

Impact Models (including uncertainties)

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**State-of-the-art computer models related to climate change
Impact model and their uncertainties**

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Abstract

Different types of impacts have been included in Integrated Assessment Models. The most advanced models currently simulate the complete chain of 'human activities – greenhouse gas emissions – atmospheric processes – climate change – impacts – costs of impacts'. However, large differences in aggregation and complexity levels exist among models. Several examples of applications of integrated assessment models, with respect to impacts, highlight their uncertainties and limitations, are presented. It is concluded that for a comprehensive treatment of impacts both the consequences of changes in CO₂ concentrations, and climate and human activities (such as land use), have to be included. Regional impacts should not be neglected. Further, systemic interactions and feedbacks within the climate system should also be addressed. The use of consistent scenarios are required to develop comparable regional and sectoral impact scenarios. Addressing the impacts comprehensively allows us one to link climate change issues, with other major environmental issues such as biodiversity and food and water security.

Introduction

Human development has not been without environmental consequences. The burning of fossil fuels, and conversion of forests and other ecosystems (e.g. wetlands) to pastures and arable lands, have increased the atmospheric concentrations of CO₂ and other greenhouse gases (GHGs; Houghton *et al.*, 1996). This increase in GHG concentrations alters the radiative balance of the atmosphere by absorbing heat and, consequently, the Earth's surface is becoming warmer. Although the magnitude, regional patterns and timing of such climatic changes are not yet completely understood, the consequences can be pronounced. Although some regions and/or socio-economic sectors may benefit, climate change generally leads to further stress on ecosystems and society (Watson *et al.*, 1996).

Integrated Assessment Models for climate change (IAMs) simulate the complete chain of 'human activities – greenhouse gas (GHG) emissions – atmospheric processes – climate change – impacts – costs of impacts'. Several models further evaluate the costs of reducing GHG emissions against positive (benefits) and negative (damages) impacts (e.g. DICE, Nordhaus 1992) or add a stochastic element to address uncertainty (e.g. ICAM, Dowlatabadi and Morgan, 1993). Unfortunately, most such analyses still only include highly aggregated representations of climate-change impacts by representing damages as a direct function of global mean temperatures. Although global mean temperature is one of the most straightforward proxies for climate impacts, such simplification does not address the full complexity and (temporal, regional) diversity of impacts and the interactions in the Earth system.

In this paper, I shall summarise and classify the different types of the impacts and review different modelling approaches to assess these impacts. My background as a plant-ecologist

logically creates a bias towards ecological and agricultural systems. This bias, however, allows one to illustrate the complexity, diversity and interactions in the climate and Earth system. For example, in determining the response of ecological systems, both the direct and indirect effects of changing atmospheric CO₂-concentrations and climate change (and, off course, their interactions) have to be addressed. Ecosystem responses depend on both the rate and magnitude of change, are highly non-linear and caused by processes at many different scale levels (cell, organ, individual, community, ecosystem, biosphere). Ecosystems therefore are not only impacted, but are also an important component in determining the strength of different feedback processes in the climate system. The importance of these complex roles can only be addressed comprehensively with more process-based, regionalised and dynamic IAMs. As such they should be capable to determine the sensitivity and vulnerability of systems and sectors.

I'll start with a short overview of earlier impacts assessments, their approaches, their scenarios used and their limitations. This overview will focus on sectoral, regional and global assessments. Finally, I'll use examples of comprehensive impact scenarios which show some interactions of the Earth systems in combination with different GHG emissions paths. Those calculations for this assessment are done with the IMAGE 2 model (Alcamo, 1994; Alcamo *et al.*, 1996), developed at RIVM and currently one of the few models capable of simulating a range of different impacts both regionally and globally. The impacts levels through time are calculated by IMAGE 2 and contain sea-level rise, ecosystem productivity, land cover patterns, agricultural productivity, biodiversity and vector-borne diseases, such as Malaria. The integration of the many different dimensions in this model do allow for advanced impact assessments at different levels. For a diverse set of transient scenarios, I'll present both globally aggregated and regional results. Globally, it can be concluded that the global mean temperature is a good proxy. This does not hold, however, for the regional assessments.

Earlier 'Integrated Assessments' of impacts of climate change

In this section I will highlight some of the earlier integrated assessments. Most of these assessments were regionally focused and based on expert judgement, modelling and scenario development. Although some very innovative and high-quality assessments have been made for water resources and river-systems (e.g. the Nile study by Yates and Strzepek (1996) and the MacKenzie Basin study by Cohen (1995)), I'll use examples from energy use (from Dept. of the Environment 1996), agriculture (from Hulme *et al.* 1992 and Rosenzweig and Parry, 1994), ecosystem distribution and the vectors transferring vector borne diseases (from Hulme *et al.*, 1996). However, before I can discuss these studies, the different approaches to develop scenarios have to be discussed to enable examination of the advantages and disadvantages of each study.

Climate Change scenario generation

Reliable climate change scenarios are needed for the assessment of impacts. In earlier efforts, only climate change or the direct effects of CO₂ was implemented, but they were seldom combined together. More recently, the climate scenarios have become more linked with the changes in concentrations of CO₂ and other GHGs. There are several ways to create such scenarios (Carter *et al.*, 1994; Table 1). The simplest approach is the arbitrary or systematic prescription of a specific climatic change attainable by varying the temperature and precipitation (or other) model input. This synthetic approach is a simple sensitivity analysis that highlights the vulnerability of the system modelled. The major disadvantage of this approach is that the scenarios do not represent a realistic future climate. Although popular in simple and rapid assessments, the approach is no longer used in more thorough assessments. Recent developments in this approach are to link such changes to weather generators. Such algorithms describe the current variability of local and regional climate, and statistically

produce climatic series that resemble realistic climatic patterns. They can be used for future climate as well, but the limitations of synthetic approaches remain to a large extent.

Table 1: Different approaches for creating climate scenarios

Approach	Advantage	Disadvantage	Examples
1 Synthetic climate change by varying T and P	Easy to assess vulnerability	No realistic climate change	Holten and Carey (1992); Boer and de Groot (1990)
2 Weather generators	Contains the climatic variability of local and regional climate	Simplifying assumptions on the climate system lead to deviations; probably no realistic scenario under future conditions	Jones <i>et al.</i> (1994)
3 Historic analogues	Realistic climate patterns	Probably no realistic future patterns	Mitchell (1990)
4 Regional analogues	Realistic climate and land-use patterns	Different socio-economic patterns	Parry <i>et al.</i> (1988)
5 Equilibrium simulation with global climate models (AGCMs)	Realistic global climate-change patterns	Rough simulated patterns of climate change; only double CO ₂ conditions tested; limited regional applications	Leemans (1992)
6 Equilibrium simulation with global climate models combined with nested regional models	Realistic global and regional climate-change patterns	Only double CO ₂ conditions tested; statistical downscaling methods often used that are less appropriate for changed climate	Giorgi <i>et al.</i> (1994)
7 Transient simulation with coupled global climate and ocean models	Realistic development of global climate-change patterns; unambiguously coupled to GHG concentrations	Computer demanding; only few scenarios possible; rough simulated patterns of climate change	Manabe <i>et al.</i> (1991)
8 Simulations with Integrated Assessment models	Transient GHG concentrations and climate change considered; feedbacks between components of the climate system considered	Relatively simple models used; difficult to implement because of lack of understanding of linkages and interactions in the climate system	Alcamo <i>et al.</i> (1996); Hulme <i>et al.</i> (1994)

A more advanced approach is to use an analogue climate, either from a past warmer or cooler period, or from a region with a climate assumed similar to the future climate. For example, the warmer period in the Holocene (the so-called climatic optimum) has often been proposed as a good analogue for early GHG-induced climate change. Unfortunately, the position/inclination of the earth relative to the sun was different, which generates climatic conditions largely different from a future greenhouse climate (Mitchell, 1990). The other approach is to use single warm or dry years from the historical record. In principle, this is a valid approach to test the vulnerability of ecosystems and/or agriculture, but single years may not show long-term impacts. The disadvantage of the regional analogue is that non-climatic factors, such as soil types, land uses and socio-economic parameters differ. These factors could influence more strongly local crop and ecosystem patterns than climatic factors. Conclusions from analogue studies can therefore be misleading.

The most generally used approach is to derive scenarios from three-dimensional Atmospheric Global Circulation Models, the AGCMs. These full three-dimensional climate models simulate global climatic patterns on a grid between 2 and 9 degrees longitude and/or latitude and several vertical layers thick, by simultaneously solving the energy-balance equations of each grid cell. The temperature exchange with the oceans are prescribed and there are no systemic interactions between the oceans and atmosphere. Generally, such equilibrium AGCM simulations perform well for current climate conditions. Seasonal temperature patterns and pressure fields are similar to observed climatologies. However, the characteristic patterns of precipitation, critical for agriculture and ecosystems, only resemble reality at the highest grid resolutions of 2 to 3 degrees. These resolutions are very computationally demanding. AGCMs are perturbed by changed GHG concentrations. Double CO₂ runs generally assume that the additional forcing resembles that of a doubling of CO₂ concentrations (often 560 or 600 ppmv) without considering the contribution of other GHGs. The simulated climate change (control run for current climate minus doubled CO₂ run) is then used for impact studies.

Generally, such AGCM derived climate change scenarios are overlaid on a higher resolution database with observed climate to obtain plausible future climatologies (for a review see Leemans, 1992). To obtain climate-change patterns for different levels of CO₂ and other GHGs, the doubled-CO₂ climate change is normalised using its global mean temperature change (the so-called climate sensitivity) and the patterns are then scaled for the desired level of GHGs (Viner *et al.*, 1995). This method represents one of the most reliable and flexible approaches for obtaining 'realistic' future climatologies with consistency between GHG-emission scenarios, climatic change and impacts. However, the resolution of these AGCM-based climatologies is coarse. Several approaches for linking AGCM with regional climate models and/or regional time series have been developed to improve spatial and temporal resolutions. Unfortunately, the systematic errors in the AGCM simulations have not been reduced.

Runs of AGCMs coupled with ocean circulation models have been performed. Here the ocean and atmosphere interact with each other continuously. These coupled models are disturbed through time with an increasing levels of greenhouse gases and simulate the transient response of the climate system (biosphere, oceans and atmosphere). These coupled models demand huge computing resources and only a few scenarios are available (Houghton *et al.*, 1996). Generally, they show a lower (or slower) climatic change than the equilibrium AGCMs. This is mainly due to the inertia of the oceans. These models can also include the simultaneous effect of sulphur aerosols, which has a regional cooling effect. The use of these complex models has led to projected future warming being less than in the earlier simulations. Some impact assessments have already used transient scenarios but due to the amount of data to process and limitation in resolution, these transient scenarios have been used only in a quasi-equilibrium mode (e.g. Prentice *et al.*, 1993). Development of truly transient scenarios will significantly advance the science.

Another approach has been developed: the integrated assessment models. These IAMs include simplified formulations for important components of the climate system. The large advantage of these models is that they simulate the emissions from land-use change and energy use, both derived from regional socio-economic, demographic and technological developments. Important aspects of the Carbon cycle and atmospheric chemistry are considered in defining the atmospheric concentrations of GHGs. Major feedbacks between the biosphere, ocean and atmosphere are often explicitly simulated. Besides, the impacts can alter such outcomes as land use or terrestrial Carbon (C) sequestration. This approach therefore gives an integrated view of the transient response of the climate/Earth system. Examples of these models are IMAGE 1 (Rotmans *et al.*, 1990), ESCAPE (Hulme *et al.*,

1994) or GCAM (Edmonds *et al.*, 1994), AIM (Matsuoka *et al.*, 1994) and IMAGE 2 (Alcamo, 1996). Often the simpler zero, one, or two-dimensional climate modules in these IAMs are improved by linking them to AGCM scenarios to get more realistic global climate-change patterns using the scaling approach described above. The result of simulations with IAMs is a time-dependent emission and concentration path combined with consistent climate change. This is especially suited for impact assessments.

Many diverse approaches for generating climate scenarios clearly exist. Although often hybrid approaches are used, no common, generally accepted approach has emerged up to now. This is probably one of the reasons for the inconclusiveness of the impact section of the second assessment report of IPCC (Watson *et al.*, 1996). Its main conclusion that 'Climate change adds a significant stress to many systems' seems trivial. However, the diversity of scenarios has led to very high heterogeneity in the results of impact studies and a seemingly very high uncertainty about impacts of climate change. Hopefully, with commonly accepted and widely available scenarios of coupled transient AGCMs and IAMs, this uncertainty will in the near future be reduced, with clearer regional impact patterns emerging.

Review of earlier Integrated Assessments

Changes in crop and ecosystem distribution

Natural ecosystem and agricultural crop models can be classified similarly. An important group of these models determines the distribution of ecosystems and crops. These biogeographical models often form an important component of land evaluation systems (e.g. FAO, 1978) and are used to assess coarse-scale effects of global environmental change. Biogeographical models are often derived from climate classification schemes. Generally, these models are relatively simple and can be implemented based on readily available soil and climate data, for example, the classification of Köppen (1936), or the Life Zone Classification of Holdridge (1947). These models regress broad-scale vegetation patterns or biomes to indices of temperature and precipitation. Currently, more process-based biome models that incorporate eco-physiological constraints on these distributions, have been developed (e.g. Prentice *et al.*, 1992). These classifications were among the first to be used to determine the impacts of climate change on ecosystems (Emanuel *et al.*, 1985; Guetter and Kutzbach, 1990). Such simulations show large shifts in ecosystem patterns; they also emphasise that impacts of climate change should not be underestimated.

Solomon and Leemans (1996) have used the BIOME model to assess changes in carbon storage of boreal forests. They mapped forests distribution under past, current and future conditions and showed that if these forests ecosystems would adapt instantaneously to climate change C storage would be enhanced due to a larger C storage in the expanding forests. This is one of the negative feedbacks on the build-up of atmospheric CO₂ concentrations. This result coincided with earlier assessments (e.g. Smith *et al.*, 1992). However, if adaptation is viewed as less rapid, by assuming that the appropriate tree species cannot migrate fast enough into the newly available areas and the abundance of existing species declines, a depauperate ecosystem will evolve, which has a lower C storage. They also showed that under climatic warming large areas of the boreal forests become suitable for agriculture and, with increasing global populations and their food and wood demands, this could lead to an additional decrease of the forests' area and C storage, especially in the southern parts of the boreal forests. This study is a nice and simple example of using scenarios based on GCM-output, current climate databases and biogeographical models to assess complex C cycle issues. It addresses the sensitivity and adaptability of the ecosystems. However, it does not comprehensively evaluate the vulnerability.

The use of biogeographical models for crop distributions also have a long history (for a review see Leemans and Solomon, 1993). These models' illustration of the climatological constraints on crops is seen, for example, in growth hindrance by temperatures too high and too low. Different climate indices, such as the length of the growing season or effective temperature sums, are applied to regress against observed crop distribution. Such simple regressions can then be applied to a changed climate. Shifts in distribution, similar to those of the biogeographical models for ecosystems, were simulated with such approaches (e.g. Blasing and Solomon, 1984; Rosenzweig, 1985; Parry *et al.*, 1988).

These simple biogeographical models have many disadvantages. First, they are only applicable to stable equilibrium conditions. Climate variability and the transient responses to climate change are not considered. Second, changes in crop physiology and ecosystem productivity, life cycles and other properties, are not adequately included. For example, warming tends to accelerate plant growth, reducing the required growth period. If growth is accelerated during the period in which the grain is filling out, the quality of the yield may decline. These models give thus only a limited assessment of climatic impacts. Finally, adaptive human behaviour and land use, especially important for agriculture, is left out. Although these models illustrate that crop distributions are sensitive to climate change, this conclusion cannot be directly extrapolated to the agricultural sector. This sector is probably less vulnerable because its current management practices create many options for adaptive capabilities (Reilly *et al.*, 1996). Only under extreme, mostly arid, conditions with marginal agriculture can the impacts of climate change on agriculture become a significant limiting factor here.

A very simple example of the agricultural suitability model is the cropping system definition used by the Meteorological Academy in China (Hulme *et al.*, 1992). This model is solely based on growing degree days (GDDs) of temperature sums, the sums of daily temperatures above a certain threshold, here 5 °C. Different levels of GDDs determine if a single crop (mostly wheat or maize), two (wheat and rice) or three crops (rice, rice and rice) can be cultivated annually. Hulme *et al.* (1992) used this rule, and map the boundaries of these cropping systems. Large increases in double and triple cropping regions could be observed. However, this approach does not include changes in moisture and/or soil factors and could therefore give an much too optimistic view of future conditions. The biogeographic models have made one aspect very clear: environmental constraints largely define limits on crop growth and ecosystem productivity. However, to fully comprehend the impact of crop and ecosystem response to environmental change, productivity models are required.

Potential impact of climate change on world food supply

Rosenzweig and Parry (1994) have used a series of models to determine the possibility of changes in the global agricultural sector under climate change. They created a network of local and regional crop researchers from 18 countries, who have estimated the potential changes in national grain crop yields using compatible crop models from the CERES family and standardised climate-change scenarios. These scenarios were derived from three different equilibrium AGCM results; the GISS, GFDL and UKMO models, and were complemented with prescribed scenarios for CO₂ concentrations. Rosenzweig and Parry (1994) assumed that the CO₂ concentration would have reached CO₂-doubling conditions (555 ppmv) in 2060. This is consistent with the IPCC-IS92a scenario (Alcamo *et al.*, 1995). An additional scenario was developed where no changes in climate or CO₂ concentrations were assumed. This was the reference scenario to compare the others with. To assess the possibilities and impacts of adaptation, two different levels were assumed. Adaptation level 1 includes changes in crop variety, planting date (less than one month) and irrigation level. Adaptation level 2 includes in addition changes in crop type, planting date (more than one month) and extension of irrigation (Rosenzweig and Parry, 1994).

When direct CO₂ effects were not included in these scenarios, there was a large decrease in global grain yields (Table 2). The decrease was most pronounced in the UKMO climate scenarios and less in the GISS scenarios. Regional changes became apparent with the direct effects of CO₂ included. In general, grain yields in the northern hemisphere increased and it decreased in lesser developed regions. The increase was most pronounced for the GISS scenario and less for the UKMO. The latter scenario has the highest temperatures and the impacts of higher temperatures seem to be important in decreasing yield. The two different farming adaptation levels have a large impact on response to climate change. Negative impacts in several temperate regions, such as China and Europe, were reversed by increasing the degree of farmers' adaptation of new management practices. Only for Adaptation level 2 was it possible to maintain current grain yields (Table 2).

Table 2: Percentage change in cereal production under different AGCM equilibrium scenarios for doubled CO₂ climate. Adaptation level 1 includes changes in crop variety, planting date (less than one month), and irrigation level. Adaptation level 2 additionally includes changes in crop type, planting date (more than one month) and extension of irrigation (Adapted from Rosenzweig and Parry, 1994).

REGION	GISS	GFDL	UKMO
World Total			
Climate effects only	-10.9	-12.1	-19.6
Plus physiological effects of CO ₂	-1.2	-2.8	-7.6
Plus adaptation level 1	0.0	-1.6	-5.2
Plus adaptation level 2	1.1	-0.1	-2.4
Developed countries			
Climate effects only	-3.9	-10.1	-23.9
Plus physiological effects of CO ₂	1.3	5.2	-3.6
Plus adaptation level 1	14.2	7.9	3.8
Plus adaptation level 2	11.0	3.0	1.8
Developing countries			
Climate effects only	-16.2	-13.7	-16.3
Plus physiological effects of CO ₂	-11.0	-9.2	-10.9
Plus adaptation level 1	-11.2	-9.2	-12.5
Plus adaptation level 2	-6.6	-5.6	-5.8

Rosenzweig and Parry (1994) then linked the results of these crop simulations to a global food trade model, the Basic Linked System (BSL: Fischer *et al.*, 1998), which is also used for the FAO future projections (Alexandratos, 1995). This model simulates the complex dynamic interactions of producers and consumers, interacting through global markets. Technological improvements are also included in BSL. For the determination of changes in demand, population and GDP growth were assumed. These were consistent with the IPCC-IS92a assumptions and thus compatible with the time path of assumed CO₂ concentrations. Additional scenarios were created with BSL: different levels of trade liberalisation, population and economic growth.

The results (Table 2) change when linked to the Basic Link System. This analysis showed that the increase in grain yields for the developed regions increased the disparities between developed and developing countries. Despite farmer adaptation, this increased cereal prices and reduced food security in the developing world. Even at a high adaptation level the agricultural sector could not prevent these negative effects. The scenarios in the absence of climate change and with full trade liberalisation and low population growth showed that global food security actually increased. However, this could be counteracted by low economic growth. Even with climate change, the scenarios with trade liberalisation and low

population growth show better results than the other scenarios. However, the discrepancies between the developed and lesser developed world remained.

This study represents an important benchmark in assessing the impacts of climate change. It highlights the importance of socio-economic factors not related to climate change. There are, however, several limitations to this study. Working at the national level typically dampens the effect of local and regional responses. This is especially important for large developed countries where the environments are heterogeneous and many marginal areas exist, possibly leading to overestimation of the positive effects in developed countries. Further, the models used are all temperate crop models. Although they are calibrated to local circumstances, their applicability to changed tropical conditions could be limited, increasing the negative effect. The disparity between developed and lesser developed regions could be partly a model artefact.

Climate sensitivities in the UK energy sector

The UK is one of the few countries that have conducted a comprehensive impact assessment (Dept. of the Environment, 1996). This study covered the most important sectors and was based both on expert judgement and model analyses. Here I only highlight some of the results for the energy sector (Refer to Table 3). This is because this sector is one of the major sources of GHG emissions. The sensitivity of the UK energy sector was generally judged to be very low. However, several components, such as offshore oil and gas production systems and hydropower, were assumed to be vulnerable for increased storminess and water availability. Energy demand could also be changed strongly by climate change. Increased temperatures decrease the need for space heating, but increase the need for a more energy-intensive air-conditioning.

The most vulnerable components of the UK energy sector were the renewable energy sources and biomass. These renewables are also of prime importance for mitigating GHG emissions. For example hydro-electric installations could be influenced by changing water availability through changes in precipitation, evaporation and runoff due to climate change. Extreme events could damage wind turbines. Most apparent, however, was the strong impacts on biomass crops. Many studies on future energy carriers (e.g. SHELL, Kassler, 1994; Ishitani *et al.*, 1996) foresee a strong increase in the use of biomass crops as a source of energy. The UK study using different types of models, showed that these crops are vulnerable to climate change. This could harm large scale development. This assessment again clearly illustrates the importance of linkages between different disciplines and approaches.

The distribution of Malaria mosquitoes in southern Africa.

Hulme *et al.* have conducted a diverse impact study for the Southern African region (SADC). This study used several GCM-based scenarios and focused on trends in climate change, impacts on natural vegetation, nature reserves, runoff, agriculture, rangelands, vector-borne diseases, ungulate diversity and policy. As such it was one of the first comprehensive studies that used a common set of scenario assumptions and baseline climatologies (a most likely, a dry and wet future climate) and addressed simultaneously the direct effects of CO₂ and climate using state-of-the-art regional impact assessment technologies. Here I'll only highlight one aspect of the study: changes in habitat suitability for disease vectors, because this aspect of climate change impact has obtained little emphasis up to now in the scientific literature.

The SADC study simulated the changing distribution of three disease vectors: mosquitoes, tsetse flies and ticks. The habitat suitability for the mosquito shows a net increase under all scenarios, while for the tsetse fly there is a net decline. The results for the tick are a little more ambiguous. Its habitat suitability increases under the most likely and dry scenarios,

while decreases under the wet scenario. There are thus noticeable changes in the suitability of different regions in Southern Africa under climate change but the response pattern is species specific. It is very difficult to generalise. Mosquitoes extend their ranges south and westwards into Namibia and northern South Africa. The areas west of their present ranges become more suitable, while eastern areas become less suitable. The consequences of these changes in habitat distribution for human and animal well-being have to be addressed. It was beyond the scope of the present study. However, the study clearly showed complex changes in the occurrence patterns of disease vectors.

Table 3: Synopsis of climate sensitivities in the energy sector (Adapted from Dept. of the Environment (1996)).
Italics character style denote significant impacts.

	Temperature	Precipitation	Windiness	Frequency of extreme events	Water availability	Sea level rise	Other
Renewables	more evaporation from resevoirs, shifting seasonal run-off	hydro-electric potential	wave potential, resevoir evaporation, wind potential	many renewable systems vulnerable- especially wind turbines, solar systems	hydro-electric potential	deisgn of tidal wave systems	insulation affects
Biomass	<i>Biomass availability</i>	<i>Biomass availability</i>		<i>damage to biomass crops</i>	<i>Biomass availability</i>		
Energy demand	less space heating, more air conditioning		space heating				More humidity, more air conditioning
Energy extraction	open-cast coal mining	open-cast coal mining		<i>off-shore oil and gas</i>		off-shore oil and gas	
Energy conversion	Slightly less efficient thermal generation				cooling water availability	coastal power stations and refineries	
Energy transport/ transmission	lower capacity of powerlines	icing of powerlines		effects on powerlines			

Conclusions on impact assessments.

Although these impact assessments were very useful to identify and frame important issues, and were critical to define the importance of feedbacks, interactions and societal responses, such as possible adaptation levels, they all have their minor or major limitations. In general, they only address few aspects of global change and consider limited interactions with other important processes or sectors. Most importantly, these assessments address a single, often equilibrium future period and do not consider the transient consequences of change and its impacts. Both transient ecological and societal responses are important in determining the

outcome. During such transient changes boundary conditions could be altered, which determines the actual direction of response. For example, Smith and Shugart (1993) have shown that a transient response could lead to forests dieback over large areas, leading to an increase in CO₂ emissions, while an equilibrium response showed an enhanced uptake of CO₂ by forests. Transient responses are also important for regions with changing land-use patterns (Turner *et al.*, 1995). Such transient responses have largely been neglected in the second assessment report of IPCC (Watson *et al.*, 1995).

One way of defining and evaluating these transient responses is to use Integrated Assessment Models (IAMs) because these models dynamically calculate GHG emissions, the build-up of atmospheric concentrations and impacts. The most advanced of these models are regionally explicit, include adequate richness in impacts sectors and can thus be used to define impact levels comprehensively. Here, I will use the IMAGE 2 model (Alcamo, 1994) to illustrate some of the most important issues for such transient impact assessments. I'll use several scenarios that span the wide range of IPCC emission profiles and the different proposed protocols during the FCCC negotiations. Although the impacts models included in IMAGE 2 models are coarse and do not simulate the full richness of responses and possible impacts, they are based on the environmental characteristics of a high-resolution 0.5x0.5° longitude and latitude grid. Interactions such as direct responses to CO₂, climate change and land use and agricultural impacts, are explicitly included. I will not use the results on this grid, but aggregate towards coarse regions. This allows to more easily distinguish comprehensive trends and draw conclusions.

The Integrated Assessment Model, IMAGE 2

The previous discussions on impacts highlighted the need for strongly improved integrated assessments and the development of models to facilitate this. The development of such models has only started recently (Weyant *et al.*, 1996).

The structure of IMAGE 2

Like other IAMs, IMAGE 2 covers the entire globe, but, in addition, also performs many calculations on a global grid and for 13 world regions. This spatial resolution increases model testability against measurements, allows an improved representation of feedbacks and provides more detailed information for climate impact analysis. Moreover, the submodels of IMAGE 2 are, in general, more process-oriented and contain fewer global parameterisations than previous models, which enhances the scientific credibility of calculations. Unfortunately, these developments also add greatly to the computational and data handling tasks of the model.

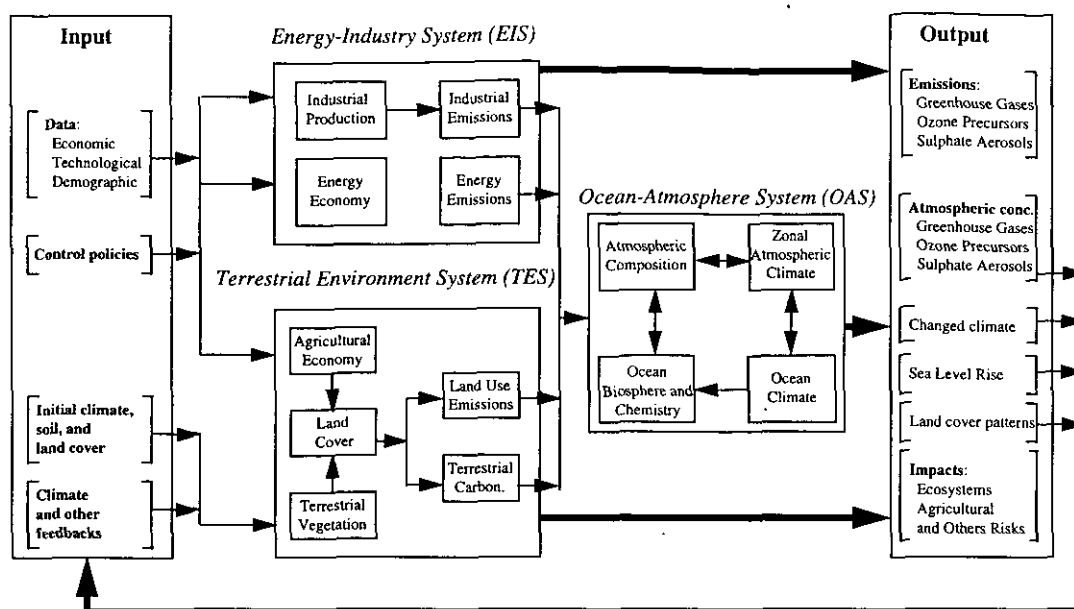


Figure 1: Structure of the IMAGE model.

The scientific goals of the IMAGE 2 model were to provide insight into the relative importance of different linkages, interactions and feedbacks in the society-biosphere-climate system, and to estimate the most important sources of uncertainty in such a linked system. The policy-related goals of the model are: 1) to link important scientific and policy aspects of global environmental change in a geographically-explicit manner in order to assist decision making; 2) to provide a dynamic and long-term (50 to 100 years) perspective about the consequences of environmental change; 3) to provide insight into the cross-linkages in the system and the side effects of various policy measures and 4) to provide a quantitative basis for analysing the costs and benefits of various measures (including preventative and adaptive) to address environmental change. These objectives have steered the design and development of the model. The model consists of three fully linked sub-systems of models (Figure 1): 1) the Energy-Industry System (EIS); 2) the Terrestrial Environment System (TES); and 3) the Atmosphere-Ocean System (AOS).

EIS computes the emissions of greenhouse gases from world regions as a function of energy consumption and industrial production (de Vries *et al.*, 1994). The EIS models are designed especially for investigating the effectiveness of improved energy efficiency and technological development on future emissions in each region, and can be used to assess the consequences of different policies and socio-economic trends on future emissions. AOS computes the build-up of greenhouse gases in the atmosphere and the resulting zonal-average temperature and precipitation patterns.

TES simulates the changes in global land cover on a grid-scale based on climatic, soil, demographic and economic factors. The role of land cover and other factors are then taken into account to compute the flux of CO₂ and other greenhouse gases from the biosphere to the atmosphere. The structure of TES is summarised as follows (Figure 1): the demand for agricultural and forest products (food, fodder, fibre, traditional and modern biomass) is linked to the regional availability of agricultural and forest resources. Available land resources are calculated on the spatial grid, characterising local climate, terrain, soil and topography. If current resources are inadequate to satisfying demand, land use expands into natural vegetation, converting it into land-cover classes such as agricultural land, pastures or

regrowth forests. This process results in deforestation and increased GHG fluxes towards the atmosphere. Because TES also simultaneously calculates intensification of agricultural productivity on the basis of technological and socio-economic assumptions, agricultural land can either expand or contract. Abandoned agricultural land converts into an early successional phase of the potential natural vegetation, often with increasing C densities through time.

There are several direct linkages with other components of IMAGE 2 (Figure 1). AOS integrates GHG emissions from both TES and EIS, and computes the final concentrations, accounting for uptake by the oceans and atmospheric chemistry. It further computes the resulting radiative forcing and latitudinal climate change. Here, the impacts of changed land-cover characteristics, such as albedo, are taken into account. The final concentration of GHGs (especially CO₂) and climate change are used again as inputs to the different models that determine the potential of terrestrial vegetation.

In order to provide a long-term perspective on the consequences of climate change, the model's time horizon extends to the year 2100. The time steps of different submodels vary, depending on their mathematical and computational requirements, but typically from one day to one year. The structure and underlying assumptions and data sets are described by Alcamo (1994).

Another goal of the model is to provide as much information as possible on the global grid. This is because nearly all potential impacts of climate change (e.g., impacts on ecosystems, agriculture and coastal flooding) are strongly spatially variable. Moreover, land-use-related greenhouse gas emissions (e.g. nitrous oxide from soils or methane from agricultural activities) greatly depend on 'local' environmental conditions and human activities (Turner *et al.*, 1995). In addition, climate feedbacks, such as the effect of temperature on soil respiration or the effect of changing CO₂ levels on plant productivity also vary substantially from location to location. There are two additional reasons for computing grid-scale information. First, policy makers are interested in regional/national policies to address climate change. Indeed, most climate policies are location-specific (e.g. sequestering carbon in forest plantations, or reducing nitrous oxide by modifying agricultural practices). Second, grid-scale information makes model calculations more testable against observations as compared to more aggregated models.

Nevertheless, it is currently impossible to provide grid-scale calculations for all components of climate change. In particular, this is unfeasible for economic calculations because of the difficulty in specifying economic/demographic factors (e.g. trade relationships, technological development and similar data) on a sub-country or grid scale for the entire world over the long time horizon of the model. As an intermediate step, economic calculations are performed for 13 world regions (Canada, USA, Latin America, OECD Europe, Eastern Europe, Africa, CIS, Middle East, India + South Asia, China + centrally planned Asian countries, East Asia, Oceania, Japan) which follows common practice in global economic studies. The criteria for grouping countries together in a particular region are mainly economic similarity and geographic position.

Since the IMAGE 2 model is based on large global data sets and poorly-understood global processes, it is unavoidable that many parameters will be ill-defined with large degrees of freedom or uncertainty. With this in mind, our basic approach is to propose submodels that have a comparable level of process detail. We will also adjust a limited number of parameters with the greatest uncertainty to obtain model calculations in reasonable agreement with 1970-90 data. We selected the period 1970-90 because of data availability, although we intend to test the model against data from a longer historical period. The individual submodels were

tested first and their parameters were adjusted, then linked and tested within the three subsystems of models, and finally the fully linked model. Results of these validations, given in Alcamo (1994), are beyond the scope of this paper. Of course, this procedure does not ensure that adjusted parameters and other inputs will be correct for scenario analysis under changed economic and environmental conditions; nevertheless, it does indicate the adequacy of the model in explaining global changes that occurred during the 1970-90 period, such as the increase in energy-related emissions, estimated changes in deforestation rate and terrestrial carbon fluxes, and the build-up of various greenhouse gases in the atmosphere.

Scenarios implemented with the IMAGE model

It is impossible to evaluate policies for climate protection without 'no action', 'business-as-usual' or benchmark scenarios. IPCC has developed a series of such scenarios (Leggett *et al.*, 1996; Alcamo *et al.*, 1995). I have selected several Baseline scenarios (A, B and C) with respectively intermediate, low and high assumptions for population growth and economic growth and activities (Alcamo *et al.*, 1996). These scenarios lead to increasing levels of GHG emissions and concentrations. For Baseline A, equivalent CO₂ concentrations have doubled by 2060, similar to the assumptions of Rosenzweig and Parry (1994). In this scenario the emissions from human energy use dominated. The population growth here, combined with changing dietary patterns (more meat), led to land-use change. Especially in Africa, India and China, all potential agricultural land resources were used, and this influenced food availability. In most other regions, food productivity increased and less land was required, so that abandonment of agricultural land occurred. However, these land use change patterns were very sensitive to the assumptions of the meat components of the regional diets. Of all land uses, meat production increased the most over the simulated period. This is partly driven by the economic growth (and consequently increasing wealth) in all regions. Such dietary and land-use changes are not considered in the Rosenzweig and Parry (1994) study and could further increase the discrepancies between developed and developing regions. The other baseline scenarios show higher (Baseline C) and somewhat lower (Baseline B) GHG emissions and concentrations and similar consequences for land use.

Several alternative scenarios were developed from this scenario. All of these assume different policy measures and their consequences. A stabilisation scenario was defined. The Framework Convention on Climate Change (FCCC) has the objective of stabilising atmospheric GHG concentrations at non-dangerous impact levels. In the scenarios, we wanted to obtain such stabilisation by 2150 at levels of 450 ppmv (Stab 450 CO₂), 550 ppmv (Stab 550 CO₂) and 650 ppmv (Stab 650 CO₂) respectively. This was obtained by selectively reducing the energy-related emissions of EIS. Land-use emissions remained the same as in baseline-A. A set of scenario was derived from the 550 ppmv stabilisation scenario in order to assess the consequences of delayed action. The emission profiles were assumed to follow the baseline A scenario for, respectively, 10, 20 and 30 years, until measures were taken to reduce emissions and stabilise atmospheric concentrations of GHGs.

The next set of scenarios are actually emission-reduction protocols as proposed during the Climate Negotiations. FCCC distinguishes Annex-1 countries as the developed countries currently emitting most of the global GHGs. The other nations are the less developed countries who, under FCCC, are allowed to increase their GHG emissions. Here, we have developed a scenario where only the Annex 1 countries stabilise their emissions of only CO₂ in 2000 and then reduce them subsequently at a rate of 1% annually (St2000 Ann1 CO₂ -1%). The other scenarios made similar assumptions but then for all countries (St2000 Glob CO₂ -1%) or all countries and all GHGs (St2000 Glob All -1%).

The last scenario used is the LESS Biomass Intensive scenario (LESS-BI) developed by Ishitani *et al.* (1996) for the IPCC second assessment report. Their aim was to illustrate the

potential for Low CO₂-Emissions Energy Supply Systems (LESS). The LESS-BI was one of their scenarios that relied heavily on renewables for energy generation. The implementation of LESS-BI in IMAGE 2 simulates the specific energy requirements and mix of energy sources, including modern biomass, in each region, by defining both the locally produced and imported/exported portions. This implementation mimics the original LESS-BI energy-sources mix. An additional assumption in LESS-BI was that total energy use was only half of what it is in the other scenarios. This was obtained by increased energy efficiency employing best available technologies world-wide. The energy mix in LESS-BI was less dependent on fossil fuels. This was obtained through a high dependence on renewable resources, such as solar, nuclear and modern biomass. The last required land to cultivate such biomass. The original LESS assessment estimated the additional need of 550 Mha biomass plantations, assuming highly productive lands. Our implementation of LESS-BI (Leemans *et al.*, 1996) required 797 Mha, in part because less productive lands were used. Such expansion of agricultural land will influence deforestation patterns and have significance for environmental issues, such as biodiversity.

These scenario studies show that this type of integrated model is capable of simulating many components of the Earth's system comprehensively. Policy options to mitigate the build-up of GHGs can be tested and their consequences for other possible options evaluated. Optimal response strategies can be developed in this way. The LESS-BI scenario is a good example of this. IMAGE 2 also has the capacity to address other environmental issues, such as food security and biodiversity. Impacts on biodiversity are, for example, a clear function of changes in potential vegetation and land use. Within IGBP, IMAGE 2 is currently used to develop scenarios for biodiversity change (Steffen *et al.*, 1996).

Impact levels in the different scenarios

The results for the individual scenarios are clearly different from each other. The outcomes span a wide range of emissions and impacts (Figure 2). There are large differences in emissions profiles (Figure 2a) among scenarios. These differences result from the underlying assumptions on population, energy use and land use. The baseline scenarios all increase their emissions, although Baseline B at the end of next century tends to stabilise emissions at a somewhat higher level than the current level. Except for scenario 'STAB 650 CO₂' and 'St2000 Ann1 CO₂ -1%', all other scenarios tend to reduce emission levels at or just below current levels. These emission profiles all coincide with significant temperature increases (Figure 2b). The climate sensitivity for doubling of CO₂ in IMAGE 2 is 2.37 °C, which is an intermediate value of the IPCC range of 1.5–4.5 °C. When higher climate sensitivities are assumed, the impact levels will consequently be higher. The baseline scenarios and several of the other scenarios present temperature increases larger than 2°C at the end of next century. However, the timing of this temperature increase is largely different. Only the most stringent scenarios (St2000 Glob All -1% and LESS BI) limit the temperature increase to values less than 1.5°C. These results indicate that to limit the impact of climate change stringent measures have to be taken which are directed to all emissions (in all countries) and all greenhouse gasses. In LESS-BI this is achieved by lowering the dependence of fossil fuels and strongly increasing the energy efficiency. During the first decades (1990-2025) few differences in impact levels can be distinguished among scenarios. The scenarios only start to diverge significantly from each other after 2025.

Sea level rise continues to increase over the simulated period (Figure 2c). In 2100 there are only difference of c. 20 cm among the scenarios. Sea level rise lags behind the temperature increase, mainly because of the time required to melt ice caps. In all scenarios a significant sea level rise is committed after 2100, even when emissions are reduced considerably. Increases in sea-level rise will have consequences for coastal area and ecosystems.

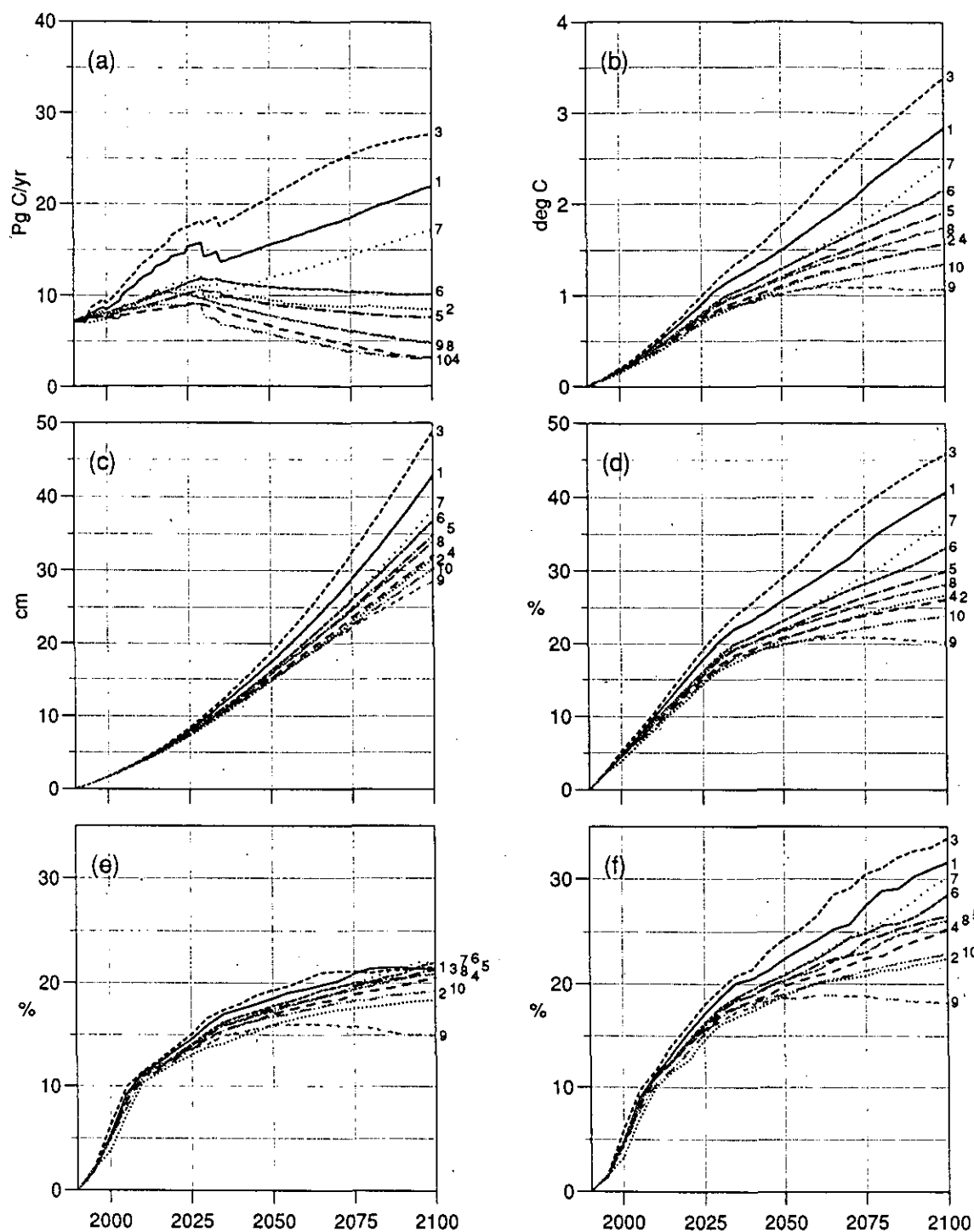


Figure 2: CO₂ emission levels (a), temperature change (b), sea level rise (c), affected extent of natural vegetation (d), area with decreased cereal productivity (e) and area with decreased maize productivity (f) for different scenarios (1: Baseline A; 2: Baseline B; 3: Baseline C; 4: STAB 450 CO₂; 5: STAB 550 CO₂; 6: STAB 650 CO₂; 7: St2000 Ann1 CO₂ -1%; 8: St2000 Glob CO₂ -1%; 9: St2000 Glob All -1%; 10: LESS BI).

The threat to natural vegetation is modelled in IMAGE 2 using the BIOME model (Prentice *et al.*, 1992). This model calculates the distribution of different, highly aggregated plant types on the basis of climate and soil characteristics and assembles biomes (large scale vegetation patterns), such as boreal needle-leaved forests, deciduous temperate forests, tropical rain forests, savannahs and deserts. Here I present shifts in these biome patterns as the aerial percentage of the original extent of each biome that is changed. Clear differences among the scenarios emerge. The scenarios with lower global emissions (e.g. STAB 450 CO₂, St2000 Glob All -1% and LESS BI) show much lower impact levels than the other scenarios. For example, in LESS BI only 25% of all natural vegetation is affected, while over 40% is affected in the baseline scenarios. The impact levels in these lower scenarios also seem to stabilise, while impacts levels continue to increase in the other scenarios. However, before 2025 all scenario show an initial impact on vegetation patterns. This analysis shows that the consequences of even smaller climate change (less than 1°C) have large effects on vegetation. This means that most of the impacts will have already occurred in an early phase of the scenarios (1990-2025). Even with stringent emissions these impacts reductions can not be avoided.

The impacts levels of yields of cereals and maize (Figure 2e and f) are based on those areas where these crops are currently grown (FAO, 1991). In IMAGE the potential productivity is calculated using the widely-used FAO-crop suitability approach (Leemans and van den Born, 1994), which simulated potential productivity under rain-fed conditions. The impact levels are defined as those areas where potential rain-fed productivity is reduced by at least 10%. In these yield indicators, shifts of cropping zones and increased yields are thus not considered. These responses, however, can also be derived from IMAGE 2 results (see below). The patterns of impact levels are similar to those of natural vegetation, although the total levels are somewhat lower. However, there is a clear difference between cereals and maize. Cereals are a so-called C3 plant, while maize is a C4 plant. C3 plants are sensitive to increased atmospheric CO₂ levels and show enhanced growth under these conditions. C4 plants do not respond very strongly to changes in CO₂. From Figure 2e and 2f it is very clear that the impacts of climate change for cereals are partly offset by increased CO₂ levels. All scenarios show a very similar impact pattern, and the scenario divergence exhibited in the other impact indicators does not occur. The does not happen for maize, where the scenarios show large differences in impact levels.

Figure 3 presents impact levels, for different regions, for the Baseline-A scenario. The other scenarios produce similar impact patterns but at different levels. These levels are dependent on the emission profiles (cf. figure 2). From the figures it becomes clear that each region has a very specific impact pattern that often does not resemble or coincide with the global patterns. For example, cereals and maize productivity in Canada and the US is affected immediately. These crops are mainly grown in the central plains. The climate scenario used (based on the IMAGE 2 climate model and scaled using the MPH-AGCM to obtain the global patterns for temperature and precipitation) simulates increased drought in this region, leading to severe and immediate impacts on rain-fed yield. Other regions are much less impacted, because drought is less pronounced or non-existent there. Later during the simulation, the drought effects are partly off-set by enhanced water-use-efficiencies under higher CO₂ levels. Evaluating the importance of these graphs, it seems relevant to distinguish and focus on the regional impacts because their significance globally can easily be averaged out (cf. Figure 2). Further, different regions show different patterns for different types of impacts. For example, cereal productivity is little affected (less than 5%) in China, while maize is moderately affected (more than 40%). Vegetation, however, is strongly affected. More than 60% of its extent will change into another vegetation type.

Summarising a series of different regional impacts, I have calculated the global average in 2050 (c.f. Figure 2) and compared the regional impact level with this average (Figure 4). I have further also included several other indicators, such as increases in cropping area and malaria occurrence. No clear impact picture emerges. In high latitude regions (Canada, CIS) annual mean temperature increases are somewhat higher, but this does not always translate into larger impacts. The sensitivity of different impacts strongly differ regionally. There are no clear regions that are impacted more (or less) severe than others. The statement that 'the developed world emits most of the greenhouse gasses, while the developing world is impacted most' does not hold in this analyses.

All regions are impacted. When adaptation is considered, or when the impact levels are values in monetary terms and calculated as a proportion of national GDP, this could be true but not for the first-order impacts.

Finally, the discussion on delaying responses to find an less costly path to reduce emissions (e.g. Wigley *et al.*, 1996) should also be more strongly evaluated against impact levels and not only against the minor differences in temperature change. Differences in temperature change of less than 0.1 °C indeed seem neglectable. In determining the transient responses of climate change, however, these impacts among scenarios can be large. As an example, I have derived several scenarios from the STAB 550 CO₂ scenarios with simple delays in which emissions were reduced in order to stabilise atmospheric CO₂ concentrations. Table 4 presents the differences. It is clear that delaying responses increases the area of natural ecosystems affected significantly. The difference is largest during the intermediate periods 2025-2050 with twice as large area less affected (6050 respectively 10790 Mha saved) than with a 30-year delayed response (only 2940 respectively 5130 Mha saved). All figures are compared with the Baseline-A scenario. This analyses illustrates that the sensitivity of different impacts will lead to differences in impact pathways, even if very small changes in climate are considered. More detailed analyses should be done to improve our understanding of transient impacts.

Table 4: Extent less affected by climate change impacts on natural vegetation in Mha (total land area 12170 Mha) for the 'stabilisation at 550 ppmv' scenario and different delays in timing the start of stabilisation. The delay-scenarios follow the Baseline scenario during their initial years leading to somewhat higher cumulative emissions over the period 1900-2100.

Scenario	T in 2100	2010	2025	2050	2100
Extent affected in Baseline A	2.8	937	1905	2956	4897
Stabilisation, no delay	1.6	79	247	512	1602
Stabilisation, 10yr delay	1.7	52	211	408	1543
Stabilisation, 20yr delay	1.8	0	195	316	1523
Stabilisation, 30yr delay	1.9	0	163	292	1418

Concluding on global and regional impact levels:

- The different scenarios show largely different impact patterns. The impacts, however, start to diverge only after 2025 when differences in GHG concentrations and climate change among scenarios become apparent.
- Scenarios with lower emission profiles generally show lower impact levels.
- Even small climate changes have serious consequences. Therefore, some of the impacts cannot be avoided. For the period 1990-2025 this means that impacts of climate change should not be neglected.
- The direct effects of CO₂ influence the final impact levels. Interactions between climate change and other environmental changes must be considered.

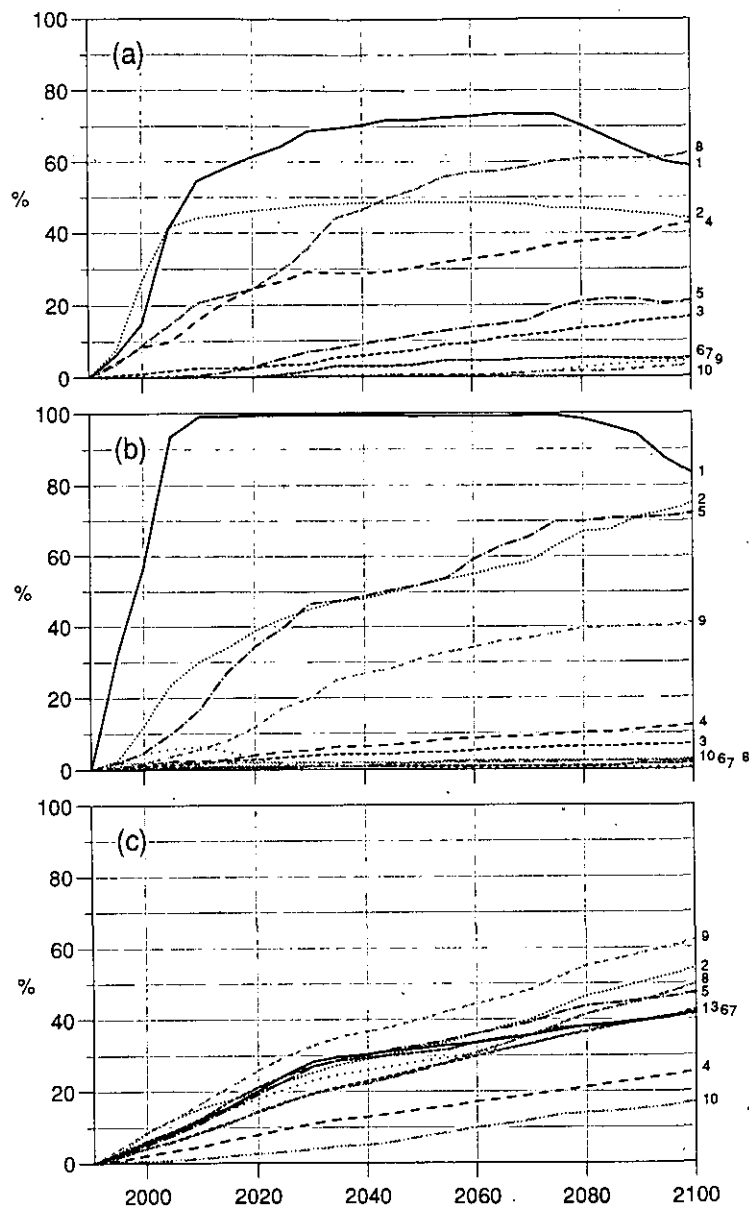


Figure 3: Regional impact levels for area with decreased cereal productivity a) and area with decreased maize productivity (b) and natural vegetation (c) for the Baseline A scenario (1. Canada; 2. USA; 3. Latin America; 4. Africa; 5. OECD Europe; 6. Eastern Europe; 7. CIS; 8. India; 9 China; 10. East Asia).

	dT	vegetation	cereals	Rice	area cereals	area rice	malaria
Canada							
United States							
Latin America							
Africa							
OECD Europe							
East. Europe							
CIS							
Middle East							
India & SAsia							
China & CPasia							
East Asia							
Oceania							
Japan							

Figure 4: Regional summary for regional impact levels when compared to average global impact levels. The black boxes denote a larger than average impact level; the white boxes a less than average impact level.

- The global curves for each impact have a consistent shape. This suggests that regressions on the impacts levels with global emissions, concentrations or temperature change, can yield meaningful relationships to define impact levels. Regional impacts do, however, not allow for this simplification. The regional responses are much more complex and diverse and must be addressed in a consistent impact assessment.
- Considering different types of regional impacts, no clear less or heavily impacted regions can be distinguished. All regions are impacted differently.
- Each emissions-scenario has its own specific impact level. Minor differences among scenarios (timing, level, etc.) give different transient impacts and responses, which should not be neglected.

Conclusions

In this paper, the different approaches to impact assessments of climate change have been discussed. Such impacts should not be treated in isolation from other components of the climate/biosphere/societal system. Many different models have been developed, environmental data sets compiled and experiments conducted, to increase our understanding of the local physiological and ecological processes. This understanding is relatively high, especially if we treat processes individually. However, the interaction between processes and factors influencing them has been neglected until recently. The importance of basic research on such interactions and under realistic conditions cannot be stressed enough. Further, the linkages with socio-economic research and understanding are needed to assess the actual responses to climate change. In this broad field of research we are only starting to enhance our knowledge (e.g. Turner *et al.*, 1995).

Integrated approaches and IAMs can highlight gaps or incompatibilities between disciplines, sectors and/or scientific understanding. These methods not only have relevance as a policy tool. Scientifically speaking, they are objective tools to emphasise the systemic and highly non-linear linkages between the different components of the Earth's system. The research activities of the major international programmes (SCOPE, WCRP, IGBP and IHDP) will advance the development of these approaches and emphasise regionally explicit applications. Linkage with remotely sensed data, for example, can assist in obtaining the geographic coverage needed. Data dissemination centres such as CIESIN and CDIAC and connections through the Internet provide a necessary link to standardising some of the input data sets. Model comparisons, such as performed in EMF will further highlight discrepancies in our understanding and guide both modelling and experimental research. Scientifically speaking, this is an exciting era, where large-scale global environmental change is pushing the advancement of both basic and applied research.

Despite the complexity of the Earth's system, the observed and projected changes in its dynamics and consequently the impacts on nature and society, major achievements in combining disciplinary expertise from many different natural and physical sciences have developed rapidly during the last few years. However, the largest challenge is still to come. The achievements from mostly the natural sciences need to be better integrated with the expertise of the social, cultural and economic sciences. The development of adequate policies for global environmental change, in which sustainable use of natural resources to accommodate an increasing human population is allowed for, demands a better understanding of the interactions between the environment and human behaviour. Scientists' major challenge is probably to guide policy-makers and leaders to appropriate ways to reduce the threats of global environmental change. It is necessary to scale the knowledge from individual to society, from leaf to ecosystem, and from local regions to the world; integration is required on all these levels.

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