33 cm between 1990 and 2100 for the 450 ppm and 550 ppm scenarios, respectively (Figure 19). Although temperature increase has begun to slow down for these two scenarios, the sea level still shows an increasing tendency in 2100; for the Kyoto scenario it is even exponentially increasing and reaching 41 cm above the 1990 level in 2100. The difference in sea level rise between all three scenarios is only 10 cm but will probably increase after 2100.

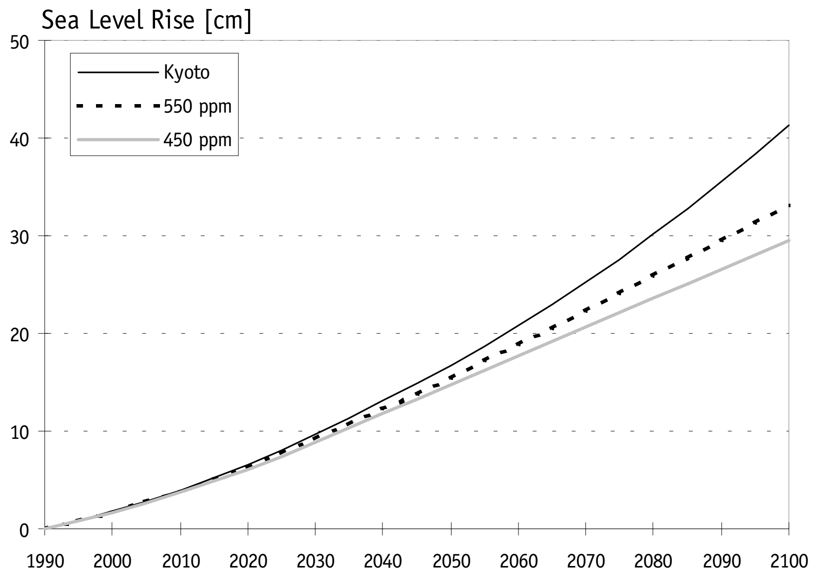

Figure 19: Global average sea level rise between 1990 and 2100.

The rate of sea level rise shows even more clearly than the cumulative sea level rise that the ocean system is reacting much slower than the atmospheric system (Figure 20): In the time period considered the rate of sea level rise per decade shows an opposite trend compared to the rate of temperature change which decreases after 2030 for the stabilization scenarios. The rate of sea level rise starts at about 1.4 cm per decade in 1990 and doubles to about 3 cm per decade in 2030 for all three scenarios. After 2030 only the 450 ppm scenario stabilizes its rate of sea level rise (not the absolute level of sea level rise) whereas for the 550 ppm and the Kyoto scenario this rate increases beyond 2100.

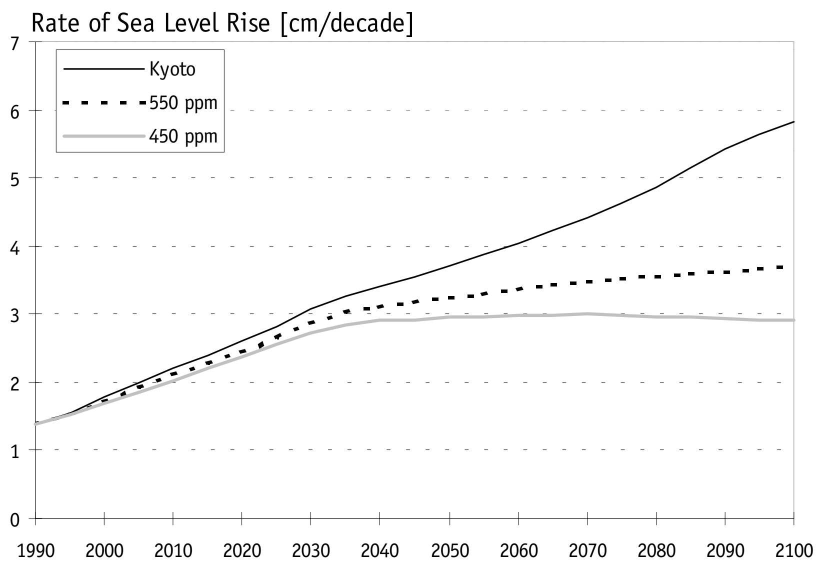

Figure 20: Rate of sea level rise between 1990 and 2100.

Sea Level Rise after 2100

The rising tendency of sea level in 2100 for the stabilization scenarios motivated Alcamo *et al.* (1997b) to perform IMAGE simulations up to the year 2500 for a number of stabilization scenarios to evaluate whether and when there will be a stabilization of the sea level after 2100. Additionally, the long-term climate goal to limit sea level rise to 20 cm after 1990 (proposed by the AOSIS states) was evaluated. With respect to this proposal, it was important to see what happens to the sea level after 2100 when we define the time-frame of this proposal to be 1990 until 2100. For this purpose, a global emissions pathway was selected so that sea level rise reaches 20 cm in 2100[3].

From Figure 21 it can be seen that after 2100 the sea level continues to rise by a factor of three under the 450 ppm scenario and by a factor four under the 550 ppm scenario. Thus, the sea level might rise by 103 cm and 122 cm between 1990 and 2500 under the 450 ppm and the 550 ppm scenario, respectively. Even for an atmospheric CO_2 stabilization at 350 ppm a sea level rise of about 80 cm in 2500 might be expected.

Although global greenhouse gas emissions were sharply reduced to reach a 20 cm sea level rise in 2100 a further rise of 18 cm might be expected between 2100 and 2500.

The main point of this analysis is that, in spite of the stabilization of the atmospheric GhG concentrations and the strong emission reductions that are necessary to achieve this stabilization, sea level will significantly rise even after the stabilization of GhG concentrations is achieved.

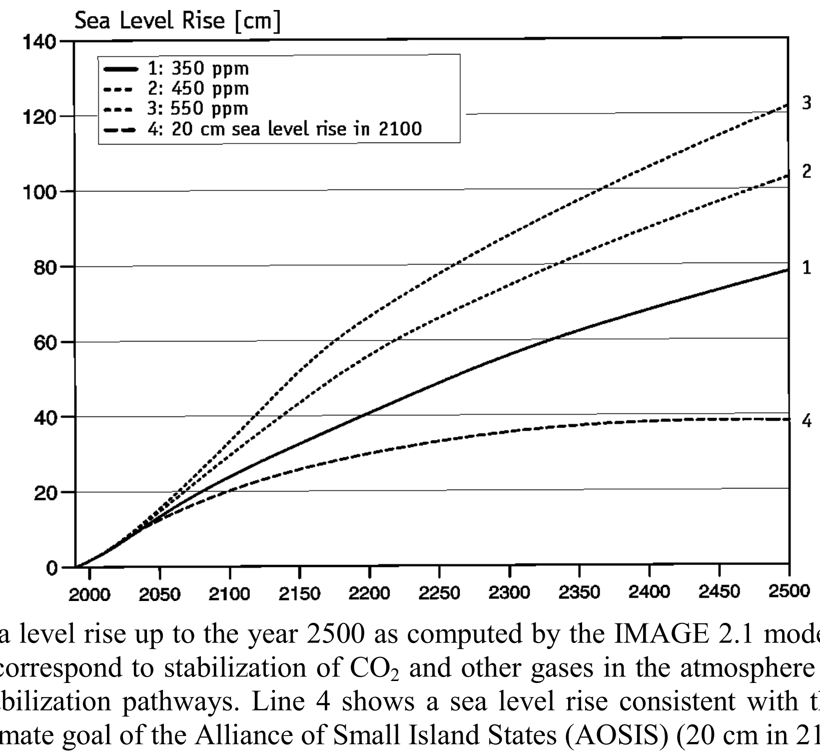

Figure 21: Sea level rise up to the year 2500 as computed by the IMAGE 2.1 model. Lines 1 to 3 correspond to stabilization of CO_2 and other gases in the atmosphere according to stabilization pathways. Line 4 shows a sea level rise consistent with the long term climate goal of the Alliance of Small Island States (AOSIS) (20 cm in 2100).

[3] For this emissions pathway global anthropogenic GhG emissions are mitigated to their 1990 level in 2010. After 2010 emissions were assumed to be reduced by 2% per year, reaching 2.0 Gt C per year in 2100. Land use changes are set to zero after 2100 for this and the stabilization scenarios. Sulfur emissions are assumed to remain constant after 1990.

Crop Productivity

In order to evaluate the impacts of climate change on food production, we selected three crop classes which play an important role for the food supply in the different regions of the world. These crop classes are temperate cereals (winter wheat and spring wheat), tropical cereals (millet and sorghum) and maize (temperate maize and tropical maize). The percentage of current global crop growing area that is affected by a decreasing potential yield due to a changing climate is used as an indicator (for a description and discussion of this indicator see chapter 5.1).

For *temperate cereals* a rapid increase of area with decreasing potential productivity might be expected for all stabilization scenarios: 11% of the current area planted with this crop is already affected in 2010 (Figure 22). This level increases to 18% and 20% in 2100 for the 450 and 550 ppm scenarios, respectively. This delay in the expansion of affected area after 2010 is caused by the stabilizing climate under these scenarios but is also partly due to an enhanced plant growth under higher CO_2 concentration levels. Temperate cereals as well as tropical cereals are C3 plants for which the so-called CO_2 fertilization effect could partly lead to a compensation of negative climate change effects. The consequence of this effect is that impacts do not differ very much for different stabilization scenarios in 2100. Although the global temperature change is stronger for the 550 ppm scenario, the affected percentage of area lies only slightly above the impact level for the 450 ppm scenario. This becomes particularly obvious for the Kyoto scenario. The impact level of this scenario is only slightly higher than that of the stabilization scenarios: 22% of the current area will be affected in 2100 (compared to 18% under the 450 ppm scenario and 20% under the 550 ppm scenario).

For the 550 ppm stabilization scenario we performed two further simulation runs with SO_2 emissions from the ”PB-95% SO_2” and ”PB-5% SO_2”scenarios instead of constant sulfur emissions after 1990. The high SO_2 emissions of the ”PB-95% SO_2” scenario diminish the climate change of the 550 ppm scenario to such an extent that the area affected by decreasing potential yield is comparable to that of the 450 ppm scenario in 2100 (Figure 22). In the mid-term (2020-2070) the doubling of SO_2 emissions in this scenario results in an impact level that is even lower than that of the 450 ppm scenario. But as the global increase of SO_2 emissions originates from an increase of emissions in the developing regions, this scenario implies a high level of acidification of the environment in these regions. These negative impacts could be significantly greater than the benefits for climate change.

The lower SO_2 emissions of the ”PB-5% SO_2” scenario lead to a negligible increase of the impact level, compared to the 550 ppm scenario with constant SO_2 emissions after 1990.

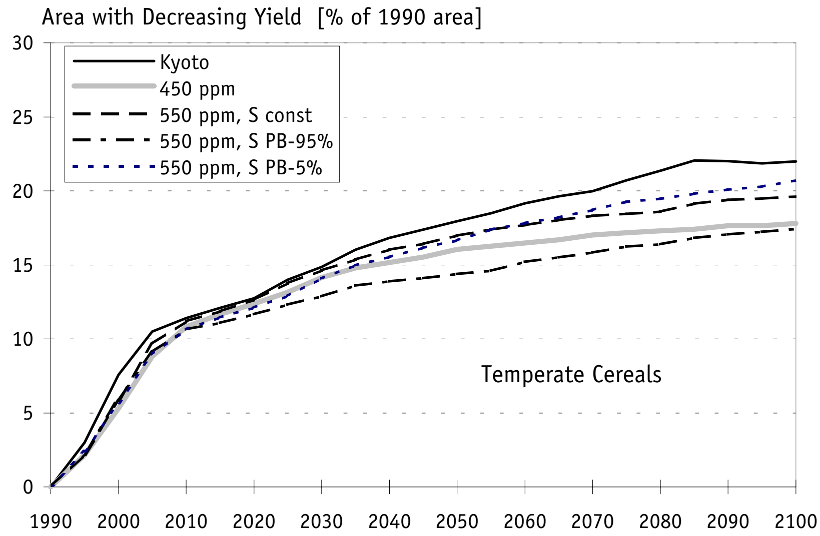

Figure 22: Global percentage of 1990 area with decreasing yield for temperate cereals.

For *tropical cereals* the impact level (percentage of current area with a decrease in potential yield) is about one half compared to that for temperate cereals in 2100. Additionally, there is not the early and rapid increase of affected area that can be seen for temperate cereals (Figure 23). This might be due to the fact that tropical cereals are mostly grown in the lower latitudes where plants are already adapted to warmer temperatures and where the global warming trend is expected to be lower than for the regions where temperate cereals are grown (Krol *et al.*, 1997). For the 450 ppm scenario about 9% of the current area is affected by decreasing yield. Due to their sensitivity to the CO_2 fertilization effect, the impacts for the Kyoto scenario and the 550 ppm scenario are almost identical in 2100: About 11% of the current area are affected by decreasing potential yield under both scenarios.

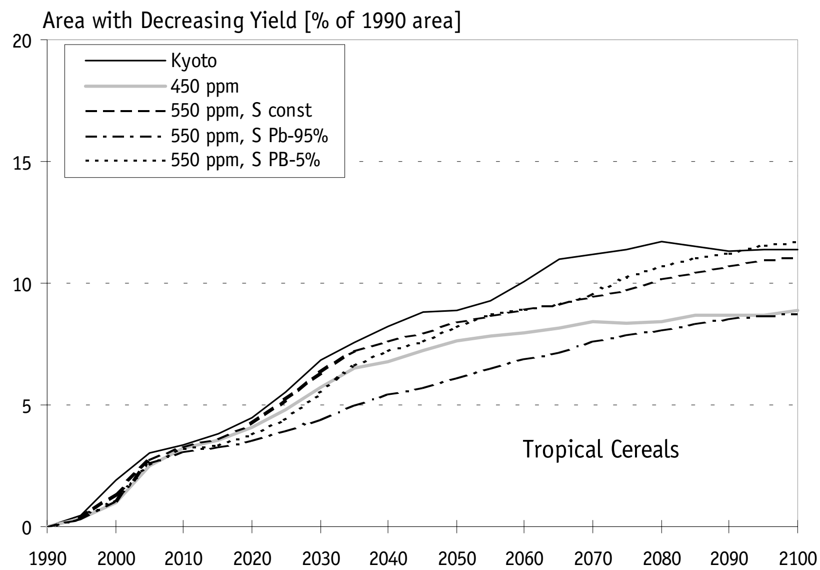

Figure 23: Global percentage of 1990 area with decreasing yield for tropical cereals.

For *maize* as a C4-plant which is not very sensitive to the CO_2 fertilization effect, the picture looks somewhat different: The percentage of current maize growing area with decreasing potential yield rises to more than 20% between 1990 and 2100 for all scenarios (Figure 24). Additionally, fifty percent of this impact level is reached quite early, namely before 2020. The results for the Kyoto scenario show a steady increase of impact up to 31% of the current area with an increasing tendency in 2100. The impacts of the 450 ppm and 550 ppm stabilization scenarios reflect the deceleration of climate change in these scenarios: after a rapid expansion of area with decreasing potential yield until 2030 (17%) the percentage of affected area reaches 21% under the 450 ppm scenario and 25% under the 550 ppm scenario in 2100.

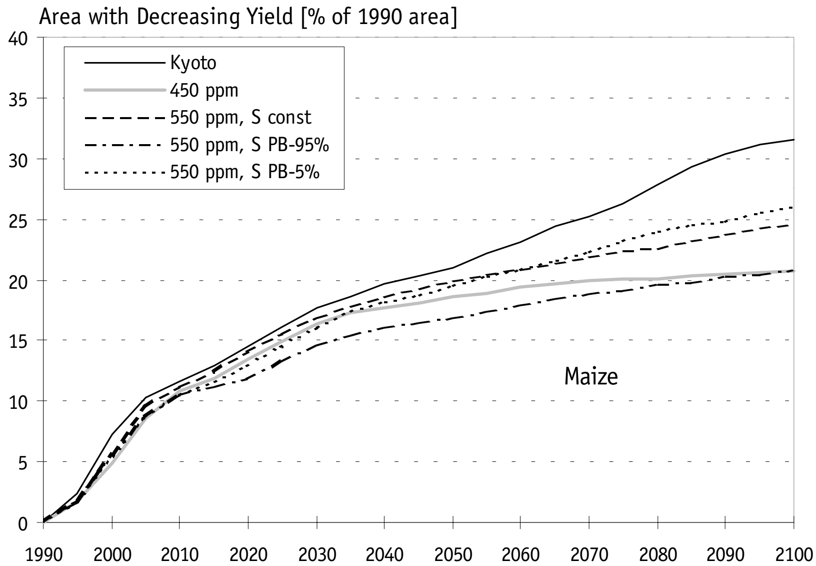

Figure 24: Global percentage of 1990 area with decreasing yield for maize.

With respect to the indicator of this impact analysis (percentage of cropping area negatively affected by climate change) it is important to note that an important factor is not yet included in IMAGE 2 land cover calculations, namely the future degradation of land. It is crucial, of course, to consider the loss of agricultural productivity because of overuse and mismanagement. We note, however, that the model does take into account the current low productivity of some areas (such as the Sahel region of Africa) because of land degradation. The net effect of this omission is to probably underestimate the area with a loss in productivity.

Threat to Natural Vegetation

To assess the threat to natural vegetation we present the percentage of land, where the existence of the current vegetation could be endangered due to climate change. For this analysis we make a distinction between nature reserves and the rest of the natural ecosystems because nature reserves have the explicit purpose to protect the ecosystem of a certain area. (For a description and discussion of this indicator see chapter 5.1).

As can be seen from Figure 25 and Figure 26 the temporal trends of impact occurrence are similar for nature reserves as well as all other natural ecosystems. They reflect the large rate of temperature change up to the year 2030 (greater than 0.15°C per decade) as well as the decrease of this rate for the two stabilization scenarios between 2030 and 2100. According to the assumptions included in the IMAGE model, however, this decrease does not seem sufficiently strong: the area where potential natural vegetation as well as nature reserves are threatened still increases towards 2100.

Even under the 450 ppm scenario 23% of the current area with natural vegetation will be under pressure from global warming in 2100. Under the 550 ppm scenario, 28% of the current area is threatened, and under the Kyoto scenario, 39%.

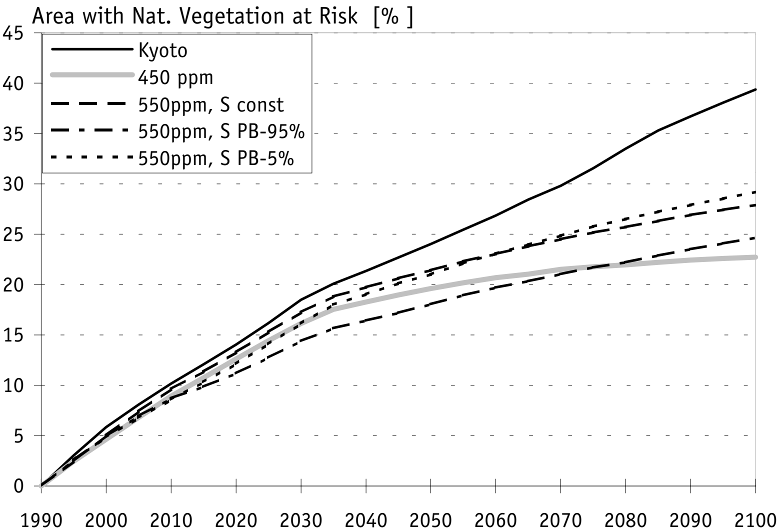

Figure 25: Percentage of area with potential natural vegetation of the year 1990 at risk.

The global picture for nature reserves resembles that of the rest of the natural potential vegetation: the affected area is sharply increasing over the whole scenario period for the Kyoto scenario, reaching 39% in 2100 (Figure 26). This picture looks somewhat different for the two stabilization scenarios, for which a sharp increase up to 2030 is followed by a moderate increase in the second half of the 21st century. But impact levels also reach 21% and 23% for the 450 ppm and 550 ppm scenarios, respectively.

Our assumptions about different future sulfur emissions change in particular the area of nature reserves that could be affected by climate change. For the 550 ppm scenario with the ”PB-5% SO_2” scenario in the background, the percentage of area affected increases to 28% in 2100 compared to 23% for the 550 ppm scenario with constant SO_2 emissions after 1990. The high SO_2 emissions of the ”PB-95% SO_2” scenario reduce the climate change impacts on nature reserves between 2020 and 2080 and have no further effects towards 2100. This effect of SO_2 emissions on nature reserves might be explained by the fact that most of the areas with nature reserves are in regions where SO_2 emission mitigation takes place rather late, i.e. where SO_2 emissions may increase until the mid of the 21st century (e.g. Africa and Latin America), and therefore still counteract the effects of climate change in this period of time.

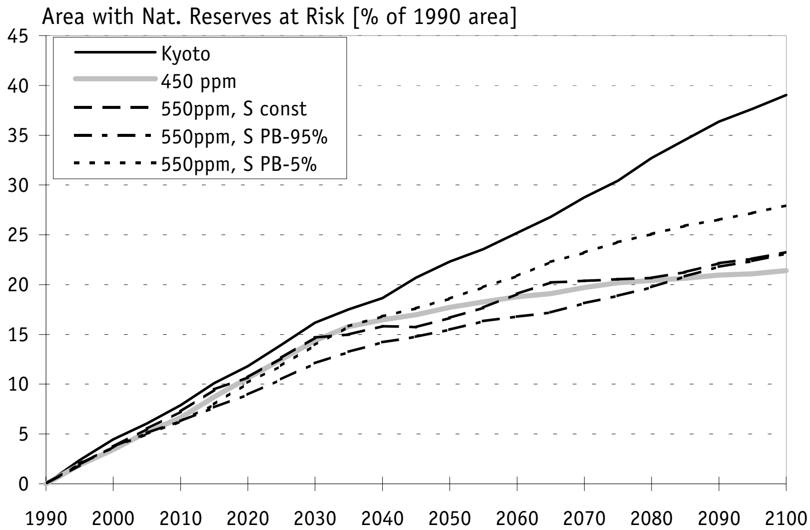

Figure 26: Percentage of 1990 area with nature reserves at risk.

5.2.2 Regional Impacts

Crop Productivity

The regional impacts of climate change on the potential crop productivity in 2100 are significantly different from those on the global level (Table 5). Only very few regions show an impact level which is comparable to that of the global level. The percentage of the regional area that is affected by a decrease of potential productivity varies widely between the regions of the world. Under the 550 ppm scenario the affected percentage of current areas with temperate cereals ranges between 0% and 74%, for tropical cereals between 0% and 85% and for maize even between 0% and 99%. i.e. there are regions that might expect only slight or no negative impacts from global climate change, such as for example, Eastern Europe or the former Soviet Union. On the other hand there are regions, such as Canada and the United States that might have to tolerate significant impacts on important crop classes. Under the 550 ppm scenario, the impact level for temperate cereals is 74% for Canada and 49% for the United States. Interestingly, these values are lower for the Kyoto scenario: 60% for Canada and 45% for the United States. This might be explained by the enhanced water use efficiency of plants resulting from the high CO_2 concentration under the Kyoto scenario. Of course for Canada and the United States this may imply only a small reduction in the fairly high potential production which is now achieved. The MPI GCM, which we used for scaling of temperature and precipitation patterns, calculates a strong decrease in precipitation for Northern America. Under the Kyoto scenario, this decrease is compensated by the increase of water use efficiency of plants. In the case of a decrease of yields caused by high temperatures, this effect is not valid and the impacts of the Kyoto scenario are higher compared to those of the stabilization scenarios; this is the case for most regions.

Not all crops are of the same importance in each region. The crops we present in this analysis are planted on 50% or more of the total cropping area of each region in 1990. The bold numbers indicated in Table 5 represent those crops that are planted on 20% or more of the current cropping area of each region, and for which the regional impact level exceeds the global impact level in 2100. So we can estimate which regions of the world will have to tolerate impacts above-average for their most important crop classes. Under the 550 ppm scenario these are, in addition to Canada and the United States, the following regions: India & South Asia, and Oceania. Thus, in spite of a stabilization of atmospheric greenhouse gas concentrations, industrialized regions as well as developing regions might be confronted with a decrease of their potential crop productivity.

Table 5: Regional impacts of climate change on the potential productivity of temperate cereals, tropical cereals and maize. We present the percentage of the current crop growing area that is affected by a decreasing yield in 2100. Results are shown for the Kyoto scenario and the 550 ppm scenario which assumes constant SO_2 emissions after 1990. Bold numbers indicate impact levels of crops that are planted on 20% or more of the agricultural area and that lie above the world average impact level.

IMAGE region	Kyoto scenario 2100, % of 1990 area			550 ppm (const. SO2) 2100, % of 1990 area		
	Temperate cereals	Maize	Tropical cereals	Temperate cereals	Maize	Tropical cereals
Canada	**60**	**85**	-	**74**	**99**	0
USA	**45**	75	54	**49**	57	52
Latin America	17	7	2	10	6	3
Africa	42	12	10	32	9	8
OECD Europe	**22**	71	93	14	55	85
Eastern Europe	8	1	0	5	1	0
CIS	5	0	0	1	0	0
Middle East	3	35	16	0	32	17
India & S. Asia	**62**	2	0	**57**	2	0
China & CP Asia	3	41	23	1	33	31
East Asia*	0	2	0	0	2	0
Oceania	**29**	9	17	**28**	7	14
Japan*	0	100	100	0	17	34
World	22	31	11	20	25	11

* For these regions the sum of the cropping area of the selected crops is lower than 50% of the total cropping area.

In addition to a decrease in potential productivity, we can also obtain an increase of potential productivity caused by the CO_2 fertilization effect or by more favorable climate conditions. Even in the United States with its large areas with decreasing yields for temperate cereals, we can expect areas with enhanced productivity in 2100 compared to 1990 (see figure 1-A in the Appendix). Nevertheless, we found that these positive impacts occur with a certain time delay. For many regions, there is a strong increase in areas with decreasing yield before 2030 whereas the percentage of area where crop yield increases starts in 2010 or thereafter (not presented).

Threat to Natural Vegetation

In order to analyze the regional effects of climate change on potential natural vegetation, we again distinguish between the threat to the vegetation of nature reserves and the threat to natural vegetation in other areas. We present the regional effects of three different scenarios. These scenarios are the two stabilization scenarios of 450 ppm and 550 ppm and the Kyoto reference scenario. As can be seen from Table 6 the impact of climate change on potential natural vegetation differs widely between regions. For the 550 ppm scenario 10% of the nature reserves in East Asia are threatened whereas 40% of the area of Canadian nature reserves is affected. This large difference in regional impacts is comparable to the climate change effects on crop productivity. But in contrast to the effects on crops, for natural vegetation we also notice a large difference of impact levels between the different scenarios evaluated. As expected, we get the largest difference in impacts between the Kyoto scenario and the stabilization scenarios. In China, for example, 58% of the area covered by nature reserves is threatened in the Kyoto scenario. For a CO_2 stabilization target of 550 ppm this impact levels off to 34%. This is still quite a high level, but it demonstrates how natural vegetation, in nature reserves as well as in other areas, is sensitive to changes in climate, which on a globally-averaged scale appear low. The difference in global temperature change between the Kyoto scenario and the 550 ppm scenario is only 1°C in 2100, but this small difference in temperature change could lead to a difference in impact levels of up to 50% in some regions of the world. Under the Kyoto scenario 22% of nature reserve area in East Asia is threatened, whereas under the 550 ppm scenario only 10% of the area is affected.

Table 6: Regional impacts of climate change on potential vegetation (nature reserves and other natural vegetation) presented as the percentage of the total area where the potential natural vegetation is threatened. Results are shown for the Kyoto scenario and the 550 ppm and 450 ppm stabilization scenarios with constant SO_2 emissions after 1990. Bold numbers indicate impact levels above the world average value.

IMAGE region	**Kyoto Scenario**		**550 ppm**		**450 ppm**	
	Nat. reserv. 2100 [%]	Nat veget. 2100 [%]	Nat. reserv. 2100 [%]	Nat. veget. 2100 [%]	Nat. reserv. 2100 [%]	Nat veget. 2100 [%]
Canada	**48**	**41**	**40**	**33**	**42**	**30**
USA	**54**	**53**	**32**	**35**	**26**	**29**
Latin America	**40**	**40**	**30**	**29**	**28**	23
Africa	29	24	13	17	13	13
OECD Europe	**66**	**47**	**42**	**35**	**39**	**29**
Eastern Europe	**58**	**41**	**43**	**32**	**36**	**29**
CIS	**49**	**41**	**32**	**30**	**27**	**25**
Middle East	39	**47**	**27**	**31**	**26**	**24**
India & S. Asia	**48**	**46**	**28**	28	**24**	21
China & CPAsia	**58**	**61**	**34**	**43**	**30**	**36**
East Asia	22	15	10	8	6	4
Oceania	34	33	21	22	17	18
Japan	**40**	30	21	17	20	10
World	39	39	23	28	21	23

As can be seen from Table 6, the climate change effects on nature reserves are comparable or even higher than those on natural vegetation in other areas. Nature reserves are often situated in more fragmented areas surrounded by land that is used for other purposes (e.g. agriculture). This raises the vulnerability of nature reserves to a changing climate because migration of new species into a nature reserve and thus a successful adaptation to changing climate conditions is difficult (Leemans and Hootsmans, 1998).

The IMAGE model takes into account whether the potential natural vegetation of an area is able to adapt to new climate conditions or not. This is realized by defining a potential migration zone which depends on a vegetation specific migration distance and -rate (Van Minnen *et al.*, 2000), i.e., whether or not a vegetation type in a certain area can adapt to changing climate conditions depends on being within the migration zone of a new vegetation type that could replace the old vegetation class. Thus, the important influence of adaptation processes of natural ecosystems on the global carbon fluxes can be taken into account (see e.g. Solomon, 1997). From Figure 2-A (see Appendix) it becomes obvious that even if the atmospheric CO_2 concentration is stabilizing at a level of 550 ppm, the potential natural vegetation of many areas will not be able to shift to another vegetation class that is better adapted to the new climate conditions. This is especially the case for large areas in the northern part of Europe and Scandinavia, but also for large areas in the former Soviet Union and in China.

Water Availability

Out of the many watersheds simulated by the WaterGAP model, we present five to illustrate possible effects of the stabilization scenarios on water availability. These are the watersheds of the Zambezi and the Senegal in Africa, the Murray-Darling in Australia and the Rhine and Guadalquivir in Western Europe. As can be seen from Figure 27, climate change could lead to an increase in runoff and, thus, in water availability. We found this result for the Zambezi river with an increase of 22% and 29% for the 450 ppm and 550 ppm stabilization scenario, respectively, but also for another number of rivers presented in Appendix 2. In many areas of the world, however, climate change can lead to a decrease in water availability as presented for the Senegal with a decrease in runoff of 32% and 37% for the 450 ppm and 550 ppm scenarios, respectively. This tendency might cause additional pressure on water resources. What becomes also obvious from Figure 27 is that a stronger climate change intensifies the trend of increasing or decreasing runoff. For the Senegal with a decreasing tendency for runoff, we get the lowest runoff for the Kyoto scenario and a somewhat higher runoff for the 550 ppm and 450 ppm scenarios but still with a decreasing tendency compared to the runoff in 1990.

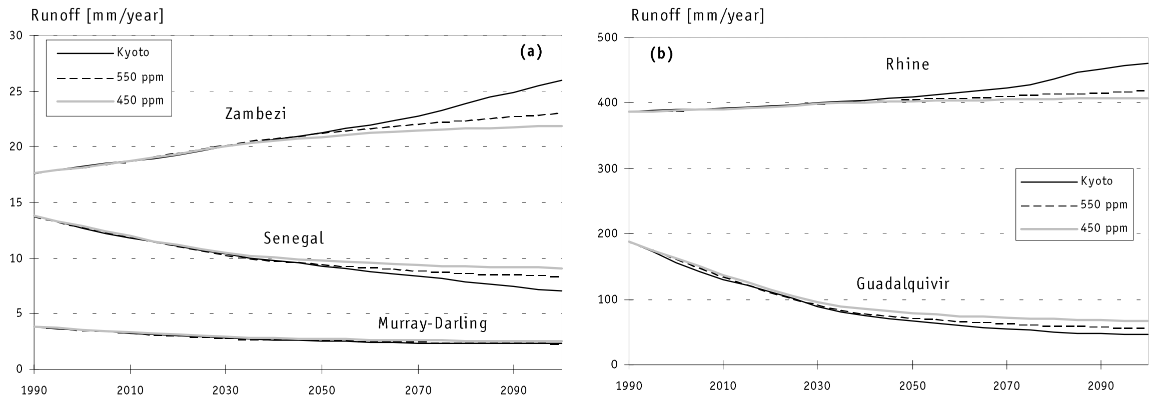

Figure 27: Mean annual runoff of (a) the Zambezi, the Senegal (Africa) and the Murray-Darling (Australia). (b) Mean annual runoff of the Rhine and the Guadalquivir (Western Europe).

5.3 Summary and Conclusions

Impact Indicators

In order to get a comprehensive picture of the impact levels that might be expected for the two stabilization targets of 550 ppm and 450 ppm CO_2 in the atmosphere in comparison to a reference scenario (the "Kyoto scenario"[4]), five impact categories were evaluated:

1. *Atmospheric temperature change* is a direct response to the build-up of GhG concentrations in the atmosphere, and is often used as an indicator in formulating climate protection targets.

[4] The "Kyoto scenario" is a modified version of the IMAGE Baseline A scenario for which we assume a 5.2% reduction of 1990 Annex B GhG emissions until 2010. After 2010 GhG emissions of Annex B remain constant. Non-Annex B emissions follow Baseline A assumptions throughout the whole scenario period.

2. *Sea level rise* is an indirect indicator of the build-up of GhG concentrations, and stems from increasing ocean temperatures and melting of ice masses. Sea level rise could irreversibly endanger small island states and countries with low lying-coastal areas.
3. The *change in potential crop productivity* is an indirect indicator of the possible impacts of climate change on the world´s agriculture system.
4. The *change in potential natural vegetation* reflects impacts on natural ecosystems.
5. The *change in water availability* could affect water supply to the domestic, agricultural, and industrial sectors.

Temperature Change

For the 550 ppm stabilization scenario, a global mean temperature change of 1.7°C was computed between 1990 and 2100. This is equal to an increase of about 2.2°C compared to pre-industrial times. Even a stricter stabilization target of 450 ppm CO_2 in the atmosphere results in an temperature change of 1.7°C in 2100 compared to pre-industrial times.

For both stabilization scenarios, the global mean temperature rapidly increases between 1990 and 2030, exceeding a rate of 0.1°C per decade in the first half of the 21st century. This rate of change is suggested as an upper limit to which natural ecosystems can adapt (Rijsberman and Swart, 1990). Only under the 450 ppm scenario the rate of temperature increase will fall below this value in the second half of the 21st century.

Sea Level Rise

The sea level rises 29 cm under the 450 ppm, and 33 cm under the 550 ppm scenario between 1990 and 2100. Although the rate of temperature increase slows down towards the end of 21st century, sea level rise continues to accelerate because of the lag time in the warming of the ocean and the warming of the atmosphere. Average sea level is computed to increase by a further factor of three and four between 2100 and 2500 for the 450 ppm and 550 ppm scenarios, respectively.

Crop Productivity

As an indicator of risk to global and regional food production we use the percentage of current crop growing area that is affected by decreasing potential yield. In this analysis we only take into account the possible effect of changing temperature and precipitation on potential crop yield, and we neglect the possible adaptation of the agricultural system to climate change.

The main outcome of the analysis is that climate change may appreciably affect the potential yield of all types of crops examined (temperate cereals, tropical cereals and maize). For the 550 ppm scenario and temperate cereals, 15% of the current global crop area is affected by 2030, and 20% by 2100. For tropical cereals and maize we get similar patterns: 11% and 25% of current areas are affected by 2100, and more than half of this level is already reached by 2030. The impact levels of the 450 ppm scenario lie only 2-5% below the impact levels of the 550 ppm scenario.

On the regional scale, the percentage of area affected by decreasing crop yield varies widely. The largest impacts were computed for Canada, the USA and India, whereas

Eastern Europe and the region of the Former Soviet Union show very low impact levels. This is valid for both stabilization scenarios and all three crop classes. Hence, for an evaluation of impacts of different stabilization targets, it is much more reasonable to consider regional effects. However, for this purpose the results of more than one climate model should be used because of the uncertainties associated with estimates of changes in precipitation.

Threat to Natural Vegetation

Even if climate protection measures lead to long-term stabilization of atmospheric concentrations of greenhouse gases, considerable areas of natural vegetation might be threatened by changing climate conditions. Under the 550 ppm scenario, we compute that climate change up to 2100 could change the potential vegetation on 28% of the global area with natural vegetation. Under the 450 ppm scenario, 23% of this area could have altered vegetation.

Also, under the 550 ppm scenario, we compute that climate change up to 2100 could change the potential natural vegetation in 23% of the area of current nature reserves. Under the 450 ppm scenario, this figure is 21%.

Water Availability

According to this first evaluation of the impacts of climate change on water availability, the climate change corresponding to the two stabilization targets could increase water availability in some watersheds, and decrease it in others. In some places, for example, the Guadalquivir in Spain, climate change will decrease water availability. For other places such as, for example, the Zambezi in Africa or the Rhine in Western Europe, we computed an increasing water availability for the two stabilization scenarios as well as for the Kyoto reference scenario.

6. Long Term Climate Protection and Short Term Action: The "Safe Landing Approach"

The Safe Landing approach was applied to overcome one of the weaknesses of the analysis we described in the previous chapters: Only one single CO_2 stabilization pathway was prescribed for each stabilization target and hence only one global emissions pathway was obtained to analyze necessary emission mitigation efforts. The development of the Safe Landing approach was a direct result of a series of science and policy workshops held in Delft, The Netherlands (van Daalen *et al.*, 1998) to support climate policy makers preparing for the climate summit in Kyoto. The main purpose of the program is to bridge the gap between the relatively short time horizon of policy decisions and the long time view necessary for climate protection. This is done by calculating emission corridors for the years 1990 to 2010 that allow to reach a climate target in year 2100. After describing the principles of the approach, we will apply it for the climate targets proposed by the Alliance of Small Island States (AOSIS) and the EU. Finally we will evaluate how the Kyoto results comply with the climate targets of the EU.

6.1 Background of the Safe Landing Approach

The concept of safe emission corridors was developed during a series of informal international workshops between 1995 and 1997 that aimed to promote a dialogue between global modelers and policy makers engaged in the climate protocol negotiations (Alcamo, *et al.*, 1996b and van Daalen, *et al.*, 1997). Safe emission corridors are the allowable range of emissions over time that comply with long- and short-term climate goals. The term emission corridors arose from an analogy with aviation: In order to land safely an aircraft needs to approach the airport in such a way that it neither hits the ground too early by going down too quickly, nor misses the runway by going down too late. To land safely it should stay within a so-called safe corridor, guiding it to the landing strip. In the context of the climate issue, the future pathway of emissions of greenhouse gases should be such that it neither disrupts socioeconomic development by reducing emissions too fast or too early, nor leads to serious climate impacts by reducing emissions too slowly or too late. As a consequence, like the airplane, the short term emissions of greenhouse gases should stay within a corridor: the so-called "safe emission corridor".

The procedure for computing safe emission corridors requires results from a global climate model. Repeated runs are required with the model, so it is desirable to use a model with a fast turnaround time. The first corridors were computed using IMAGE 2, an integrated model of global change. However, other global models are now also being used to compute emission corridors (see, for example, Matsuoka, *et al.*, 1998), and results from different models are being standardized and compared (Alcamo, 1997). In this paper, we use IMAGE 2 to compute emission corridors.

Results from a global model are employed in such a way that an analyst can select certain climate and other goals, and the emission corridors are automatically calculated. The procedure for calculating the emission corridors is described in Appendix 1. Other applications of the approach are given in Alcamo and Kreileman (1996a) and Swart, *et al.* (1998). The emission corridors approach has been automated in an interactive program; for this report, we use Version 3 of this program (Kreileman and Berk, 1997).

In the current version, the safe emission corridor is computed after setting constraints on four main indicators:

1. Cumulative increase in global average surface temperature in °C (1990-2100)
2. Rate of temperature increase in °C per decade (and the number of decades this rate may be violated)
3. Cumulative increase in global average sea level in cm. (1990-2100)
4. Rate of global emission reduction in % per year

These indicators can be related to the goals and conditions stated in the ultimate objective of the Framework Convention on Climate Change as noted in the main text. Given the level of uncertainty about the future level of climate change and related impacts, and the normative nature of evaluating these impacts, the safe emission corridor approach does not use any predefined values for the selected indicators. Instead, it offers decision makers a flexible framework to evaluate their own sets of climate goals. The fast accounting software enables this to be done in an interactive way.

For each set of indicator values, an emission corridor can be calculated for global greenhouse gas emissions (in CO_2 -equivalent emissions) for the target year selected (e.g. 2010 or 2020). Between the target year and year 2100, there is at least one emission pathway emerging from the emission corridor that will comply with the specified set of indicator values. The top of the corridor indicates the maximum allowable emissions in the target year compatible with the selected climate goals. Near the top of the corridor, there are only few emission pathways that comply with these goals. Lower in the corridor there are many more pathways available after the target year that are compatible with the climate goals, and there is more room for a tightening of constraints if future scientific knowledge of climate change would make this desirable. The bottom of the corridor is defined by the constraint on maximum rate of emission reduction. To account for the present rate of climate change, resulting from historical emissions, the analysis also allows for specifying a number of decades after 2000 that the specified rate of temperature increase may be violated.

6.2 Emission Corridors of the AOSIS Proposal

The Protocol proposal of the AOSIS sets limits on global mean sea level rise of 20 cm, and global temperature increase of 2.0 °C above its pre-industrial value. The temperature limit is equivalent to an increase of about 1.5 degrees above its present level. To compute the emissions corridor of the AOSIS proposal we must make some additional assumptions about other constraints. First, we assume that the target year for achieving the limitation on sea level rise and temperature increase is 2100. We also assume that the global rate of temperature increase is limited to 0.15 °C per decade (being the average rate for an 1.5 °C increase over the 21st century) except for the first two decades, and that the maximum rate of global emission reduction is 2% per year. These are taken to be intermediate values, although the emission reduction rate is considered to be an upper limit by some (Swart *et al.*, 1998). Global sulfur emissions, which lead to sulfate particles in the atmosphere that somewhat compensate for global warming, are assumed to remain constant at their 1990 level.

The global emission corridor computed for these assumptions is shown in Figure 28a. In year 2010, emissions range from 7.6 to 9.5 Gt C per year. Since global emissions in 1990 are estimated to be approximately 9.8 Gt C per year (Legget *et al.*, 1992), the bottom and top of the corridor correspond to 78% to 97% of estimated 1990 emissions (Figure 28a). (We remind the reader that these emissions are the sum of anthropogenic emissions of CO_2, N_2O, and CH_4 in units of CO_2 equivalents and reported as Gt C per year.) These are the short-term range of global emissions that comply with the long-term climate goals of the AOSIS protocol proposal.

To compute the allowable emissions in Annex B (industrialized) countries, we subtract non-Annex B emissions from the above global emissions. Our assumptions are that non-Annex B emissions in 2010 range from 5.5 to 7.0 Gt C per year, with a medium estimate of 6.3.

Because of the narrow global emissions corridor, we also compute a narrow corridor for Annex B emissions, spanning from 1.3 to 3.2 Gt C per year in 2010 (Figure 28b). This is equivalent to 25% to 60% of 1990 emissions (5.3 Gt C per year).

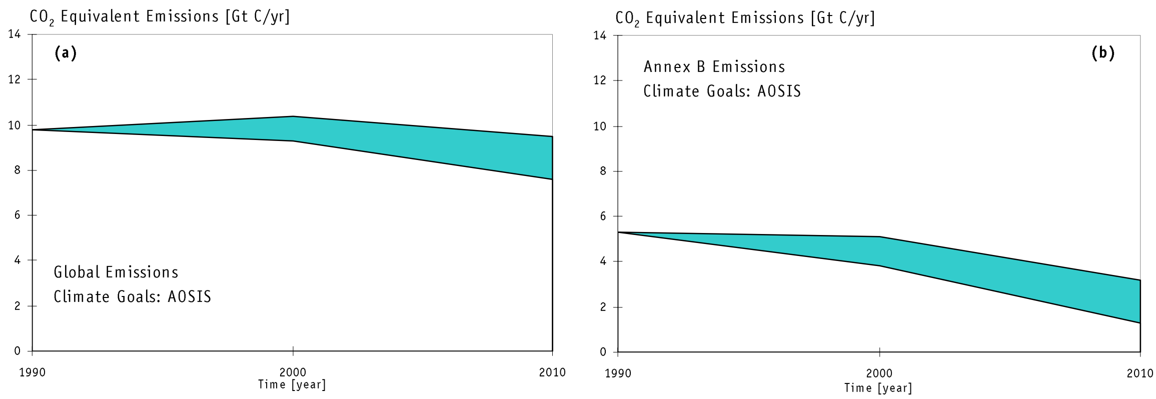

Figure 28: Emission corridors to achieve the long-term climate goals of the AOSIS. (a) Global emissions; (b) Annex B emissions calculated by subtracting uncontrolled non-Annex B emissions (medium estimate) from global emissions.

6.3 Emission Corridors of the European Union Proposal

The EU Protocol proposal stipulates that "global average temperature should not exceed 2°C above the pre-industrial level", which we noted above is equivalent to about 1.5 degrees above the present level. To compute the safe emissions corridor corresponding to this target, we make some of the same assumptions as in the AOSIS example: (1) the target year for this temperature limitation is 2100, (2) the global rate of temperature increase may not exceed 0.15 °C per decade, and (3) the maximum feasible rate of global emission reduction is 2% per year. An exception is that, for the EU proposal, we increase the constraint on sea level rise from 20 cm (in the AOSIS proposal) to 30 cm. We increase this constraint because the EU proposal does not specify a sea level target, and because a limit of 30 cm sea level rise does not have a strong influence on the width of the corridor (under the assumption that other constraints have values specified earlier in this paragraph). As later presented in the sensitivity analysis Figure 31a shows how the width of the corridor becomes very narrow when sea level rise is limited to less than 25 cm.

Under the above assumptions, the global emissions corridor in 2010 ranges from 7.6 to 12.4 Gt C per year, which is 78% to 127% of emissions in 1990 (Figure 29a). This is substantially wider than the AOSIS example (compare Figure 28a) because of the higher limit set on sea level rise. Figure 29a shows the short-term range of global emissions that comply with the long-term temperature limit specified in the EU Protocol proposal.

To compute the allowable emissions from Annex B countries, we follow the same procedure as in the AOSIS example and assume that emissions from non-Annex B countries in 2010 are 6.3 Gt C per year. The corridor for Annex B emissions is then computed to span from 1.3 and 6.1 Gt C per year in 2010, or between 25% and 115% of their 1990 level (5.3 Gt C per year), with a median value of 3.7 (70%) (Figure 29b).

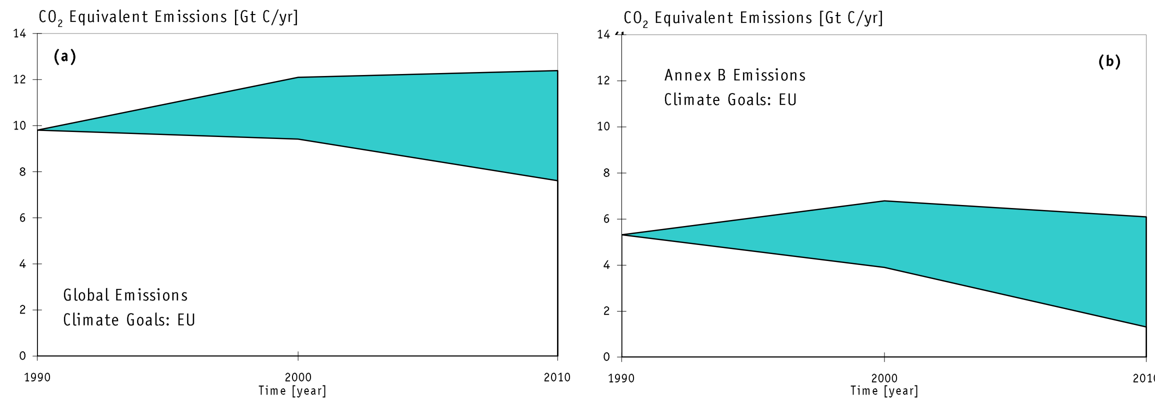

Figure 29: Emission corridors to achieve the long term climate protection proposal of the European Union. (a) Global emissions; (b) Annex B emissions calculated by subtracting uncontrolled non-Annex B emissions (medium estimate) from global emissions.

6.4 Long-Term Climate Goals and the Kyoto Results

In order to evaluate the consequences of the outcome of the climate summit in Kyoto we expand the analysis to the time after the first commitment period and construct the global emissions corridor for the time 2010 to 2030 (right side of Figure 30). Using the medium estimate of unmitigated emissions for non-Annex B (6.3 Gt C per year) and a 5.2% reduction of Annex B emissions compared to 1990, global emissions will reach 11.3 Gt C per year in 2010. Hence, the global emissions level lies above the top of the corridor that complies with the climate goals of the AOSIS (9.5 Gt C per year) but within the corridor for the EU climate goals. To stay within the 2010 to 2030 corridor (and to achieve the climate goal of the EU), global emissions must be reduced after 2010. The 2010-2030 corridor allows global emissions between 7.5 and 10.4 Gt C per year in 2030. This is equivalent to 92% of emissions in 2010 to reach the top of the corridor and to 66% of 2010 emissions to reach the bottom of the second (2010 to 2030) corridor.

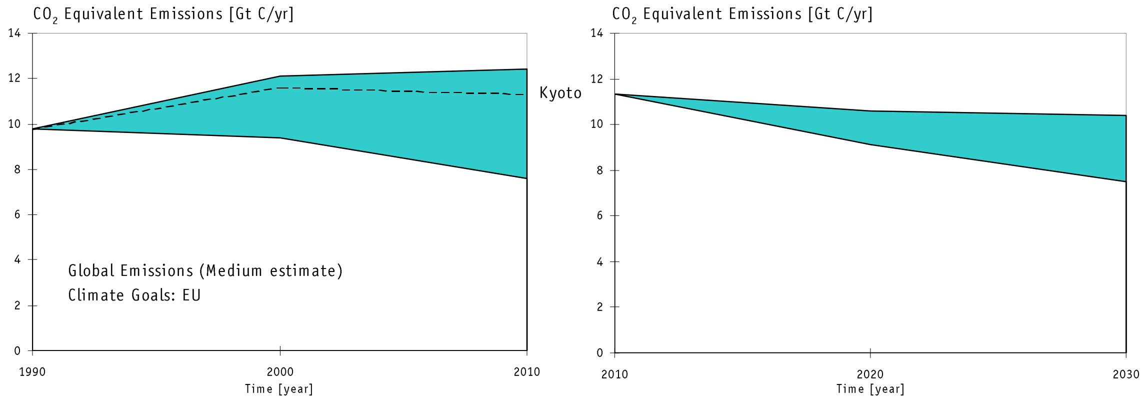

Figure 30: Safe emission corridors from 1990 to 2010, and their continuation from 2010 to 2030. Both corridors are constructed by using the limits on climate change of the EU climate protection goal. The global emissions resulting from the reduction commitments of Annex B parties to the Kyoto Protocol and medium emissions for non-Annex B countries are overlaid. The corridor on the right side begins where the Kyoto emissions end in 2010.

6.5 Sensitivity and Uncertainty

It is important to remind the reader that results presented in this chapter have many sources of uncertainty. A significant source of this uncertainty is the model used to perform calculations in this report, namely the IMAGE 2 model. The IMAGE 2 model, as all global models, can only approximate and never accurately predict global environmental changes. Another important source of uncertainty is the method used to compute safe emission corridors. Alcamo and Kreileman (1996a) and Swart, *et al.* (1998) point out some of the sources of these uncertainties, for example (1) the statistical correlations used to compute the corridors, (2) the uncertainties of environmental impacts related to the indicators, (3) the effect of sulfur emissions on global cooling, and the effect of this cooling on calculations of emission corridors. With regards to this last uncertainty, sulfur emissions in this report are fixed at their 1990 level but Alcamo and Kreileman (1996a) have pointed out that emission corridors could be significantly wider if sulfur emissions substantially increase in developing countries. The width of an emission corridor is also strongly dependent on the climate sensitivity of the global model used for computations. The model used in this report for computations has a climate sensitivity of 2.37, which is an intermediate value.

Finally, it is worthwhile repeating that computed corridors are very dependent on the selected values of indicators. For example, we showed earlier the dependence of corridor width on the specified limit for sea level rise (Figure 31a). Likewise, Figure 31b and c show the dependence of the corridor width (in year 2010) on limits for the rate of temperature change and emission reduction rate, respectively.

However, in spite of these uncertainties we got a clear tendency in results. Therefore, the "safe landing" approach seems to be valuable instrument for policy analyses.

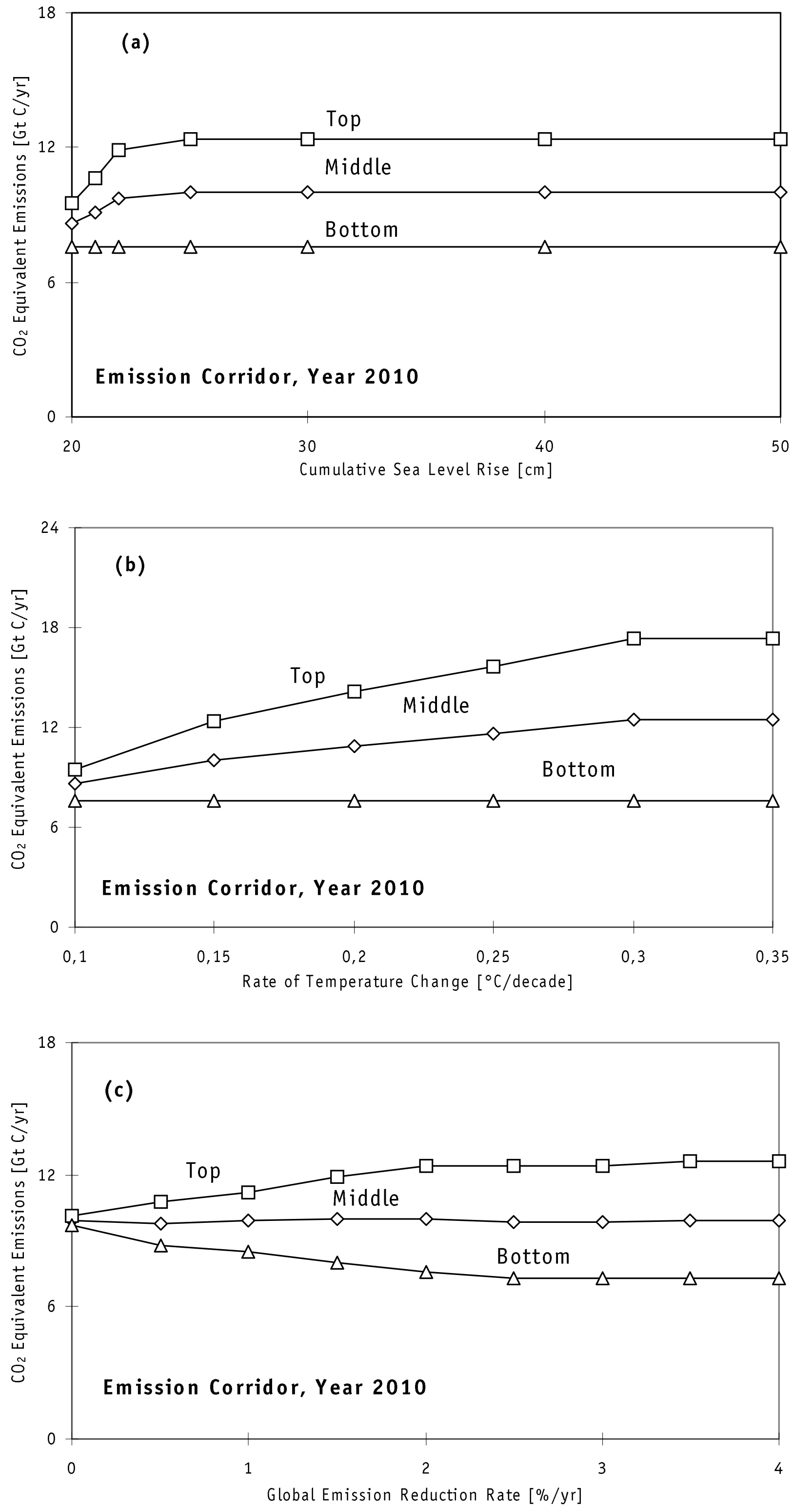

Figure 31: Sensitivity of width of safe emission corridor in 2010 to changing the limit of: (a) sea level rise, (b) decadal rate of temperature change, (c) emission reduction rate. Default values of indicators are set to: cumulative increase in global average temperature relative to 1990 = 1.5 °C, rate of temperature change = 0.15 °C/decade (this can be violated during 2 decades in the period 2000 to 2100), sea level rise relative to 1990 = 30 cm, rate of emission reductions = 2%/year.

6.6 Summary and Conclusions

Using the ”Safe Landing Approach” we computed the emission corridors between 1990 and 2010 that are permitted in order to comply with the long term climate goals of the AOSIS countries (20 cm sea level rise and 1.5°C temperature increase between 1990 and 2100) and the EU (1.5°C temperature increase between 1990 and 2100). Additionally, we assumed that the rate of temperature change may not exceed 0.15°C per decade and that the necessary rate of global emission reductions should not exceed 2% per year over the time period 1990-2100. For the climate goal of the EU we also limited sea level rise to 30 cm between 1990 and 2100.

The climate goals of the AOSIS proposal lead to a very low and narrow emission corridor between 1990 and 2010. To fall within the corridor, emissions in Annex B countries must be stringently reduced by 2010 relative to 1990 assuming that non-Annex B countries do not control their emissions.

The climate goal of the EU proposal leads to a wider corridor for allowable emissions than the AOSIS proposal. Nevertheless, to reach the middle of the corridor, Annex B emissions must be significantly reduced, and to reach the top of the corridor only small increases in Annex B emissions are allowed.

Global emissions resulting from the commitments of the Kyoto protocol lie outside of the emission corridor of the AOSIS proposal but inside the ”EU emission corridor” in 2010. But as they lie near the top of this corridor, a further increase in global emissions is not allowed after 2010 if the EU climate goal is to be achieved.

7. Conclusions

The determination of long-term climate protection goals is a very complex issue which was up to now of secondary importance in the international climate policy. A reason for this might be the difficulty to define a climate target that fulfills Article 2 of the Climate Convention: On the one hand, the food supply must be guaranteed and natural ecosystems must be able to adapt to climate change, on the other hand, a sustainable development of the economy must be possible. But in the case of reaching a stabilization of atmospheric greenhouse gases, as Article 2 also demands, some adverse effects of climate change might, nevertheless, be expected. At the same time, significant reduction measures are necessary (depending on the level of stabilization) which need extensive structural changes, especially in the energy economy. In other words, this means that climate policy has to solve the difficult task to decide which negative effects might be accepted and, at the same time, to initiate efforts to minimize the adverse impacts of climate change.

The purpose of this report is to provide a first estimate of global and regional impacts of two long term stabilization targets of 550 ppm and 450 ppm CO_2 in the atmosphere. We analyzed (1) the allowable global and regional greenhouse gas emissions to achieve these stabilization targets, and (2) the impacts of climate change of these stabilization targets on important natural and socioeconomic systems. All calculations were performed with the IMAGE 2.1 model. A brief summary of the results of this analysis as well as some conclusions from these results are given in the following text.

Global and Regional Greenhouse Gas Emissions

A significant reduction of emissions is necessary on the global and regional scale to achieve the targets for the stabilization of atmospheric CO_2. This is valid for the 450 ppm stabilization target (global emissions must be halved in the long term in order to achieve this target) and for the 550 ppm target (global emissions may not exceed 1990 emissions in the long term under this scenario). If non-Annex B countries are allowed a delay in taking part in climate protection regimes (their current emissions are low compared to their population), Annex B emissions must be reduced significantly in the medium term. In the long term, however, a participation of non Annex B countries in taking emission reduction measures is inevitable in order to achieve a stabilization of greenhouse gas concentrations.

Impacts of Climate Change

Even if a stabilization at 450 ppm or 550 ppm CO_2 in the atmosphere is achieved, a decrease of crop yields in agriculture and a risk for large areas of natural ecosystems caused by climate change might be expected. The pathways of the 450 ppm and the 550 ppm scenario allow a strong increase of concentrations in the short term. In the coming decades, we might therefore expect a climate change with a rapid increase in temperature and other climate-related variables. Especially in the short and medium term (until about 2030), we might expect a significant increase in areas with decreasing crop yields and natural ecosystems under risk. The decelerated increase of greenhouse gas concentrations in the middle of the 21st century causes a slower increase of impact levels. This is not valid for the sea level rise, which continues to increase in 2100. Impacts on agricultural systems strongly vary from region to region. This is also valid for the impacts on natural ecosystems. A strong increase of sulfur emissions in some regions of the world can lead to a mitigation of climate change impacts but these emissions can also cause significant and irreversible damages to human health and the environment.

Uncertainty of Results

The model results presented in this report have many sources of uncertainty:

1. The simulation of climate change is uncertain, especially that of precipitation patterns which is an important factor for the regional distribution of impacts.
2. The computation of the capacity of the biosphere and the oceans to remove CO_2 from the atmosphere is highly uncertain. These are used to back calculate the allowable anthropogenic CO_2 emissions to achieve a stabilization target on a prescribed CO_2 concentration pathway. The allowable emissions of the IMAGE model, however, are in the middle of the range of the models that participated in an IPCC model comparison (Enting *et al.*, 1994).
3. The quantification of the physiological reaction of plants on increasing CO_2 concentrations in combination with changing climate conditions is uncertain. Especially the role of the nutrient balance under enhanced biomass production is not yet clear and needs further exploration (Rosenzweig und Hillel, 1998).
4. In our analysis of climate change impacts on agricultural productivity and natural ecosystems, several factors were not considered. A change in climate conditions can change the regional patterns of pests and diseases and can therefore cause an additional threat to agricultural and natural ecosystems. Additionally, we did not take into account a change in climate variability which could result in a changing frequency and intensity of drought and/or flood occurrence. The results of the WaterGAP model on the climate-related change in water availability are a first step in this direction, but further research is needed.

In spite of these uncertainties the trends for the temporal development of emissions and impact levels are plausible from the current state of knowledge so that we can draw some general conclusions from the results of this study.

Final Results

From the results of this study we conclude:

1. A Strict control of global greenhouse gas emissions is necessary to achieve a stabilization target of 550 ppm or 450 ppm CO_2 in the atmosphere. Reduction measures will have to be carried out or financed (e.g. under the Clean Development Mechanism) mainly by the Annex B parties if Annex B and non-Annex B countries will be given the same right of (per capita) emissions in the long term.
2. In spite of a reduction of global greenhouse gas emissions and a long-term stabilization of greenhouse gas concentrations, the climate will change and some adverse impacts of this climate change might be expected. In the short term, impacts of climate change might rapidly increase, although a stabilization of CO_2 is realized on the prescribed

concentration pathway. A delay of reduction measures as it is often proposed from an economic point of view (e.g. Richels and Edmonds, 1995) could lead to a more rapid climate change with all its consequences for natural and socioeconomic systems. It is, therefore, necessary to thoroughly weigh the costs of early emissions reductions and consequently a deceleration of climate change, on the one hand, against an early occurrence and increase of negative impacts of climate change together with its costs, on the other hand.

3. Since a significant change of climate is soon to be expected (or is already occurring), the planning and increasing of adaptation capabilities should play a role of comparable importance to that of greenhouse gas emissions reductions. Adaptation measures e.g. in the agriculture system of industrialized countries can be realized relatively easily and within a short time. Developing countries, however, where the economy depends on agriculture are much more vulnerable even to small changes in agricultural productivity (see e.g. Watson *et al.*, 1997). The adaptation of natural ecosystems is difficult in principle (in industrialized countries as well as in developing countries) and, therefore, these systems can be seen as especially vulnerable with respect to climatic change.

The aim of this study was to provide policy makers with information which can be helpful to develop a long-term perspective for climate protection. In spite of the uncertainties contained in the results of this report, and because of the precautionary principle agreed on in Article 3 of the Climate Convention, it seems appropriate to begin with thorough reduction measures in industrialized countries and to plan and start adaptation measures in industrial as well as in developing countries.

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Appendix 1: Calculation of ”Safe Emission Corridors”

To compute the safe emission corridors for emissions between 1990 and 2010, the following steps have to be carried out:

1. The IMAGE model was run for a large number of different emission scenarios between 1990 and 2100 such as, for example, the Baseline A scenario and others.

2. Using the results from step 1, a correlation analysis is performed between the cumulative CO_2 equivalent emissions of these emission profiles and three indicators of climate change (global temperature change between 1990 and 2100, rate of temperature change per decade, and sea level rise between 1990 and 2100).

3. In the next step, the cumulative emissions of several thousand emission profiles from 1990 to 2100 were calculated. For these emission profiles, a minimum and a maximum constraint was set for the yearly rate of change of emissions. They may maximally increase by 3% per year and maximally decrease by 4% per year. Unlikely pathways such as, for example, oscillating emissions were excluded.

4. The width of an emission corridor mainly depends on the constraints we define for the indicators of climate change. Hence, to compute a corridor we have to specify a set of climate goals (e.g., a limit of 30 cm for the sea level rise between 1990 and 2100, a maximum temperature change of 2°C, and a maximum rate of temperature change of 0.1°C per decade). Additionally, a maximum emission reduction rate must be set which defines the bottom of the emission corridor. Then the correlation of step 2 is used to calculate the maximum cumulative CO_2 equivalent emissions between 1990 and 2100 to achieve these climate goals.

5. Once the maximum allowable cumulative emissions are known, and a limit is set on the maximum rate of global emission reductions we can select those emission profiles from step 3 that comply with the maximum of cumulative emissions and that do not exceed the allowable rate of change of global emissions.

The safe emission corridor between 1990 and 2010 consists of the large number of emission profiles from step 5 that allow to reach the specified climate goals since each of the emission pathways that lies within this corridor has a continuation after 2010 up to the year 2100. But of course, to achieve the specified climate goals also depends on the emission pathways after 2010 as we demonstrated for the global emissions that could be achieved by the realization of the Kyoto Protocol (see chapter 6.4 of this report).

Table 1-A: Runoff in 1995 and change in runoff of selected watersheds under the Kyoto Scenario and the 550 ppm and 450 ppm Stabilization Scenario.

		Average 1995	**1995**	**10-percentil dry year**								
				2020			**2050**			**2100**		
				Kyoto	550ppm	450ppm	Kyoto	550ppm	450ppm	Kyoto	550ppm	450ppm
IMAGE Region	**River**	[mm/year]	[mm/year]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
Oceania	Murray	7	4	-18	-17	-16	**-31**	-29	-27	**-37**	**-36**	**-31**
Africa	Senegal	41	14	-16	-17	-16	**-30**	-29	-27	**-47**	**-37**	**-32**
Africa	Zambezi	79	18	7	9	8	18	19	17	**45**	29	22
China+CPA	Huanghe	63	20	10	10	10	**31**	27	22	**106**	**48**	**31**
Oceania	Burdekin	75	28	-14	-15	-14	-26	-26	-24	**-38**	**-33**	-28
Middle East	Al_Furat	88	45	**65**	**67**	**63**	**156**	**143**	**126**	**340**	**215**	**161**
USA	Mississippi	141	78	22	24	22	**58**	**53**	**46**	**140**	**83**	**60**
Africa	Rufiji	188	88	2	3	3	6	6	5	14	9	7
CIS	Ob	181	106	**42**	**40**	**38**	**89**	**79**	**70**	**168**	**113**	**87**
Eastern Europe	Odra	200	114	**47**	**52**	**51**	**62**	**66**	**65**	**92**	**75**	**69**
India+S. Asia	Godavari	329	144	29	**32**	**30**	**68**	**66**	**59**	**154**	**100**	**78**
OECD Europe	Loire	228	159	3	2	2	7	6	5	26	10	7
CIS	N. Dvina	230	163	-3	-3	-3	-7	-6	-6	1	-8	-7
CIS	Lena	253	173	14	13	12	31	27	24	**69**	**40**	**29**
OECD Europe	Guadalquivir	230	189	**-36**	**-36**	**-34**	**-61**	**-59**	**-55**	**-73**	**-68**	**-62**
Eastern Europe	Danube	326	200	6	6	6	8	8	8	**33**	11	9
USA	Columbia	267	211	3	3	2	10	8	6	**37**	15	9
Latin America	Uruguay	459	216	-4	-4	-4	-6	-6	-5	6	-5	-5
Africa	Zaire	500	296	11	12	12	27	26	23	**63**	**41**	**31**
China+CPA	Changjiang	484	326	4	4	4	11	10	8	**37**	18	12
Canada	Fraser	446	355	-3	-3	-3	-3	-4	-4	9	-2	-4
OECD Europe	Rhine	475	386	2	2	2	5	4	4	19	8	5
Latin America	Amazonas	1047	782	13	14	14	28	27	25	**55**	**39**	**31**
Japan	N-Jap.	1028	819	-2	-2	-2	-4	-4	-3	-6	-5	-4
India+S. Asia	Brahmaputra	1271	996	8	9	9	20	18	16	**47**	29	21
East Asia	Barito	1856	1501	0	0	0	1	1	1	2	1	1

> 10% decrease > 10% increase
> 30% decrease **> 30% increase**

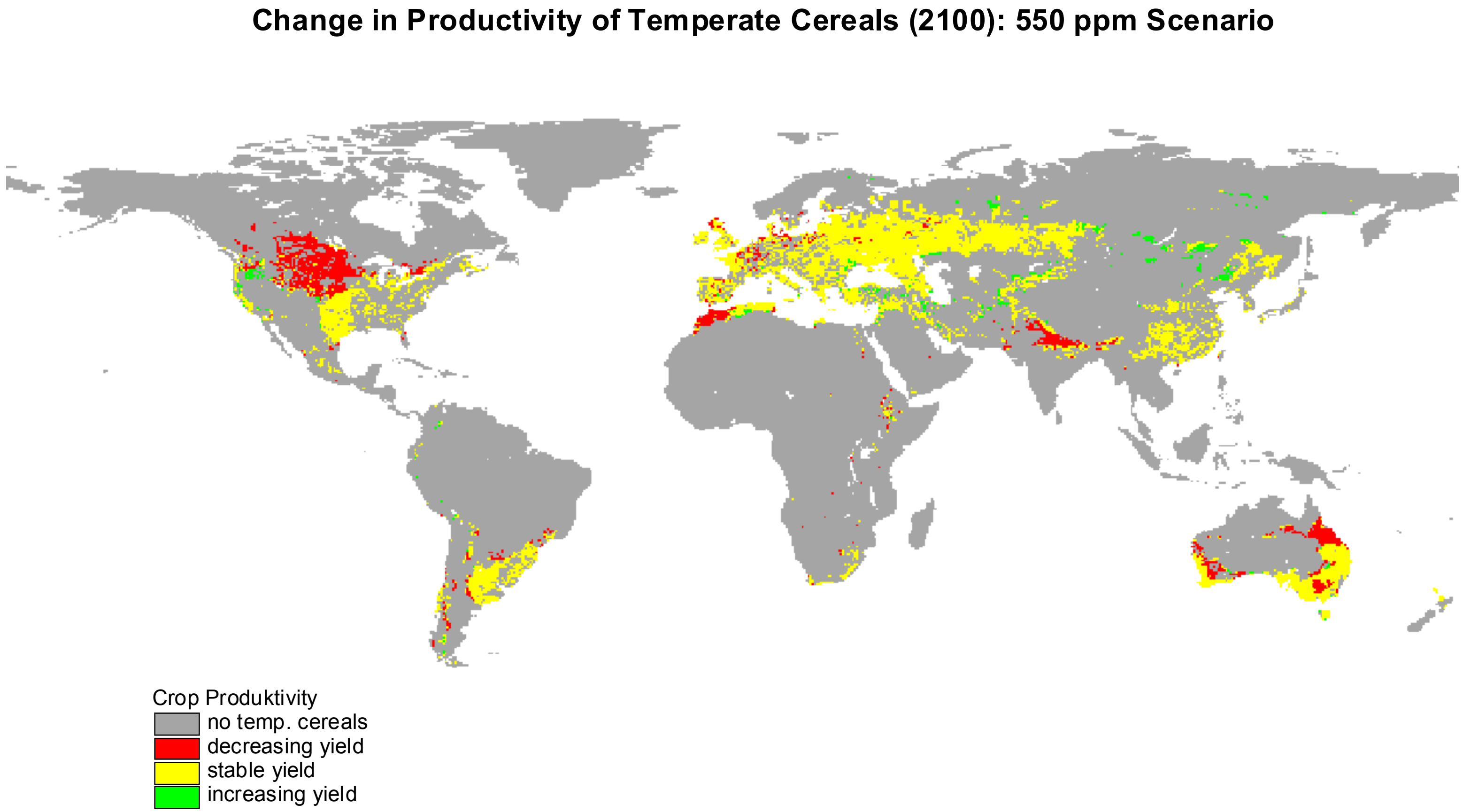

Figure 1-A: Change in potential yield of temperate cereals in 2100 under the 550 ppm CO_2 scenario. Presented are only those areas where temperate cereals are grown in 1990.

Risk to Potential Natural Vegetation (2100): 550 ppm Scenario

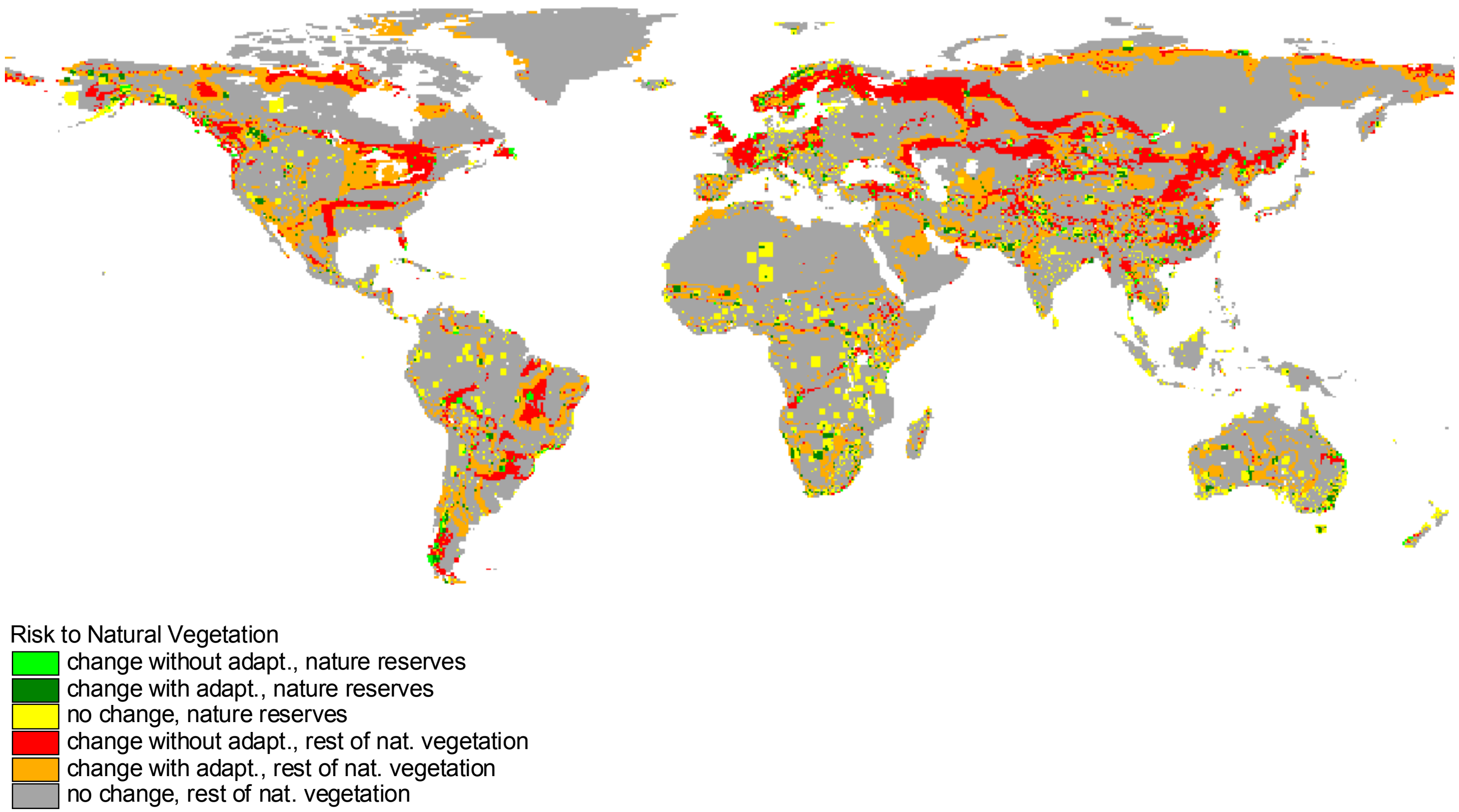

Figure 2-A: Risk to the 1990 potential natural vegetation in 2100 under the 550 ppm CO_2 scenario. The possibility of adaptation to climate change is taken into account.