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NATIONAL INSTITUTE FOR PUBLIC HEALTH AND THE ENVIRONMENT
BILTHOVEN, THE NETHERLANDS

RIVM Report 481 508 012

Applying Global Change Scenarios to Assess Changes in Biodiversity

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August 1999

This research has been performed by order of the Ministry of Housing, Spatial Planning and the Environment, Directorate-General for Environmental Protection, directorate Air and Energy, within the framework of RIVM project number MAP 481508 (Development and Application of IMAGE 2). Additional financing for participating in the workshops was provided by IGBP-GCTE, NCEAS and EPRI.

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Contents

List of figures

List of tables

Abstract

This report presents the results of applying IMAGE 2 to assess changes in biodiversity. The organisers of two separate workshops solicited for these applications. Pre-prints of the resulting papers are presented in this report.

The first workshop 'Managing for biodiversity: Incentives for the protection of nature' focussed on incentives for optimising biodiversity. Here, integrated assessment modelling and scenario analyses were presented as a tool to evaluate different incentives. The scenarios highlighted that rapidly increasing consumption patterns, rapid expansion of rangelands to support changing diets and too slow-moving technological innovations are major attributes of land-use change and biodiversity decline. It was concluded that scenario studies transparently highlight the complex systemic interactions and feedback between society and the other components of the earth's system. In addition, scenario studies contribute to improving the understanding of changes in biodiversity at global and regional levels of assessment.

The second workshop focussed on the use of environmental scenarios to determine the current and future threats to biodiversity. A group of experts on all biomes used the scenarios and estimated changes in biodiversity. This report presents a summary of results by the expert team. The results suggests that land-use change will be the driver with the largest impact on biodiversity followed by climate change, nitrogen deposition, biotic exchange, and elevated CO_2 concentrations. However, large regional differences emerged.

Although local pressures often cause threats to biodiversity, both papers show that scenario analyses with integrated assessment models can help to define future trends. The strength of this approach is that the interactions between different stressors can be determined. Further, the effectiveness of different policy measures can effectively and comprehensively be evaluated with scenario analyses.

Executive summary

This report presents the results of applying IMAGE 2 and its scenarios to assess changes in biodiversity. These applications were solicited for by the organisers of two separate workshops on different aspects of biodiversity. Pre-prints of the resulting papers, which will soon be published in the peer-reviewed literature, are presented in this report.

The first workshop 'Managing for biodiversity: Incentives for the protection of nature' (Savannah, Georgia) was organised by Electrical Power Research Institute, Resources for the Future, Southern Company, the Smithsonian and the Nature Conservancy, and focussed on incentives for optimising biodiversity. Here, integrated assessment modelling and scenario analyses were presented as a tool to evaluate different incentives. This presentation strongly focussed on the different scientific approaches in determining positive and negative environmental trends in relation to the major international environmental conventions.

The biodiversity convention aims at conserving biodiversity and guaranteeing fair and sustainable human use of biodiversity. The convention further requires that the causes of biodiversity decline are identified and evaluated, and that effective conservation and monitoring strategies are developed. Resolving these needs requires a different approach than those described in the last Global Biodiversity Assessment. This assessment tended to be descriptive and did not comprehensively attempt to describe future trends in biodiversity in relation to the major threats: habitat destruction, overexploitation, alien species, pollution and climate change. Integrated assessment modelling and scenario development have therefore been introduced and applied to assess changes in biodiversity. These tools were originally developed for acidification and climate-change impact assessments but are also well suited to analysing other environmental problems. The implemented business-as-usual scenarios show the causes of biodiversity decline to differ regionally. Although complex patterns of causal factors and changes occur in many regions, a valid (but generalised) statement is that climate change causes biodiversity decline in industrialised regions, while in developing regions expanding land use is the major contributor. The scenarios further highlight that despite population growth contributing to the problem, rapidly increasing consumption patterns, rapid expansion of rangelands to support changing diets and too slow-moving technological innovations are major attributes of land-use change and biodiversity decline. Finally, it is concluded that scenario studies transparently highlight the complex systemic interactions and feedback between society and the other components of the earth's system. In addition, scenarios can contribute well to improving the understanding of changes in biodiversity at global and regional levels of assessment.

The second workshop 'Scenarios of Future Biodiversity; Causes, Patterns, and Consequences' (Santa Barbara, California) was organised by the 'Global Change and terrestrial Ecosystems' core project of the International Geosphere Biosphere Programme and the National Center for Ecological Analysis and Synthesis, and focussed on the use

of climate, land-use and other environmental scenarios to determine the current and future treats to biodiversity. A group of experts on the causes and consequences of biodiversity change in each major terrestrial biome was convened at the workshop. Based on the published literature, this group first estimated for each biome the relative sensitivity of biodiversity to changes in the physical and biotic environment that are occurring at a global scale. The group then considered, for each driver of diversity change, the relative sensitivity of diversity in different biomes to changes in that driver. The global changes considered having the greatest impact on biodiversity by this group were land use, atmospheric CO_2 concentration, nitrogen deposition/acid rain, climate, and biotic exchanges. The synthesis developed for each biome was then reviewed by other ecologists familiar with controls over biodiversity in other geographic regions of that biome.

The analysis of the second workshop used changes in biodiversity for the year 2100 based on scenarios of changes in atmospheric CO_2, climate, vegetation, and land use and the known sensitivity of biodiversity to these changes in each biome. This analysis suggests that land-use change will be the driver with the largest impact on biodiversity followed by climate change, nitrogen deposition, biotic exchange, and elevated CO_2. Mediterranean and grassland ecosystems will likely suffer the greatest proportional change in biodiversity, due to substantial impact of all drivers of biodiversity change. Northern temperate ecosystems will likely experience least biodiversity change because land-use change has already occurred. The plausibility of changes in biodiversity in other biomes depend on assumptions about the interactions among causes of biodiversity change. These interactions, however, are poorly known.

Although local pressures often cause threats to biodiversity, both papers show that scenario analyses with integrated assessment models can help to define future trends. The strength of this approach is that the interactions between different stressors can be determined. Further, the effectiveness of different policy measures can effectively and comprehensively be evaluated with scenario analyses.

Samenvattting

Dit rapport presenteert de resultaten van het gebruik van IMAGE-2 scenario's om veranderingen in biodiversiteit te evalueren. Deze scenario's werden ontwikkeld als onderdeel van analyses die zijn gedaan in het kader van twee internationale workshops over verschillende aspecten van biodiversiteit. De IMAGE-2 presentaties, die ook binnenkort in internationale wetenschappelijke tijdschriften worden gepubliceerd, zijn in dit rapport opgenomen.

De eerste workshop 'Managing for biodiversity: Incentives for the protection of nature' (Savannah, Georgia) was georganiseerd door het Electrical Power Research Institute, Resources for the Future, Southern Company, de Smithsonian en de Nature Conservancy. Deze workshop richtte zich vooral op het stimuleren van maatregelen ter verbetering van biodiversiteitsbeheer. Tijdens deze workshop werd geïntegreerde assessment modellering en scenario analyse gepresenteerd als een middel om de effectiviteit van verschillende beheersmaatregelen te evalueren. Daarnaast had de analyse als doel om de verschillende wetenschappelijke benaderingen om mogelijke positieve en negatieve trends in biodiversiteitsveranderingen in te schatten en deze ontwikkelingen in relatie te brengen met de afspraken in de belangrijke internationale milieuconventies van UNCED.

De biodiversiteitconventie heeft tot doel om de biodiversiteit te beschermen en er voor te zorgen dat het antropogene gebruik ervan duurzaam en eerlijk verloopt. Deze conventie verlangt dat de oorzaken van biodiversiteitveranderingen in kaart gebracht en geëvalueerd worden, en dat effectieve monitoringsstrategieën worden ontwikkeld. Het invullen en oplossen van deze doelstelling noodzaakt tot een andere benadering dan die in de "Global Biodiversity Assessment". Deze assessment beschrijft vooral de historische en huidige trends, maar verzuimt om een samenhangend beeld te schetsen van mogelijke trends in toekomstige biodiversiteitveranderingen. Deze trends moeten worden gedefinieerd in relatie tot de belangrijkste bedreigingen: habitat vernietiging, geïntroduceerde soorten, vervuiling en klimaatverandering.

Geïntegreerde assessment modellering en scenario ontwikkeling zijn gepresenteerd als een effectieve methode om dit hiaat op te vullen. Enkele toepassingen op biodiversiteitveranderingen zijn gepresenteerd. De methoden zijn in eerste instantie ontwikkeld voor verzuring en klimaatverandering, maar zijn wel degelijk toepasbaar op andere milieuproblemen. De zogenaamde "business-as-usual" scenario's laten zien dat de oorzaken van biodiversiteitvermindering regionaal sterk kunnen verschillen. Ondanks deze complexe patronen van oorzakelijke factoren en veranderingen in de verschillende regio's, een geldige (maar veralgemeniseerde) conclusie is dat klimaatverandering bijdraagt tot biodiversiteitvermindering in de geïndustrialiseerde landen, terwijl toenemend landgebruik juist in ontwikkelingslanden de belangrijkste bijdrage is. De scenario's laten verder zien dat, naast een kleine bijdrage van bevolkingsgroei, vooral de toename van welvaart en de daarbij horende consumptiepatronen leiden tot een uitbreidend landgebruik (vooral een snelle toename van vleesproductie). De begeleidende

technologische ontwikkeling die leidt tot productieverhoging, is onvoldoende om deze uitbreiding te neutraliseren. Zulke complexe interacties zijn een belangrijke aspect van landgebruikverandering en dus biodiversiteitvermindering.

Concluderend, scenario analyses kunnen deze complexiteit op een redelijk transparante manier aanschouwelijk maken door interacties en terugkoppelingen in maatschappelijke, biologische en milieu-systemen expliciet te modelleren. Daarom kunnen scenario's studies goed bijdragen in het verbeteren van het begrip omtrent biodiversiteit-veranderingen op regionale en mondiale schalen en helpen om de effectiviteit van verschillende beleidsmaatregelen te evalueren.

De tweede workshop 'Scenarios of Future Biodiversity; Causes, Patterns, and Consequences' (Santa Barbara, California) werd georganiseerd door het 'Global Change and terrestrial Ecosystems' project van het International Geosphere Biosphere Programme en het National Center for Ecological Analysis and Synthesis. Deze workshop had als doel om het gebruik van klimaat-, landgebruik en andere omgevingsscenario's om de huidige en toekomstige bedreigen van biodiversiteit te kunnen bepalen.

Een internationale groep met experts evalueerde de oorzaken en gevolgen voor biodiversiteit in de verschillende terrestrische biomen. Op basis van gepubliceerde inzichten, deze groep schatte allereerst de relatieve kwetsbaarheid van elk biome in. Deze kwetsbaarheid is gedefinieerd als een functie van grootschalige regionale en mondiale veranderingen in het fysische en biotische milieu. Daarna oordeelde de groep over de individuele oorzaken voor biodiversiteitverandering en bepaalde de relatieve bijdrage van elke oorzaak. De oorzaken die leiden tot de grootste verandering op biodiversiteit zijn landgebruikverandering, toename van atmosferische CO_2 concentratie, stikstof depositie en verzuring, klimaat en soorten introducties. Deze analyse is door de expertgroep gedaan voor elk afzonderlijk biome. Daar de samenstelling van de groep beperkt was, is de analyse daarna beoordeeld door onderzoekers met expertise uit andere regio's, waar datzelfde biome voorkomt.

De analyse maakte een schatting van de veranderingen in biodiversiteit voor het jaar 2100. Deze schatting was gebaseerd op veranderingen in de atmosferische CO_2 concentratie, klimaat, vegetatie, landgebruik en de bekende gevoeligheid van biodiversiteit op deze veranderingen in verschillende biomen. Deze analyse suggereert dat landgebruikverandering het grootste effect op biodiversiteit zal hebben, gevolgd door klimaatverandering, stikstofdepositie, introductie van soorten en de toename van atmosferische CO_2. De biodiversiteit in mediterrane en grasland ecosystemen zullen waarschijnlijk het sterkst beïnvloed worden. Dit wordt veroorzaakt door het gecombineerde effect van verschillende oorzaken. In de noordelijke gematigde ecosystemen zullen relatief kleine veranderingen in biodiversiteit optreden, omdat landgebruikveranderingen hier reeds in het verleden heeft plaatsgevonden. De geschatte veranderingen in biodiversiteit in de andere biomen hangen sterk af van de veronderstellingen in de scenario's en de interacties tussen de verschillende oorzaken van de verslechtering van biodiversiteit. Deze interacties zijn echter nauwelijks bekend.

Ondanks dat de verslechtering van biodiversiteit vaak is afgeleid van lokale stressoren, tonen beide artikelen aan dat de scenario-analyse met geïntegreerde assessment modellen kan helpen in het definiëren en evalueren van toekomstige trends. De kracht van deze benadering is dat het belang van verschillende individuele stressoren en de interacties en terugkoppelingen ertussen goed bepaald kan worden. Daarnaast kan de effectiviteit van diverse beleidsmaatregelen om biodiversiteit te beschermen geëvalueerd worden.

Acknowledgements

I appreciate the enthusiasm of Osvaldo Sala, Terry Chapin and Brian Walker of inviting me to the NCEAS workshop and Joe Wisniewski and Bill Coleman to the Savannah Workshop. The high-level and stimulating discussions in these workshops contributed to my understanding of possibilities and difficulties in defining and developing biodiversity scenarios. I wish to thank Eric Kreileman for assisting in supplying the IMAGE-2 scenario data to all the workshop participants, Jan Bakkes, Jack B. Waide and Michael Sonntag for helpful comments and suggestions on earlier drafts of this report and/or the individual papers, and Ruth de Wijs for carefully checking the English of the report and the forthcoming papers.

This IMAGE-related research has been performed by order of the Ministry of Housing, Spatial Planning and the Environment, Directorate-General for Environmental Protection, directorate Air and Energy, within the framework of RIVM project number MAP 481508 (Development and Application of IMAGE 2). This work at RIVM was further supported by the Dutch National Research Programme on Global Air Pollution and Climate Change under contract number 954225. The IMAGE project officially recognised contribution to IGBP-GCTE core research.

The NCEAS workshop in Santa Barbara (California, USA) was funded by UC Santa Barbara, National Center for Ecological Analysis and Synthesis, InterAmerican Institute for Global Change Research, NSF OCE-9634876, CONICET, UBA and FONCyT. The workshop in Savannah (Georgia, USA) was funded by Electrical Power Research Institute (EPRI), Resources for the Future, Southern Company, the Smithsonian and the Nature Conservancy.

1 Introduction

Changes in biodiversity is one of the major issues of global change (Groombridge , 1992; Schulze and Mooney , 1993; Heywood and Watson , 1995; United Nations Environment Programme, 1997). At the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in 1992 everyone agreed that the decline in biodiversity had to be stopped. This led to the Convention on Biodiversity, which is currently being implemented. The implementation strongly relies on adequate data and understanding of past and recent changes in biodiversity. Moreover, to evaluate the effectiveness of different policy measures to protect and/or observe biodiversity additional tools are required to assess plausible future changes in biodiversity. Such tools allow the development and evaluation of different scenarios. Unfortunately, although these tools are developed for the assessment of different aspects of climate change, which is another component of global change, they are not (yet) widely used for biodiversity assessments.

This report presents the results of applying IMAGE 2 and its scenarios to assess changes in biodiversity. These applications were solicited for by the organisers of two separate workshops on different aspects of biodiversity. Pre-prints of the resulting papers, which will soon be published in the peer-reviewed literature, are presented in this report.

The first workshop 'Managing for biodiversity: Incentives for the protection of nature' (Savannah Georgia, 15-18 November 1998) was organised by Electrical Power Research Institute (EPRI), Resources for the Future, Southern Company, the Smithsonian and the Nature Conservancy. The workshop focussed on incentives and policies for optimising biodiversity. Such incentives can be designed to treat species and habitats as important components of a landscape. For decision makers and society at large, these policies can help to achieve environmental goals by increasing focus of resource managers on the health and integrity of landscapes, ecosystems, their species and the ecological services they provide. The workshop was therefore intended to identify and promote incentive-based policies for the protection of biodiversity and tools to develop and comprehensively evaluate those.

I introduced integrated assessment modelling and scenario analyses as a tool to evaluate different sets of incentives. My presentation, printed in chapter 2, focussed on the different scientific approaches in determining positive and negative environmental trends in relation to the major international environmental UNCED conventions and drew from published examples in the context of climate-change assessments. I concluded that, despite large differences between the underlying causes of the decline in biodiversity and climate change, integrated assessment and scenario analyses offers some major advantages in evaluating future trends.

The second workshop 'Scenarios of Future Biodiversity; Causes, Patterns, and Consequences' (Santa Barbara, California, 2-5 May 1998) was organised by the 'Global

Change and terrestrial Ecosystems' core project of the International Geosphere Biosphere Programme and the National Center for Ecological Analysis and Synthesis, and focussed on the use of climate, land-use and other environmental scenarios to determine the current and future treats to biodiversity (Appendix A).

A group of experts on scenario development and on the causes and consequences of biodiversity change in each major terrestrial biome was convened at the workshop. Based on the published literature, this group first estimated for each biome the relative sensitivity of biodiversity to changes in the physical and biotic environment that are occurring at a global scale. The group then considered, for each driver of diversity change, the relative sensitivity of diversity in different biomes to changes in that driver. The global changes considered having the greatest impact on biodiversity by this group were land use, atmospheric CO_2 concentration, nitrogen deposition/acid rain, climate, and biotic exchanges. The synthesis developed for each biome was then reviewed by other ecologists familiar with controls over biodiversity in other geographic regions of that biome and will be published separately (Sala *et al.*, 1999). The paper included in this report (Chapter 3) summarises the results of this workshop.

2 Modelling for species and habitats: new opportunities for problem solving

2.1 Introduction

The alarming decline of the world's biological diversity or biodiversity is perceived by many as an irreversible process, which could eventually obliterate the very base of human existence. Humans strongly depend on biological resources for food, construction materials, medicine and energy. Currently, humans use, either directly or indirectly, most of the available biospheric resources (Vitousek *et al.*, 1997). These resources are in principle renewable. With proper management they can be used sustainably. Unfortunately, human use often exceeds the renewal capacity, after which the biological resource base becomes degraded. Ultimately, resource management thus defines the fate of biodiversity. Additionally, such degradation can also increase the vulnerability to other stresses than human use, such as environmental change.

Biodiversity is the collection of genes, species, communities and ecosystems which constitute the living component of the earth's system. Unfortunately, it is difficult to quantify biodiversity is such a way that all components are effectively included. This component responds to (changes in) the physical and biological environment in many complex ways. Unfortunately, it is largely unknown how resilient these responses are. Recently, the question 'Can biodiversity decline continue without curtailing ecosystem functioning?' has generated in-depth discussions (Schulze and Mooney, 1993; Tilman *et al.*, 1995; Walker, 1995 and Chapin *et al.*, 1997) and led to several innovative ecological experiments with new insights (Naeem *et al.*, 1994; Tilman *et al.*, 1996; McGradysteed *et al.*, 1997; van der Heijden *et al.*, 1998). These discussions and insights indicate that with increasing biodiversity several properties of ecosystems, such as carbon uptake and productivity, increase and that ecosystem response becomes more predictable and less variable. Most of these studies, however, have used simple model and experimental ecosystems; the results are therefore difficult to extrapolate to determine the actual responses to environmental change of the wide variety and diversity of ecosystems on earth.

This scientific understanding has made one important issue very clear: biodiversity matters and biodiversity conservation is of utmost importance in maintaining the life-sustaining systems of the biosphere. The recognition of this issue resulted in the widespread adoption of the Convention on Biological Diversity at the UNCED Earth Summit in Rio de Janeiro in 1992. The main objective of this Convention (Article 1) is to conserve biodiversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of its utilisation. This objective is not very specific with respect to minimum or desirable levels of biodiversity, nor does it make a strong plea for defining the relation or dependence between other human activities and those that threaten biodiversity. The Framework Convention on Climate Change (FCCC), for example, is much more explicit in its objective (see below).

Large parts of the convention deal with the genetic resources, biotechnology and different industrial, national and regional interests. Elaborating on those issues falls beyond the scope of this paper. The convention further stimulates parties to develop national strategies for conservation and sustainable use, which are linked with other environmental and societal issues (Article 6), and develop appropriate identification and monitoring systems (Article 7). These monitoring systems should identify and quantify the biodiversity threatening processes and activities. The convention especially focuses on one way to conserve biodiversity (Article 8): protected areas, where natural habitats and viable populations can be maintained and the influence of humans and alien species is reduced. The convention also promotes the development of research, training, educational and awareness programmes (Articles 12 and 13). Finally, the convention urges the parties to develop the appropriate assessment capacity to evaluate processes and activities that potentially can have an adverse impact (Article 14). This article led to the Global Biodiversity Assessment (GBA) (Heywood and Watson, 1995), which presents and discusses many aspects of biodiversity, changes therein and some of the causes of change.

Some central questions arising from the Convention on Biodiversity are thus:

- *How do humans influence biodiversity?*
- *What are the underlying causes of these influences?*
- *What are the socio-economic and ecological consequences of changes in biodiversity?*

The ultimate question probably is:

- *How do human-induced changes in biodiversity (and the species and ecosystems responses to these changes) affect the societal goods and services provided by biodiversity?*

Leemans (1995) evaluated changes in the focus of biodiversity research both immediately after the UNCED conference in 1992 and a few years later (1995). He classified many scientific publications with 'Diversity' or 'Biodiversity' in the title and found that the majority of papers focused at the genetic and population levels of biodiversity, i.e. within species diversity. Most of the remaining papers emphasised species and communities, and described or compared geographic differences. Very few papers focused on biodiversity at the ecosystems level and its interactions with the environment, i.e. ecosystems functioning. Only few papers actually described changes in biodiversity. Habitat loss and alien species were the most common threat discussed. No comprehensive linkages were made to the socio-economic driving forces. Leemans' analysis further showed that there was only a small shift towards the higher organisational levels (ecosystems) after the adoption of the Convention on Biodiversity. More recently, many more papers involving ecosystems and biodiversity have appeared. But the skewed distribution of biodiversity issues in the literature still reflects the 'genetic to species' bias of the Convention. Besides, almost all papers are descriptive and qualitative. Quantitative approaches are rare.

Unfortunately, these biases do not provide the answers to the central biodiversity questions specified above. Only some aspects of the first question are addressed. To fully comprehend the breadth of the above questions, different approaches are needed. Comparing the FCCC and the biodiversity convention yield different notions. The Objective of FCCC (Article 2) is to stabilise the atmospheric concentrations of greenhouse gases (GHGs) at non-dangerous levels. These levels should allow ecosystems to adapt to climate change in a natural way, guarantee food security and let economic development proceed sustainably. Although on a very general, but highly conceptual level, this FCCC objective implicitly defines targets and time paths for GHG emissions Swart *et al.*. This much more explicit objective has resulted over the last decade in the development of approaches that analyse, evaluate and synthesise major socio-economic, physical, chemical and biological aspects of climate change. Such approaches are currently labelled 'Integrated Assessment (IA)'. The first (Houghton *et al.*, 1990; Izrael *et al.*, 1990), which was published prior to the UNCED conference, and the second (Houghton *et al.*, 1996; Watson *et al.*, 1996 and Bruce *et al.*, 1996) assessment of the Intergovernmental Panel on Climate Change (IPCC) are good examples of such an approach. Scientifically, these assessments have led to a much more integrated way of looking at climate change. The IA approaches, first comprehensively developed for acidification (Alcamo *et al.*, 1996), have since become mature and potentially bridge the interests of scientists and policy makers (Weyant *et al.*, 1996).

A central approach within IA is scenario development. Scenarios include a description of the current situation of a possible or desirable future state, as well as of the series of events that lead from the current to the future state. Scenarios require a consistent and coherent set of assumptions on the phenomena and processes analysed, their determining factors and expected future development. Scenario analysis is thus not a simple sensitivity analysis or trend extrapolation because scenarios should explicitly include systemic feedbacks, interactions and inertia. Generally, scenario analysis involves one or more no-policy or reference scenarios (Carter *et al.*, 1994; Alcamo *et al.*, 1995 and Alcamo *et al.*, 1996) and scenarios including different measures. By comparing the results of all these scenarios, the effectiveness of each measure can be evaluated (Alcamo and Kreileman, 1996). Scenario analysis actually deals with many aspects of the different UNCED conventions and could be of help in generating understanding, could define the timing and level of policy action, and could, beforehand, indicate the effectiveness of policy measures.

Scenario studies have up-to-now been instrumental in the scientific and policy discussions concerning climate change. The earliest scenarios defined different reference GHG emissions assuming different levels of population, economic and technological development (Leggett *et al.*, 1992). Later, different aspects of the FCCC objective were evaluated, such as stabilisation (Enting *et al.*, 1994), mitigation (Ishitani *et al.*, 1996), and other policy scenarios (Alcamo and Kreileman, 1996 and Swart *et al.*, 1998). These studies have influenced the viewpoints of different parties in the FCCC negotiations. For example, the requirement of a minimal reduction of 50% of current global GHG emissions for the stabilisation of GHG concentrations is an important conclusion resulting from these scenario studies. This conclusion has contributed to the historical first agreement to start reducing GHG emissions made at the FCCC Conference of Parties in Kyoto, 1997.

Comprehensive scenario analysis is thus a powerful tool in bridging the gap between science and policy (van Daalen *et al.*, 1998) and has already been frequently used in assessing environmental problems (Alcamo *et al.*, 1996). Unfortunately, the Global Biodiversity Assessment (GBA) (Heywood and Watson, 1995) has not applied scenarios analysis for future projection of biodiversity levels, although its objective was to provide an independent, critical, peer-reviewed, scientific analysis of current issues, theories and views on major global aspects of biodiversity and its threats. Most of the concern emerging from the GBA document is that current extinction rates are dramatically higher than background extinction rates. This would eventually reduce the resilience and functioning of ecosystems, jeopardising continued availability of all goods, services and figures provided by the biosphere. Much emphasis in the GBA is on preservation, conservation and sustainable use of biodiversity. Only 10 pages (792-802) deal with possible future developments, although only a limited inventory is presented. The notion that societal growth increases pressures on biodiversity, however, is well presented and discussed. Further, possible accelerating effects of climate change on extinction are introduced but not elaborated upon. Despite the section's valid conclusion that ecosystem management should focus on adaptability, variability and resilience to allow for future environmental change, it does not comprehensively determine future dynamics and levels of biodiversity, nor does it link quantitatively to other environmental problems such as acidification, climate change, deforestation and land degradation, and socio-economic issues, such as land-use change, food security and sustainable development. To date, no more detailed and comprehensive quantitative approaches have been published. Only the International Geosphere-Biosphere Programme (IGBP) is currently developing this capacity (Chapin, pers. communication). Quantitative scenario analysis could well bridge the gap between climate change, societal dynamics, resource use and biodiversity.

In this paper, I will go one step beyond the qualitative descriptions in the GBA and identify major problems, obstacles and challenges in developing future biodiversity scenarios. To do so, I will use one of the most advanced global integrated assessment models to date, the IMAGE 2 model (Alcamo, 1994 and Alcamo *et al.*, 1998), developed over the last decade at RIVM. This model was originally aimed at projecting GHG emissions stemming from energy use, land use and industrial activities, then calculating the build-up of atmospheric concentrations, and finally determining climate change and assessing its effects. To do so, the model actually dynamically simulates changes in biospheric carbon uptake and release, shifts in crop and vegetation zones under climate change, and expanding or contracting agricultural areas. These aspects are also applicable and important for biodiversity assessments.

In order to represent important interactions within the society–biosphere–climate system, adequate regional, and spatial and temporal, resolutions had to be defined in IMAGE 2. This resulted in the determination of socio-economic trends, which are often externally defined as scenario assumptions; energy use for 13 socio-economic regions and the simulation of land-use and climate-change impacts on a 0.5x0.5° longitude and latitude grid were also determined. The realistic simulation of land-use and environmental-change processes has recently expanded the application of the model towards food security, land degradation and biodiversity. Some of these broader results were published in the Global Environmental Outlook (GEO) (United Nations Environment Programme, 1997)

First, I will shortly discuss the processes and activities that influence terrestrial biodiversity, and evaluate the possibilities of including these realistically in the scenario development with IMAGE 2. Second, I will summarise some of the relevant aspects of the IMAGE 2 model and define scenarios, mainly differing in population and economic growth assumptions. The results of these scenarios will be presented and possible changes in biodiversity will be discussed. Finally, I will discuss the limitation and uncertainties imbedded in this approach and conclude with some recommendations for improvements and future developments.

2.2 Human influences on biodiversity

Throughout history humans have influenced and altered biodiversity in diverse ways (McNeely *et al.*, 1995). In many regions biodiversity has increased through the domestication of plants and animals. Traditionally, human activities have supported the maintenance of species and genetic biodiversity. For example, shifting cultivation systems throughout the world have had a profound effect on biodiversity. Certain areas, such as sacred groves, were kept permanently out of rotation. Here, the original vegetation and wildlife flourished. In the cultivated areas, a high diversity of domestic plants and animals was generally maintained, while the fallow fields provided productive habitat and feeding grounds for many non-domestic species. The farmers often grew crop varieties and cultivars well adapted to local conditions in order to reduce risk to pests and extreme weather conditions.

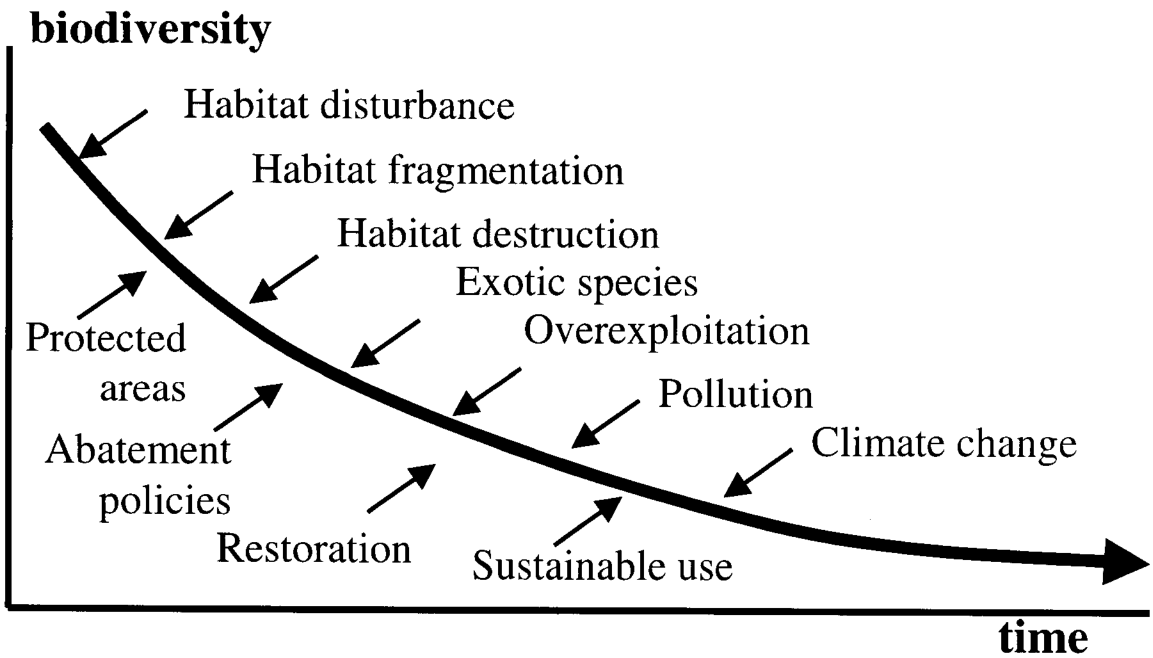

Figure 1. Major factors that influence biodiversity gains and losses.

With the increasing population pressures and the development of modern agriculture, the sustainable use of biodiversity has lost role in these systems. This trend has rapidly led to the destruction of local and regional biodiversity in agricultural systems and marginalised natural vegetation and wildlife as a natural resource. Modern agriculture relies on fewer crop varieties. The intensification through increased dependence on artificial fertiliser, irrigation and pesticides for pest and weed control has led to high and stable yields but has also led to a significant reduction in the genetic diversity of common crops and livestock. This trend is now also accelerating in developing countries. In India, for example, it is estimated that over 95% of the traditional varieties are lost locally.

Currently, many factors threaten, while others help to maintain biodiversity levels (Fig. 1). The most obvious threatening factors are those that alter habitats of species, introduce new exotic species, overexploit species and habitats, and/or change environmental conditions. The establishment of protected areas can compensate some of these aspects. Further restoration, the development of more sustainable uses and other abatement measures could enhance biodiversity levels. The influences on biodiversity strongly depend on the long-term evolutionary and shorter-term historical context, local population structure, species composition and habitat availability. Therefore large regional differences occur in the threats to biodiversity and the possibilities for maintaining or restoring them. This regionally specificity must be addressed in biodiversity scenarios.

2.2.1 Introduction of species

The intentional or accidental introduction of exotic or alien species is currently one of the major threats to biodiversity in many regions. These introductions occur for many reasons, such as improvement of forest productivity, new agricultural (cash) crops and horticulture. Many of the dominant crops have their origin elsewhere. With the introduction of new crops, other weed and pest communities too were introduced or evolved. Many unintentional introductions, such as the zebra mussels in the North American Great Lakes, have been documented (Heywood and Watson, 1995). Initially, such introduction could increase biodiversity but often the species introduced fits into a slightly different niche than the locally occurring species. Such niche differentiation could allow for a rapid expansion and out-competing indigenous species, which will inevitably lead to enhanced extinction rates. Globally, the increased rates of species introduction has therefore resulted in a net loss of biodiversity (McNeely *et al.*, 1995). The spread of alien species is not very well understood. Many alien populations remain local and relatively small over long time periods and do not pose a significant impact on regional biodiversity. Suddenly, however, some species spread rapidly and become a pest. The conditions and processes triggering such spread are not clear. Pitelka *et al.* (1997) evaluated many changes in distributions of alien species but conclude that quantifying the spread beforehand is very difficult because too many local, regional, environmental and societal factors are involved in a complex way. Although globally important, inclusion of the introduction of alien species and their consequences will be difficult, if not impossible.

2.2.2 Changes in habitats

Another important control on biodiversity is land-use and land-cover change. Human land use and other activities have been and are transforming ecosystems and landscapes rapidly. Since 1700 the extent of cropland has increased fivefold. During this period the extent of grasslands has remained relatively constant. The loss of grassland to cropland was balanced through deforestation and drainage of wetlands. Initially these land-cover conversions occurred mostly in the temperate regions but have now shifted towards the tropics. The extent of temperate forests is currently relatively stable and is even increasing somewhat but that of tropical forests is rapidly decreasing. Most of all forest areas are currently, however, intensively managed. Plantation forests with non-native species are becoming more and more abundant. Such modifications of the original land cover also have important implications for biodiversity. Regionally large differences occur but humans now dominate most of the land (Table 1) and its resources (Hannah *et al.*, 1994 and Vitousek *et al.*, 1997). Many regional changes in land cover and land use, and the diverse causes of these changes are documented by Turner *et al.* (1990). The examples show that the approximate causes of land use change involve a complex interplay of biological, environmental, social, cultural, economic, political and historical factors. This complexity could hamper the development of comprehensive land-use scenarios; however, assuming that population growth, basic food requirements, plausible agricultural and technological management levels, trade patterns and environmental conditions are known, coarse projections or scenarios of land use can be made (Fresco *et al.*, 1994 and Turner *et al.*, 1995).

Changes in land use and land cover influence the habitats of many species. The habitat is the space used by an organism. A species' habitat includes both the physical environment (climate, soil, terrain) and the biological components (species and ecosystems). The habitat is thus the place where an animal or plant usually lives and reproduces. A habitat is strongly species-specific and can change in different phases within the life of a species. The expansion of human land use alters the habitat of many species through disturbance, fragmentation and destruction. Tropical deforestation, for example, has not only reduced the total area of forests but has also influenced their spatial pattern. In areas with extensive deforestation, many small patches in different phases of regrowth and succession form (Skole and Tucker, 1993). Most of these patches are unsuitable habitats for many species because their sheer size is too small or the isolation between patches it too large too support viable populations. Regional deforestation rates and statistics on forest areas could therefore well underestimate the impacts on biodiversity.

Several regional and global models have simulated future patters of land-use and land-cover change (Alcamo, 1994; Matsuoka *et al.*, 1994 and Rabbinge *et al.*, 1994). Generally, these simulations all show an expansion of land use in developing regions and a stabilisation or even a contraction in industrialised regions. Simultaneously, management of arable land and pasture become intensified, leaving less room for natural vegetation and wildlife.

The difficulty in determining the consequences of land-use change on habitats is not straightforward. If a species' habitat is altered, the immediate impact during an individual's life may not be too apparent. The final extinction due to habitat destruction and fragmentation could become manifest only after decades and centuries (Tilman *et al.*, 1997). Further, habitats of different species involve many different temporal and spatial scales and often consist of only small parts of a specific landscape. Global and regional land-cover characterisations on the contrary are limited to relatively few classes (e.g. forests, grasslands, deserts, infrastructure and a few sub-classes, such as boreal, temperate and tropical). These are mainly based on the prevailing climate and soil conditions (Leemans *et al.*, 1996), and aggregated species types (Smith *et al.*, 1997). These classes are too coarse to define habitats of individual species, let alone changes in these on the species' own scale. However, indicators that approximate impacts on biodiversity can readily be derived from these coarse classes. Examples are affected nature reserves (Leemans and Halpin, 1992) and extent of domesticated land (United Nations Environment Programme, 1997). Applications of these indicators in global and regional scenarios show that with continuously expansion and intensification of land use, biodiversity will decline.

Table 1 Habitat and percentage human disturbance by continent (Hannah *et al.*, 1994)

Continent	Area (millions km^2)	Undisturbed	Partially disturbed	Human-dominated
Europe	5.8	15.6	19.6	64.9
Asia	53.3	42.2	29.1	28.7
Africa	34.0	48.9	35.8	15.4
North America	26.1	56.3	18.8	24.9
South America	20.1	62.5	22.5	15.1
Australasia	9.5	62.3	25.	12.0
Antarctica	13.2	100.0	0.0	0.0
World total	162.0	51.9	24.2	23.9
World total minus rock, ice and barren land	134.9	47.0	26.7	26.3

2.2.3 Overexploitation

Habitats are also threatened by overexploitation of resources, such as forests for fuelwood. Especially in poor developing countries fuelwood is used much more rapidly than that it is being replenished. Further, numerous fisheries and wildlife resources have been overexploited, often to the point of extinction (Groombridge, 1992). Extinctions are per definition irreversible and will also negatively influence the societal sectors originally exploiting such resource. Even if population levels are only reduced locally, inbreeding and the consequent loss of genetic diversity could become serious problems. Harvesting imposes an additional selection on a species and thus alters competitive conditions and selection pressures, which results in changed community structures and functioning of ecosystems. Even if the harvesting proceeds in a sustainable manner, biodiversity will be affected. For example, the harvesting of trees for timber reduces diversity in terms of tree species and structural variation. This has effects on insect populations, breeding birds and other wildlife (Järvinen *et al.*, 1977). Also the removal of biomass influences nutrient cycling and thus future development and states of biodiversity.

Again the causes and consequences of overexploitation on biodiversity are location-, species-, community- and ecosystem-specific. Determining the carrying capacity of an ecosystem to define, for example, sustainable harvest levels do not consider the systemic side-effects on other species and biodiversity. The causes of overexploitation always are societal. Increasing population pressures and consumption levels could lead to overexploitation (Ehrlich and Daily, 1993). These factors can easily be included in scenarios. Unfortunately, they only define a pressure on the resource, not the actual use and impact. Through protective policies, refrain can be shown in use of resources can be refrained from and alternative resources can be developed. The dynamics of resource use are therefore highly non-linear and less predictable. A good example of this complexity is the development of land degradation in the Kenyan Machakos region (Tiffen *et al.*, 1993). In the thirties, although population pressures were low, land degradation was very pronounced here and food production was severely threatened. The increasing population pressures caused a more sustainable agricultural system to be implemented. Currently, this region is the most important agricultural region in Kenya. An important condition for this positive development was the proximity of Nairobi, where a lot of the income required for the development could be generated. The example also shows that the projections of future exploitation levels can be developed. This can result in the notion of possible overexploitation and the resulting degradation which, in turn, initiates a learning curve to mitigate, ameliorate or alleviate conditions (Grubb *et al.*, 1995). These dynamics are now being implemented in socio-economic models (Rotmans and de Vries, 1997), the model being an important prerequisite to defining exploitation and overexploitation and its impacts on biodiversity. Unfortunately, there is still a long way to go until the link between exploitation and biodiversity is made satisfactorily.

2.2.4 Pollution and climate change

Finally, pollution and climate change will alter biodiversity patterns. Pollutants cause stress on ecosystems and may reduce or eliminate communities of sensitive species. Pollutants have direct and indirect effects on species and ecosystems. SO_2, NO_x, O_3 and other organic pollutants directly affect plant growth. The use of pesticides on crops leads to accumulation in the food chain, negatively affecting predator species. The abundant use of fertilisers in agriculture has led to large-scale eutrophication of surface water, causing drastic changes in flora and fauna. SO_2 and NO_x are oxidised to strong acids, which precipitate on and affect terrestrial and aquatic ecosystems by decreasing pH and by mobilising toxic metals. Such acidification has made many North American and Scandinavian lakes virtually lifeless and damaged many forests throughout the region.

Many of these pollutants are emitted locally and transported regionally, often crossing national boundaries. The acidifying substances, for example, remain up to a few weeks in the lower atmosphere. Regional policies have therefore to be implemented to curb the negative effects. In Europe, the development of such have used (and depended on) scenario-based indicators, such as critical load exceedance (Hettelingh *et al.*, 1995), which have been directly linked to the emission levels and (transport and chemical) atmospheric processes of the pollutants involved. These pollution mitigation policies present a good example of an efficient use of IA and scenarios. The impacts on ecosystems (especially forests and soils) and biodiversity formed an integral part of these scenarios.

Such regional emphasis does not apply to the emissions of CO_2, CH_4 and N_2O. These pollutants have a much longer atmospheric lifetime, are rapidly spread globally and contribute to the enhanced greenhouse effect and climate change (Houghton *et al.*, 1996). Besides climate change, CO_2 has additional effects on plants and ecosystems (Table 2) because plants incorporate CO_2 into their biomass through photosynthesis. This process forms the basis of all food chains and biodiversity. Enhanced atmospheric CO_2 concentrations will influence plant growth in a very species-specific way. Some species will respond strongly, others not (Bazzaz, 1996). These responses will alter competition between species and thus their relative abundances. Further, and also as a consequence of climate change, a geographic distribution of species will change. This leads to worldwide shifts of ecosystems and biomass as occurring in the past (Huntley and Webb, 1988). IPCC (Watson *et al.*, 1996) estimated that over 40% of the global land surface would change over the next century. This makes CO_2 and climate change at least equally important as a cause for biodiversity decline as alien species, land-use and exploitation.

Many scenarios for climate change have been developed over the last decade (Leggett *et al.*, 1992). These scenarios start with projections of socio-economic developments, the subsequent emission levels and concentrations of GHGs, climate change and impacts. Several models have been used to realise these scenarios (Harvey *et al.*, 1997). All of them show significant effects on global biogeochemical cycles, crop yields and agriculture, vegetation and land-use patterns, the distribution of pests and diseases, sea-level rise and the hydrology. An important lesson to be learned from all these scenarios is that there are large regional and sectoral differences. Another lesson is that the most rapid changes will occur over the coming decades and that with appropriate and immediate measures the impacts of climate change can be limited but not neutralised or overcome completely (Swart *et al.*, 1998).

The impacts of pollution and climate change on biodiversity have been discussed ever since the onset of the climate-change debate. Peters and Lovejoy (1992), for example, have assembled many different local and regional impacts. They were among the first to conclude that in modern landscapes, adaptation capabilities of species and ecosystems to climate change were limited. More recently, Huntley *et al.* (1997) explicitly addressed the consequences by integrating understanding from different biological and ecological disciplines, and case studies on specific genera and species. They stress that all responses to rapid climate change are species-specific and involve spatial and evolutionary mechanisms. This leads to large regional differences and variation.

Table 2 Direct and indirect effects of elevated CO_2 and climate

Direct effects	Possible indirect effects
Changes in elevated $_{CO2}$	
Changes in plant growth	Changes in species abundance
Changes in water use efficiency	Changes in ecosystem patterns and biogeochemical cycling
Changes in nutrient use efficiency	Changes in competitive abilities of species
Changes in climate	
Changes in plant growth	Changes in species abundance
Changes in decomposition	Changes in ecosystem structure and biogeochemical cycling
Changes in ecosystem patterns	Changes in biogeochemical cycling
	Changes in disturbance regimes
	Changes in competitive abilities of species and ecosystem structure and function

Historical evidence has illustrated that biodiversity was always reshaped according to regional environmental characteristics but that major extinctions during the Quaternary period all occurred during periods of rapid change. The projected rate of change is thus important. The far-reaching conclusion of Huntley *et al.* (1997) was that it is very likely that future climate change will lead to a rapid increase of extinction rates. These rates will be much higher than the evolutionary speciation rates. Climate change would therefore certainly reduce biodiversity regionally and globally. Further, the authors have concretely identified vulnerable regions, ecosystems and species.

The impact studies have collected mostly empirical and observational evidence to conclude that biodiversity will be strongly impacted by climate change. Studies do not focus on 'How much?', 'Where?', 'When?' and , 'Why?'. These questions can be better addressed by comprehensive scenario and modelling studies, which link emissions of pollutants and greenhouse gases with the rate of environmental change in order to define and evaluate changes in the patterns of biodiversity and ecosystem functioning.

2.2.5 Concluding remarks

In the above discussion, I have tried to convey the notion that the different influences on biodiversity are highly correlated, complex and act simultaneously on local, regional and global scales. Further, many of the causal factors impacting on biodiversity decline are demographic, cultural and socio-economic. Fortunately, the biological and ecological responses with respect to ecosystem and biospheric functioning are becoming more predictable with some of the recent advances in understanding ecosystem functioning (Walker *et al.*, 1997). The translation of these responses to lower organisational levels (genes, species and communities) and thus the complete scope of biodiversity, however, still remains a major challenge. Local and regional differences in environmental heterogeneity, species and population characteristics, and cultural and socio-economic conditions, will probably always lead to rather general translations hampered with many uncertainties. But, they can at least sketch the emerging trends in a transparent way.

For many researchers, such uncertainty and generality would imply that the development of scenarios for changes in biodiversity is a trivial and unrealisable exercise and therefore not worth the effort. Despite the inherent limitations of scenarios, the comprehensive analysis of plausible linkages between the societal developments (i.e. the causes of biodiversity decline), the subsequent resource use and its consequences for ecosystem functioning and biodiversity is more than just describing an alarming trend of biodiversity decline. It puts the many local and regional examples of biodiversity into a convincing societal perspective, which is much more appealing for policy makers and their advisors.

In the next section, I will describe the IMAGE 2 model, which is developed to make this linkage, especially for terrestrial systems. Several coarse biodiversity indicators are used to emphasise biodiversity. These indicators are only coarse proxies for biodiversity. The implemented scenarios, however, will show that the trends in biodiversity decline can be relieved with the development of proper land-use management and the mitigation of climate change.

2.3 The structure and assumptions of the IMAGE 2 model

Maintaining consistency in scenarios is a major challenge. This is partly solved by using Earth System Models for generating these scenarios. These integrated models are tools for accomplishing a measure of harmony between the many disparate components of the scenarios. I will use IMAGE 2 for this discussion. Its goal is to provide a disciplinary and geographic overview of global environmental change. The model is fully documented (Alcamo, 1994 and Alcamo *et al.*, 1998) so a brief overview will suffice here.

Assumptions about the regional demographical, technological and economic developments are the major driving forces for the scenarios. These assumptions allow IMAGE 2 to compute future changes in energy and land use. These changes lead to emissions from fuel combustion, industrial production and land-use change, and changes in carbon fluxes. Consequently, the atmospheric concentration of various greenhouse gases changes, as well as the flux of heat and moisture between the terrestrial, oceanic and atmospheric compartments. This affects climate at regional level. These climatic changes then feed back to the biosphere in different ways by, for example, changing the productivity of crops and consequently the required acreage of future agricultural land.

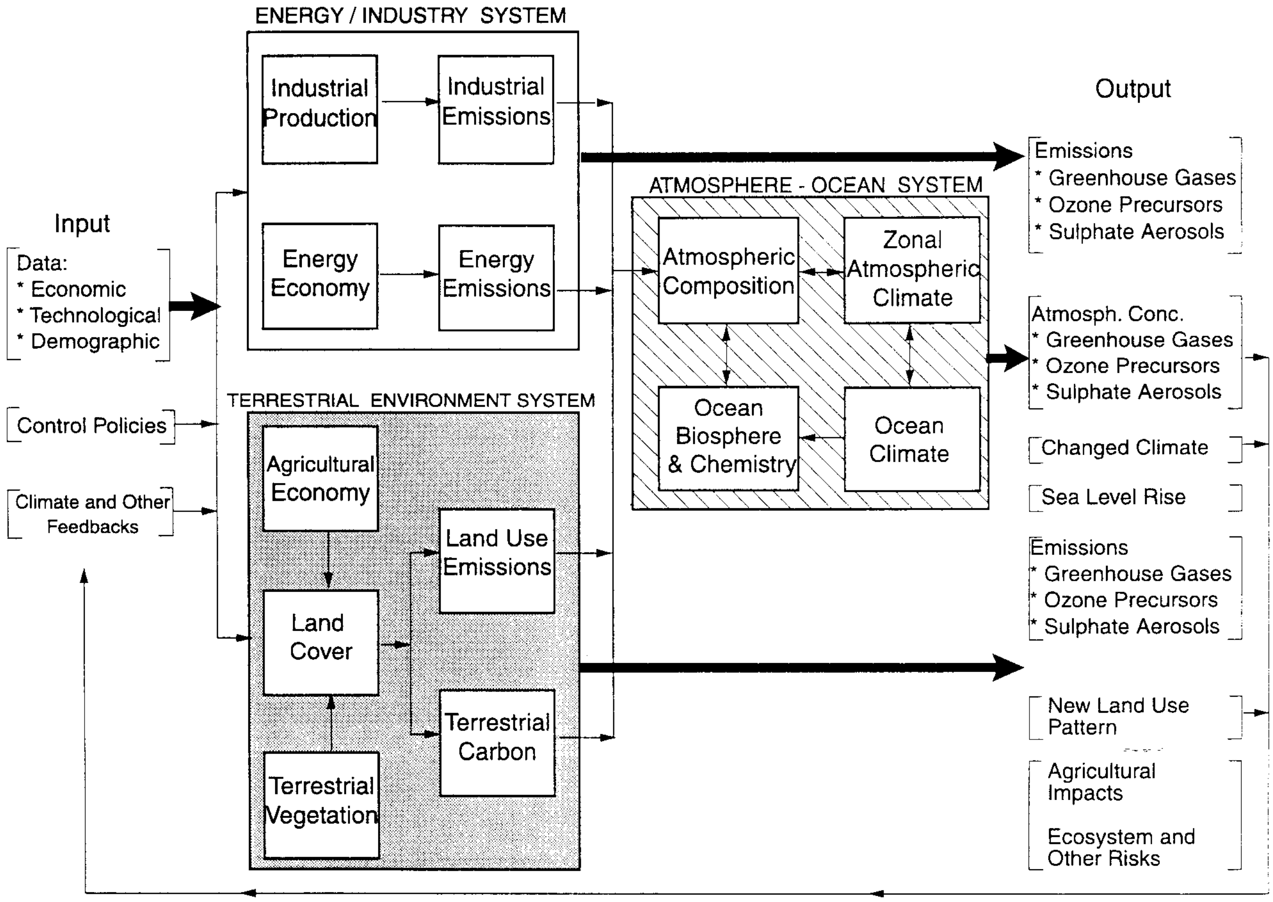

Figure 2. A flow diagram of IMAGE 2.

The IMAGE 2 model consists of several individual global submodels organised into three fully linked subsystems: Energy–Industry, Terrestrial Environment, and Atmosphere–Ocean (Fig. 2). The Energy–Industry models compute the emissions of greenhouse gas and other gases from five sectors in 13 large world regions on the basis of 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 biosphere and the atmosphere. The Atmosphere–Ocean models calculate the changes in atmospheric composition of greenhouse gas 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. Simulations of IMAGE 2 result in scenarios for the period up to 2100.

Table 3 Assumptions for population (millions) and Gross Domestic Product (US$ per capita)

	Population						Gross Domestic Product					
Region	Observed		Scenario A		Scenario B		Observed		Scenario A		Scenario B	
	1970	1990	2050	2100	2050	2100	1970	1990	2050	2100	2050	2100
Canada	21	27	32	32	23	15	13001	21273	65523	115454	46102	64815
USA	205	250	298	295	235	166	15931	21866	65531	114178	48209	66522
Latin America	284	446	820	873	771	773	2024	2569	8425	25048	5198	10762
Africa	360	639	2198	2862	1621	1611	613	646	1956	6553	1205	2803
OECD Europe	351	377	394	388	323	218	12268	19065	58722	103470	41317	58088
Eastern Europe	108	123	149	148	129	97	1213	1913	9584	16768	6047	7278
CIS	243	289	350	347	302	228	1452	2476	7666	13413	4777	5749
Middle East	115	202	726	932	439	345	2883	2823	7018	19773	4166	7893
India + S.Asia	739	1171	2375	2644	1897	1479	220	327	1907	7436	1185	3240
China + C.P. Asia	899	1242	1886	1953	1390	950	127	369	3481	15226	2117	6552
East Asia	240	368	746	831	596	465	569	1508	8795	34293	5465	14941
Oceania	16	21	23	23	17	12	11670	15579	58690	103093	42862	59305
Japan	104	124	132	130	101	69	12088	23734	89411	157058	65299	90349
World	3686	5280	10129	11455	7844	6427	3073	3971	9473	21319	6566	10453

2.4 Scenario description

The main driving forces of global change in these scenarios are population and economic growth and activities. I have selected an intermediate and a low scenario for this paper (scenarios A and B, respectively). Scenario A was intended to reflect IPCC's medium estimate of global CO_2 emissions (Leggett *et al.*, 1992). Scenario B was intended to give lower overall consumption levels, with hopefully lower impacts on biodiversity. Both scenarios, however, depict business-as-usual or reference developments. No global change or biodiversity policies are assumed.

Both scenarios use the population and GDP estimates of IPCC (Table 3) (Leggett *et al.*, 1992). The population estimates in scenario A are probably more likely than in scenario B (low) (Lutz *et al.*, 1994). The GDP assumptions are based on the estimates of the World Bank (1991). These assumed regional figures imply a substantial increase in GDP per capita in both scenarios (Table 3). For example, GDP per capita in Latin America and East Asia will exceed current levels in OECD Europe in constant dollars. Nevertheless, a large income gap will remain between industrialised and developing regions.

To calculate a scenario of energy consumption and the consequent emissions for each of 13 world regions, IMAGE 2 takes four main factors into account:

- Changes in the level of activity in different economic sectors as a function of changes in income and population.
- Structural change of the economy that lead to changes in energy intensity of the different sectors.
- Technological change that improves the performance of devices and appliances used to deliver energy services and emission levels.
- Changes in fuel prices that stimulate energy conservation and shifts in fuel mix and their emission factors.

The precise energy and industry assumptions are beyond the scope of this paper. They are presented in Leemans *et al.* (1998). Land-cover change is an essential aspect for determining changes in biodiversity. The underlying scenario assumptions leading to changes in land use will therefore be discussed in much more detail.

IMAGE 2 computes changes in land cover by taking into account the need for agricultural land, which includes pasture, cropland and managed forests. The model computes land-use change by computing the growing demand in the different regions for livestock, crops and forest products and the cropland, pasture and forest acreage required to provide these products.

To define a land-use scenario, IMAGE 2 takes into account such factors as agricultural trade between regions, potential productivity, livestock, cropping intensity and yield improvements. The need for agricultural land will depend, first and foremost, on regional agricultural demands. However, for some regions, the acreage of agricultural land will also depend on the amount of food traded with other regions. The trade patterns must be specified for each scenario. In scenarios A and B the trade patterns are similar: currently importing countries maintain their current dependence on imports, also in future. The other factors, except potential productivity, are also scenario assumptions. Potential productivity influences the amount of food that can be produced per hectare of land and is computed internally by the model using local climate and soil characteristics, and global CO_2 concentrations.

Agricultural demand consists of the need for all agricultural commodities, specifically meat and crops consumed by humans, and feed required by livestock (demand for forest products are computed separately in the model, while the demand for modern biomass[1] is generated by the Energy Economy model). To compute regional demands, the model multiplies per capita consumption of food by population estimates. IMAGE 2 computes this consumption under the main premise that people eat more food as their income increases, up to a particular 'preferred' consumption level. When the availability of

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[1] Modern biomass is frequently proposed as a carbon-neutral energy source, but its production requires land. Many energy scenarios assume that after 2020 this source will become abundant and provide about 20% of the global energy demand.

agricultural land decreases, prices increase and this shifts the consumption levels away from the preferred (often meat) towards achievable consumption levels. IMAGE 2 thus computes food consumption based on (1) population, (2) income, (3) land productivity and availability, and (4) preferred level of food consumption. The first two factors are taken from the population and GDP assumptions (Table 3). The third factor is computed internally in the IMAGE 2 model. The last factor, preferred level of consumption, is difficult to specify because it varies greatly from region to region, and depends on difficult-to-quantify cultural and geographical factors. Hence we have taken a pragmatic approach and run the IMAGE 2 model 'backwards' from 1970 to 2010 in order to obtain the trend of this factor. This is done by specifying for this period what the model is supposed to compute -- per capita consumption of different foods from 1970 to 2010. Data for food consumption comes from AGROSTAT (FAO, 1991) for 1970 to 1990, and from trend estimates of IFPRI (Rosegrant *et al.*, 1995) from 1990 to 2010. We then extrapolate these trends from 2010 to 2100. The same estimates of preferred consumption are used for both scenarios.

An important variable affecting the overall land needed in a region for cropland is the cropping intensity (i.e. the number of crops grown per hectare of land over a calendar year). This must be specified for each scenario and region over the scenario period. Historically, there has been an upward trend, and both scenarios assume that this trend will continue up to a region-specific maximum. Cropping intensities of temperate cereals sharply increase for most developing regions up to the second half of the next century, while they level off in industrialised regions in the early part of the century.

Improvements in management, fertiliser use and irrigation, high-yield crop varieties and machinery have contributed to a steady increase in crop yields throughout the world. The future rate of technological improvement in crop yield must be specified for each scenario and region. The industrialised regions are assumed to have already passed the 'green revolution' although yields will continue to improve at somewhat lower rates due to biotechnology (Table 4). Scenarios for these regions are based on a slowing down of the 1970 to 1990 trends. For the developing regions, trends up to 2010 are taken from the FAO data for 1970-1990 (FAO, 1991) and the IFPRI projections up to 2010 (Rosegrant *et al.*, 1995). These rapid improvement rates level off after 2030. Different rates of improvement are assigned to the two scenarios, depending on their rate of economic growth (Tables 3 and 4).

The assumptions concerning livestock also have an important influence on estimating future land requirements (for feed crops and rangeland). First, animal productivity, i.e. the amount of meat produced per animal, strongly determines the area of land used. It is assumed that industrialised countries are already nearing their maximum land area and that other regions will reach the current OECD Europe level when their GDP per capita reaches the current OECD income level. Hence, the trend of this factor varies from scenario to scenario along with economic assumptions of the scenarios.

Table 4 Assumptions for yield improvements relative to 1990 in temperate cereals. Other crops are defined accordingly, for details see Leemans *et al.* (1998)

	FAO Agrostat		IFPRI	Scenario A		Scenario B	
	1970	1990	2010	2050	2100	2050	2100
Canada	1.01	1.00	1.10	1.28	1.45	1.24	1.38
USA	0.77	1.00	1.27	1.60	1.82	1.52	1.68
Latin America	0.59	1.00	1.37	2.17	2.80	1.90	2.32
Africa	0.73	1.00	1.37	2.17	2.80	1.90	2.32
OECD Europe	0.64	1.00	1.10	1.21	1.21	1.21	1.21
Eastern Europe	0.63	1.00	1.27	1.47	1.61	1.44	1.56
CIS	0.75	1.00	1.27	1.60	1.82	1.52	1.68
Middle East	0.71	1.00	1.27	1.60	1.82	1.52	1.68
India + S.Asia	0.60	1.00	1.37	1.92	1.92	1.92	1.92
China + C.P. Asia	0.39	1.00	1.27	1.53	1.53	1.53	1.53
East Asia	0.85	1.00	1.10	1.28	1.45	1.23	1.35
Oceania	0.62	1.00	1.27	1.60	1.82	1.52	1.68
Japan	0.62	1.00	1.10	1.28	1.45	1.24	1.38

Second, two different ranging systems can be distinguished from the AGROSTAT statistics: intensive and extensive ranging. The first is located in the European countries and Asia, while the latter is found in the Americas, Africa and Australia or mainly the arid areas. Productivity on the intensively managed rangelands is about five times as high as on the extensively managed ones. This is the result of the numbers of cattle per hectare, the stocking density. Although initially regional differences are apparent, this productivity gap between regions is assumed to close during the simulation time period but the differences between intensive and extensive stocking densities remain. The result of this set-up is that in the intensive ranging regions, much less land is required to produce a kilogram of meat than in the regions with extensive ranging.

The agricultural demand for food, fodder, fuelwood, timber and modern biomass (Johansson *et al.*, 1993) is satisfied by continued production on current agricultural land, by intensification and expansion of agricultural land. If demand exceeds the current production capacity, land is taken out of production and returns to its natural vegetation. The simulation of land use and land cover results therefore in a consistent pattern between regional demand and production potential. We use a heuristic scheme to incorporate some of the spatial interactions, inertia and societal preferences in defining future agricultural patterns (Alcamo *et al.*, 1998). For example, expansion occurs predominantly in areas close to current agricultural land and rivers to mimic the availability of infrastructure and labour. Of these 'nearby' areas, those with highest potential productivity are used first. Expansion of agricultural land can lead to deforestation. Some of the cleared trees are used to satisfy timber demand. Unfortunately, the amount of wood stemming from deforestation is much larger than the demand so that a large part is burned; this leads to emissions of greenhouse gases. The land-cover simulations lead to frequently updated land-cover patterns with arable land, rangeland, regrowth forests (i.e. the land cover type that results from clear-cut or abandonment of agricultural land) and natural vegetation on a 0.5^o longitude and latitude grid.

All the emissions stemming from energy use, industrial activities and land use enter the atmosphere. By accounting for atmospheric chemistry, carbon uptake by the oceans and the biosphere, IMAGE 2 then calculates the final atmospheric GHG concentrations. These are used in a simple climate model to determine climate change (both temperature and precipitation). Regional and seasonal climate patterns are defined by a simple downscaling procedure using the results of an advanced climate model, an observed climatology and the determined climate change of IMAGE 2.

2.5 Scenario results

The simulated climate patterns are used in subsequent years to calculate potential crop productivity and vegetation patterns, which are also corrected for the increases in CO_2 concentration (compare Table 2). Climate change thus influences the land-use and vegetation patterns directly in the model and these influences are presented as impacts. The vegetation models included in IMAGE are the same, which led to the alarming vegetation shifts discussed by IPCC (Watson *et al.*, 1996), Peters and Lovejoy (1992) and Huntley *et al.* (1997) (Table 5). The only difference is that we have developed a simple adaptation and migration scheme (Alcamo *et al.*, 1998), which allows some ecosystems to adapt (a component of FCCC, Article 2).

Unfortunately, with the simulated climate change in these business-as-usual scenarios, natural adaptation occurs only in a small percentage of the impacted vegetation. Forests generally do not adapt effectively. Another analysis with IMAGE 2 (Swart *et al.*, 1998) indicated that effective adaptation is only possible at a very slow rate of climate change (less than 0.1^oC per decade) and limited absolute climate change (less than 1^oC in total). Such rate and level would limit impacts on vegetation. To reach this, global emission levels should be reduced immediately by 1-2% annually. Such draconian measures are currently not discussed at the FCCC negotiations. The current target is a meagre 5.5% reduction in 2010 compared to 1990 levels for only the industrialised countries.

The simulated changes in vegetation patterns (Fig. 3) indicate some concrete impacts on biodiversity. Regionally, the impacts are largest in the boreal regions, where higher than average temperature changes also occur.

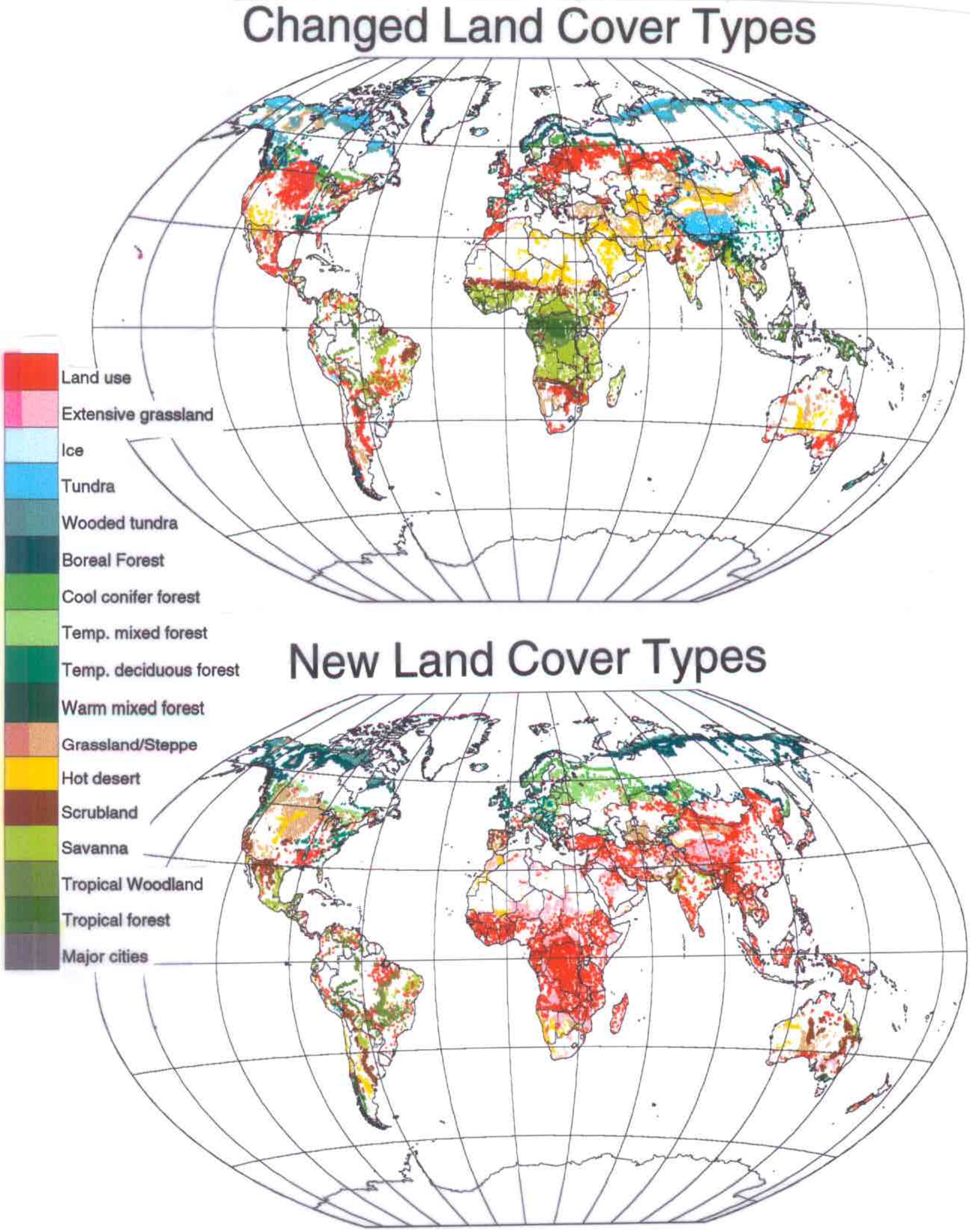

Figure 3. Change in land cover and land use in 2100 for scenario A. White depicts 'no change'. The top panel presents the changes on the original vegetation. Red denotes agricultural and grazing land (i.e. land use) that is abandoned. The lower panel presents the future land cover; Red denotes the expansion of land use.

Table 5 Relative impact levels on natural vegetation (vs. total land area) and nature reserves (vs. total reserve area) of different levels of increases in global mean annual temperatures

	0.5 °C	1.0 °C	1.5 °C	2.0 °C	2.5 °C	3.0 °C
Natural vegetation	11	19	26	32	37	43
Nature reserves	9	17	24	32	37	42

Tundra vegetation declines rapidly and boreal forests shift polewards. At the end of next century much of the European boreal and alpine forest in both scenarios will be replaced by temperate broad-leaved forests. But because migration rates are too slow to cope with such rapid change, depauperate or degraded forest types results, dominated by opportunistic species with wide distributions and rapid spread. The abundance of specialised and late successional species with small niches will decline. Most extinctions will occur in this group of species. In boreal regions the shifts are strongly determined by changes in temperature, in temperate regions more by moisture. The simulations show that in the more maritime regions precipitation simultaneously increases with temperature. Here, only small changes are calculated. In continental areas, however, precipitation remains the same or decreases. The resulting drought kills many forests and grasslands spread. These changes are also detrimental to biodiversity.

Simulated natural vegetation change in the tropics is much smaller (Fig. 3). The average increase in temperature is also much smaller than in the higher latitudes. Much of the simulated changes in the tropics are generated by increases in aridity, not in temperature. Some of the current moist and wet areas with rainforests will in the future experience more frequent drought periods. This could increase fire occurrence (Fig. 4) and rapidly change the structure and species composition of these forests, which for biodiversity are a very important biome.

As already stated earlier (compare Table 1), much of the land is currently managed by humans. Although the shifts in vegetation zones make clear that climate change will result in a major change in biodiversity patterns and that some of the changes already have been observed (Grabherr *et al.*, 1994; Parmesan, 1996 and Myneni *et al.*, 1997), many policy-makers remain sceptical that these rapid changes are possible. Many believe that ecosystems are resilient and will evolve, and if not, adaptive management will mitigate the negative effects. To extract managed land from natural lands, I have analysed the impact on nature reserves (Table 5). A database with many large nature reserves from the World Conservation Monitoring Centre (Groombridge, 1992) was used. The elegance of vegetation shifts in nature reserves is that they are legally protected to conserve specific species, and their habitats and ecosystems.

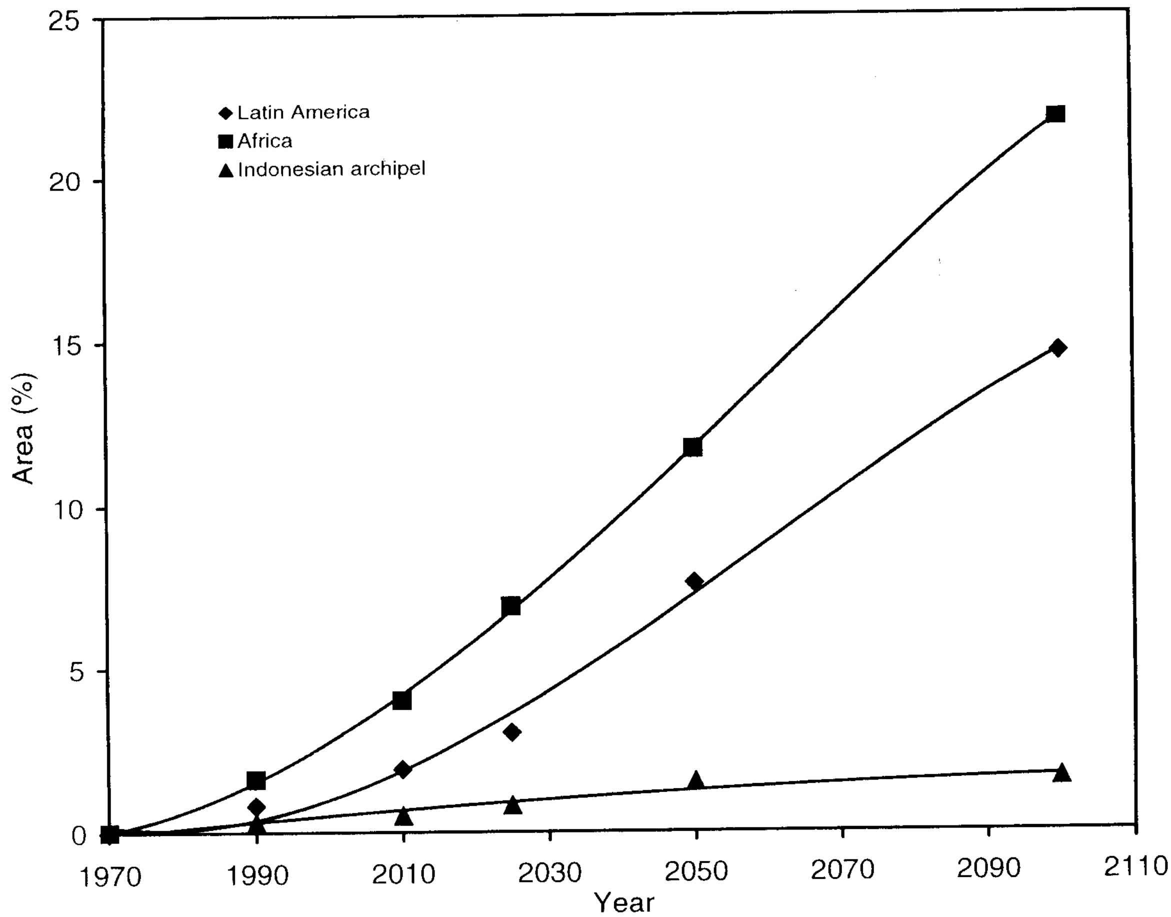

Figure 4. Changes in the moist and wet tropics (i.e. no dry season) due to possible fire occurrence of Latin America, Africa and Asia. This occurrence is defined as the appearance of a structural period of drought of at least two weeks.

The expansion of nature reserves are found at the heart of the abatement measures specified in the Biodiversity Convention. Nature reserves cannot move and therefore cannot adapt naturally. Under climate change, they just change and will probably not comply with the original conservation objectives any more. Table 5 shows that even with a small climate change, a large portion of the selected nature reserves are impacted. A geographic analysis shows that the impacted sites are located throughout the world and not only in specific regions.

This above analysis shows that changes in biodiversity due to climate change can be expected everywhere. Similar results are obtained for changes in land use (Fig. 3). Globally, the consumption of food crops, animal products (and also rangeland) and modern biomass increase threefold. Part of this increase is due to increases in population and part to changed consumption patterns. The result is that in the 1990 to 2100 period, the global extent of cropland (not grassland) increases from 9 to 14 million km^2 (Fig. 5).

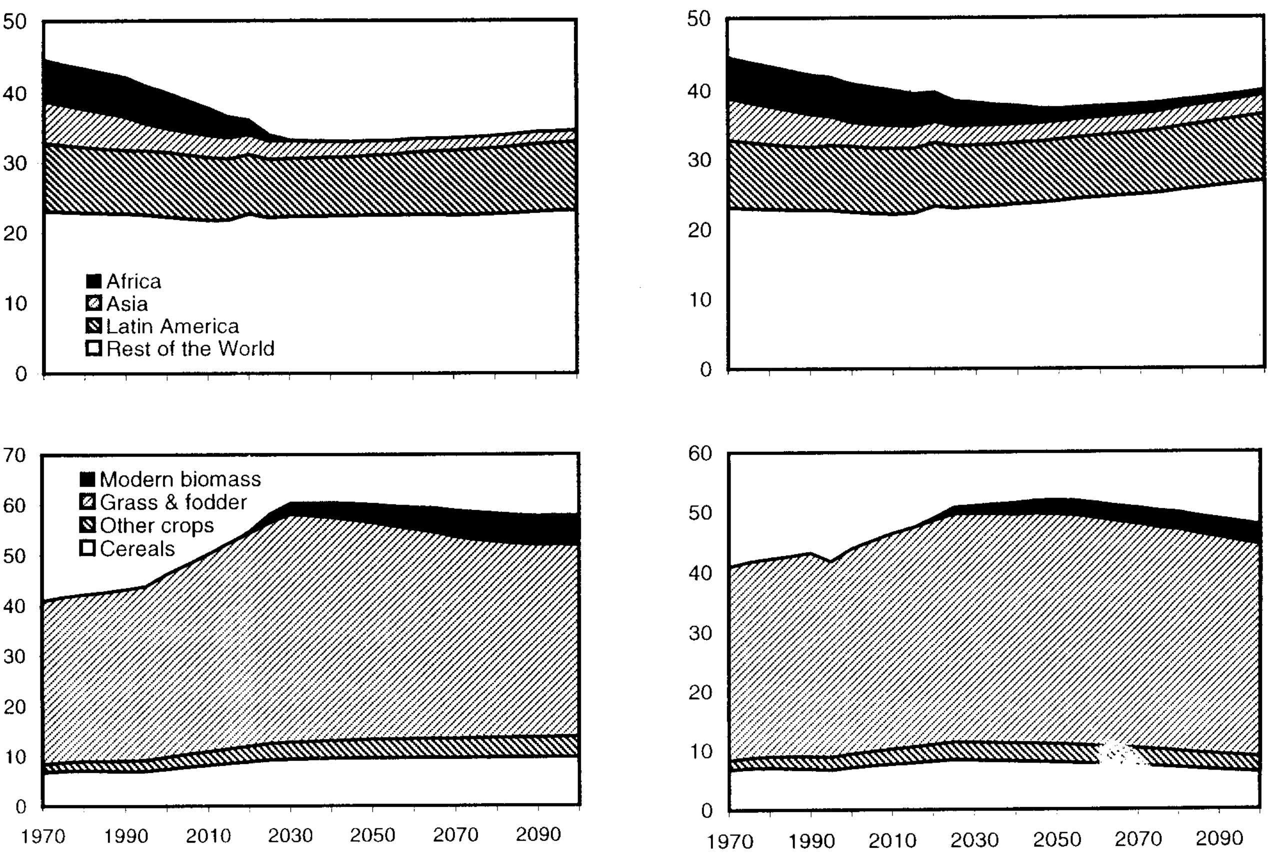

Figure 5. Changes in the extent (million km^2) of forests (top) and land use (bottom). The left graph depicts scenario A and the right one, scenario B.

The production of modern biomass additionally requires about 6 million km^2 in 2100 (30% of all arable land). The global extent of pastureland increases more rapidly, from 34 to 44 million km^2 in 2030, after which the total extent decreases somewhat. This is most apparent in Africa, where currently about 9 million km^2 are used for grazing. This increases to 15 million km^2 in 2025 in scenario A; the increase is somewhat slower in scenario B, where this upper level is reached in 2050. The arable land in Africa increases from 1 million km^2 in 1990 to 3 million km^2 in 2100. This increase in arable land mostly stems from converting pasture land. The total increase in land use saturates in 2025 and 2050 for scenarios A and B, respectively, because of the lack of available and suitable land. Deforestation rates are also different for both scenarios (Fig. 5). The initial deforestation rates in scenario B are lower than in scenario A and after 2030 there is even a slight increase again in the extent of forest.

These changes in land use lead to sustained global deforestation rates up to 2025, after which the total forest area tends to stabilise. However, regionally there are large differences. In the simulations there is a shift of major deforestation areas away from Latin America towards Africa. Asian deforestation just continues, while in Latin America in the second half of next century grazing and other agricultural land is abandoned and returns to natural vegetation. In Europe and North America the decrease in agricultural land starts immediately after the start of the simulation. Here, agricultural land is converted to natural vegetation and the forest areas increase. Potentially this can have positive effects on biodiversity, but the simulations also show that timber production increases. Although reforested, a large proportion of these forests therefore remain managed and are 'harvested' at least once during the simulated period.

The impacts of climate change on land use is also pronounced (Fig. 3). Changes in potential crop yields are very regionally specific. Often at the warmer edge of a crop's distribution yields decline, while extent and productivity increase at the colder edge. New opportunities emerge for cereals in Scandinavia, Canada and Russia, while yields decline in southern China and the African plateau. Moisture availability also has a significant effect, especially in the central Great Plains. The simulated dryer conditions here result in productivity losses. The model then simulates a shift of these major agricultural regions towards the southeast of the USA, with consequences for biodiversity in the new land-use regions.

These scenario results show that inclusion of simultaneous climate change and land-use change is important. Both strongly determine the future land-cover patterns and thus biodiversity. One should be cautious, however, by taking these results very literally. IMAGE 2 is far from perfect and does not include all the complex drives of land use change. It sketches a broad picture. Some of the results are a direct consequence of the assumptions. For example, if animal production in Africa was assumed to be more intensive, less land would be required and more forest would probably be saved. However, the sensitivity of the model to changes in assumptions can be easily tested as I have shown. Some interesting feedbacks and interactions could be observed in scenario A. The availability of suitable land in Africa became limited, which led to changes in diets away from the preferred diets with more meat towards a basic diet with more cereals, pulses and roots. Assuming a rapidly increasing animal productivity initially relieved some of the land constraints, but simultaneously saturated the preferred diet. At the end of the simulation the higher productivity made little difference in these simulations, mainly because of the lack of suitable land to fulfill the dietary preferences. However, this example shows that these models can be used to analyse complex systemic interactions.

Table 6 Non-domesticated land as a percentage of total regional land area for scenarios A and B

Region	1990	2025		2050		2100	
Scenario		A	B	A	B	A	B
Canada	91	91	91	90	91	86	91
USA	62	61	62	59	64	60	70
Latin America	68	62	66	63	65	71	71
Africa	72	50	63	48	55	50	50
OECD Europe	69	68	68	67	69	63	71
Eastern Europe	32	30	31	31	33	25	35
CIS	76	77	78	76	78	76	82
Middle East	91	74	82	71	79	69	81
India + South Asia	59	46	52	40	52	42	62
China + other CP Asian countries	59	47	48	44	46	37	44
East Asia	74	56	58	46	50	34	48
Oceania	62	63	61	65	71	68	85
Japan	60	50	49	35	35	27	24
World	71	62	67	61	65	61	67

It is not easy to make land-use change have an impact on biodiversity. Ideally, changes in habitats of individual species should be evaluated. This is impossible because of the coarseness of the model. We have therefore developed a proxy or indicator: the total of land used (Table 6) defined as the sum of the extent of arable land, pastures and managed forests. This area is strongly dominated by humans, which leaves little room for biodiversity. The original biodiversity probably cannot sustain itself under such intense land use. If we look at the simulated changes, a clear pattern emerges. In tropical areas the extent of land use increases, while in temperate regions it remains largely stable. This means that over the coming decades the largest stresses from land use will probably occur in the tropics and not in the temperate regions. The differences between scenarios is also apparent. Scenario A with high resource use leaves less room for biodiversity than scenario B.

2.6 Concluding remarks

Developing regions have in the scenarios presented both the highest population and relative income growth (Table 3). This results in the largest increases in consumption and thus resource use. The resulting expansion of rangelands and arable land will lead to additional losses of biodiversity. This changed land use could easily lead to overexploitation, additional pollution, habitat destruction and fragmentation, and thus strong declines in biodiversity. Direct human-induced changes in biodiversity and additional pressure on nature reserves will thus be largest in those regions. Indeed, many examples from GBA illustrate this. However, problems also arise in the industrialised regions. First, there is the direct land-use component: agriculture does not expand, but forestry does. The higher proportion of managed forests could place a toll on the original biodiversity. Further, the impacts of climate change caused by the anthropogenic emissions of GHGs are severe and influence large parts of the industrialised world. In the near future, rapid climate change will probably be the largest threat to biodiversity in these regions.

An additional lesson that can be learned from these scenarios is the connectivity between components of the society–climate–biosphere system. Most future energy scenarios strongly depend on the use of modern biomass as a major energy carrier. This fuel has no net CO_2 emissions but requires land. This scenario analysis has already shown that the additional land requirements will be substantial (Fig. 4). Not only does the production of modern biomass compete with food production, it could also pose an additional threat to biodiversity through its land-use consequences. The analysis presented here illustrates that an obvious solution to one environmental problem can create additional obstacles to solving other problems. To analyse and advise on optimal solutions for series of environmental problems, comprehensive integrated assessment will be a must.

I have shown that integrated assessment and scenario development can help to address and probably answer the questions posed in the introduction. In this paper, however, I have not tried to make the full circle and limited the presentation and discussion to the 'How?', 'Why?' and 'What?' questions. We have seen that the dynamic interactions between socio-economic developments and natural resources will, if unabated, lead to a severe decline in biodiversity. The ultimate question on 'how a decline in biodiversity will affect the biosphere and society' has been left unanswered. The emerging understanding on biodiversity and ecosystem functioning, however, supplies some clues to the answer: ecosystems with lowered biodiversity levels are likely to be less productive, less resilient and, when stressed additionally, respond in a highly unpredictable way. This could well erode the certainty with which we rely on the continued supply and availability of natural resources needed for our daily lives. The definition of the dynamic role of biodiversity, the 'Insurance Hypothesis', resulting from redundancy discussion in the biodiversity debate (Schulze and Mooney, 1993; Walker, 1995; Chapin *et al.*, 1997 and Tilman *et al.*, 1997) is that species redundant under normal, relatively constant environmental conditions may be critical for the maintenance of ecosystem processes in the face of environmental variation and change.

The two business-as-usual scenarios have illustrated that environmental change will control future conditions. This means that, in line with the 'Insurance Hypothesis', high levels of biodiversity should be maintained and protected worldwide and that the causes of its decline should be strongly abated. This not only means the liquidation of alien species, and connecting and restoring species' habitats, but (and probably more important) also a curbing of the rapid increase of land use and sharp reduction in the emissions of greenhouse gases and other pollutants. The scenario analysis illustrates that although population growth contributes to the problem, rapidly increasing consumption patterns, rapid expansion of rangelands to support changing diets and technological innovation which is too slow are the major drivers of environmental change. This makes solving the problems of environmental change not only a technical environmental issue but particularly a developmental issue.

The scenario studies transparently highlight the complex systematic interactions and feedback between society and the other components of the earth system and provide a broad outline of possible future developments. As such, these scenarios already contribute to the understanding of trends in biodiversity. However, many aspects of biodiversity are not included in these scenarios. First, the genetic and species levels of biodiversity are not considered. Second, the expansion and intensification of agricultural land only approximates habitat disturbance, fragmentation and destruction. Finally, the influence of alien species is ignored. In the current set-up of the analysis and its emergence from climate-change assessment, addressing these aspects are impossible. Much research, therefore, has to be directed to the development of proper indicators that can bridge the gap between the coarseness of the global scenarios and the detailed aspects of the biodiversity issues that should be subject of the study.

Finally, the analysis shows that the advantages of such comprehensive scenario studies should not be denied. Although these business-as-usual scenarios sketch a grim future for biodiversity, their integrated characteristics interest many scientists and policy makers. This could help to initiate the development and analysis of effective abatement policies. The often-heard argument that such grim or doomsday scenarios do not become reality is not due to their being unrealistic but to them being convincing cases. The main lesson is found in the realisation that continuing to follow a business-as-usual track could be harmful. The insights provided by these scenarios will help us to review the alternatives and select more appropriate and successful tracks.

3 Global biodiversity scenarios for the year 2100

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3.1 Introduction

Global biodiversity[2] is changing at an unprecedented rate (Pimm *et al.*, 1995), as a complex response to several human-induced changes in the global environment, including changes in land use, climate, chemical composition of the atmosphere, and the global cycling of nitrogen (Vitousek, 1995). The magnitude of this change is so large (Pimm *et al.*, 1995) and so strongly linked to ecosystem processes (Chapin *et al.*, 1997; Tilman, 1997) and society's use of natural resources (Daily, 1997; Costanza *et al.*, 1997) that biodiversity change is now considered an important global change in its own right (Walker and Steffen, 1996). We include all naturally occurring organisms in our definition of biodiversity, at scales ranging from genetic diversity within populations, to species diversity, to community diversity across landscapes. Our definition excludes exotic organisms that have been introduced and communities such as agricultural fields that are maintained by regular human intervention. International conventions seek to minimize changes in biodiversity, just as other conventions seek to reduce the atmospheric concentration of CO_2, which is linked to global warming, and chlorofluorocarbons, which are linked to increased UVB exposure and skin cancer. Scientists and policy makers are familiar with, and frequently use, scenarios of change in climate or of concentrations of greenhouse gases in projecting the future state of the global environment (Houghton *et al.*1996). Although biodiversity changes are just as important for the functioning of ecosystems and the well being of humans, there are currently no scenarios for biodiversity comparable to those of climate and greenhouse gases.

3.2 Scenario development

We developed global scenarios of biodiversity change in ten terrestrial biomes for the year 2100 based on (1) global scenarios of changes in environment and land use and (2) the understanding by ecological experts of the sensitivity of biodiversity in each terrestrial biome to these global changes. First we identified the five most important determinants of changes in biodiversity at the global scale, which are changes in land

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[2] We define change in biodiversity at the biome level as the changes in number and relative abundance of species that naturally occur in that biome.

use, atmospheric CO_2 concentration, nitrogen deposition/acid rain, climate, and biotic exchanges (the deliberate or accidental introduction of new plants and animals to an ecosystem)[3] (Sala *et al.*, 1999). Second we estimated for each biome, the impact that a unit change in each driver has on biodiversity. Finally, we derived three scenarios of future biodiversity for each biome, relative to its initial diversity, based on alternative assumptions about interactions among the drivers of biodiversity change. We assumed that either (1) there are no interactions among the various causes of biodiversity change, (2) there are antagonistic interactions and biodiversity will respond only to the driver to which it is most sensitive, or (3) there are synergistic interactions and biodiversity will respond multiplicatively to the drivers of biodiversity change. Since the nature of interactions among causes of biodiversity change is poorly known, we present all three alternatives as plausible scenarios of biodiversity change.

We used a "business-as-usual" scenario generated by global models of climate (Had CM2), vegetation (Biome3: Haxeltine and Prentice, 1996), and land -use (A1 scenario of Image 2 (Alcamo *et al.*, 1998) to estimate the change in magnitude of the drivers of biodiversity change for each biome between 1990 and year 2100. We ranked the projected changes in drivers to be small (value of 1) to large (value of 5) with an average value of 2.5 for each driver. We used the A1 scenario of the IMAGE model to estimate changes in land-use for each biome (Alcamo *et al.*, 1998). The IMAGE model projects that most land-use change will continue to occur in the tropical forests and in the temperate forests of South America and that least will occur in the arctic and alpine, where human population density will likely remain low and in northern temperate forests, where reforestation is expected to exceed deforestation, also causing small negative effects on biodiversity (Table 7). The extent of habitat modification is projected to be modest in desert and boreal forest, and intermediate in savannas, grasslands, and Mediterranean ecosystems. Atmospheric CO_2 mixes globally within a year (Fung *et al.*, 1987), so we assumed all biomes would experience the same change in CO_2 concentration. Nitrogen deposition is greatest in the northern temperate zone near cities and least in biomes such as the arctic and south temperate forests, which are generally distant from pollution sources.

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[3] We assembled a group of experts on the causes and consequences of biodiversity change in each major terrestrial biome. Based on the published literature, this group first estimated for each biome the relative sensitivity (on a scale of 1-5) of biodiversity to changes in the physical and biotic environment that are occurring at a global scale (columns in Table 7). The group then considered, for each driver of diversity change, the relative sensitivity of diversity in different biomes to changes in that driver (rows in Table 8). The global changes considered to have the greatest impact on biodiversity by this group were land use, atmospheric CO2 concentration, nitrogen deposition/acid rain, climate (including associated changes in disturbance regime), and biotic exchanges (the deliberate or accidental introduction of new plants and animals to an ecosystem). The synthesis developed for each biome was then reviewed by other ecologists familiar with controls over biodiversity in other geographic regions of that biome and published separately (Sala *et al.*, 1999).

Table 7. The expected changes for the year 2100, in the five major drivers of biodiversity change which are land use, atmospheric composition CO_2, atmospheric composition-nitrogen deposition, climate, and biotic exchange for the principal biomes of the earth.

	Arctic tundra	Alpine tundra	Boreal forests	Grassland	Savanna	Mediter-ranean	Deserts	Northern Temper. forests	Southern Temper. forests	Tropical forests
Land use	1.0	1.0	2.0	3.0	3.0	3.0	2.0	1.0	4.0	5.0
Atmospheric CO_2	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
N Deposition	1.0	3.0	3.0	3.0	2.0	3.0	2.0	5.0	1.0	2.0
Climate	5.0	3.0	4.0	2.0	2.0	2.0	2.0	2.0	2.0	1.0
Biotic Exchange	1.0	1.0	2.0	3.0	3.0	5.0	3.0	3.0	2.0	2.0

Note: Estimates vary from low (1) to high (5) and result from existing global scenarios of the physical environment and knowledge from experts in each biome (see text).

Table 8. The impact of a unit change in each driver on the biodiversity of each biome. In this exercise, a unit change of the driver was defined for land-use as conversion of 50% of land area to agriculture, for CO_2 as a 2.5-fold increase in elevated CO_2 as projected by 2100, for nitrogen deposition as 20 kg .ha-1.yr-1, for climate as a 4°C, or 30% change in precipitation, and for biotic exchange as the arrival of 200 new plant or animal species by 2100.

	Arctic tundra	Alpine tundra	Boreal forests	Grassland	Savanna	Mediter-ranean	Deserts	Northern Temper. forests	Southern Temper. forests	Tropical forests
Land use	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Atmos CO_2	1.0	1.0	1.0	3.0	3.0	2.0	2.0	1.5	1.5	1.0
N deposition	3.0	3.0	3.0	2.0	2.0	2.0	1.0	3.0	3.0	1.0
Climate	4.0	4.0	3.5	3.0	3.0	3.0	4.0	2.0	2.0	3.0
Biotic Exchange	1.0	1.0	1.0	2.0	2.0	3.0	2.0	1.5	3.0	1.5

Note: Estimates vary from low (1) to high (5) and result from existing global scenarios of the physical environment and knowledge from experts in each biome (see text).

Other biomes are intermediate, with regional variation in deposition generally associated with cities or industrial point sources. Climate is expected to warm most dramatically at high latitudes (arctic and boreal zones), change least in the tropics, and show intermediate changes in other biomes (Houghton *et al.*, 1996: Tables 7 and 8).

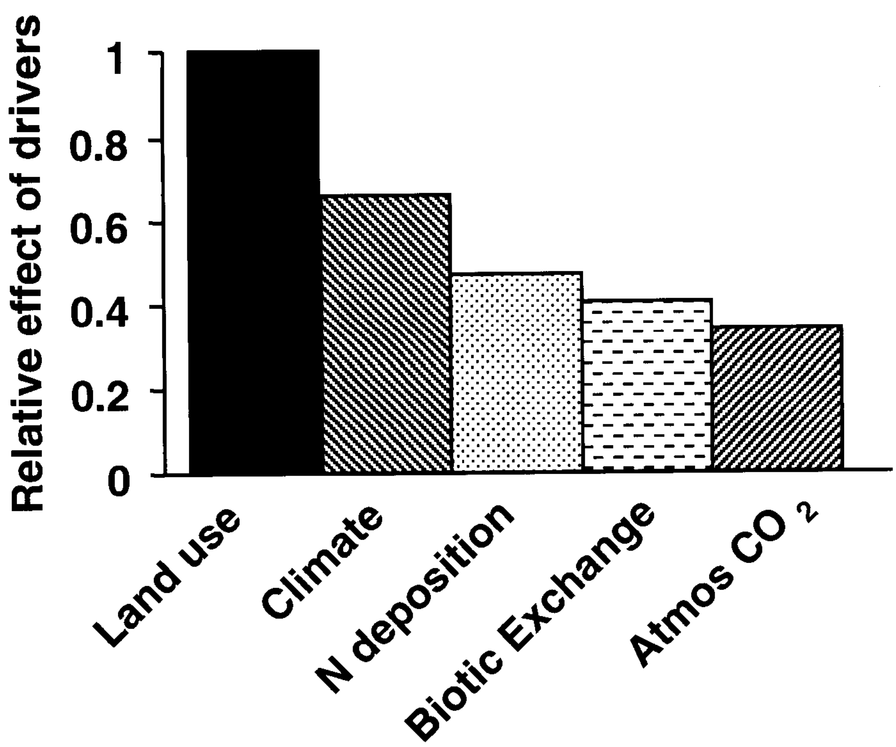

Figure 6. The relative effect of the major drivers of changes in biodiversity. The expected biodiversity change for each biome for year 2100 was calculated as the product of the expected change in drivers times the impact of each driver on biodiversity for each biome. Values are average of the estimates for each biome and they are made relative to the maximum change, which resulted from change in land-use.

Changes in precipitation are uncertain and difficult to generalize at the biome level. The pattern of biotic exchange reflects the pattern of human activity. Remote areas with little human intervention receive fewer exotic species than areas which are in the middle of trade routes or which host intense human activity (Drake *et al.*, 1989).

3.3 Biome evaluations

The second step of our exercise was to evaluate, for each biome, the impact that a unit change in each driver has on biodiversity independently from the expected magnitude of change in the driver (Table 8). Land-use change is the most severe driver of changes in biodiversity (Mooney *et al.*, 1995). For example, conversion of temperate grasslands into croplands or tropical forests into grasslands results in the local extinction of most plant species and the associated animals whose habitat is largely determined by plant species composition. Belowground organisms are also affected most severely by land-use change (Mooney *et al.*, 1995). We assumed no differences among biomes in the response to a unit change in land use and we assigned land use the maximum impact factor because of the consistently large effect of land-use change on biodiversity. The increase in atmospheric CO_2 is expected to have the largest impact on biodiversity in those biomes where growth is most limited by water availability and where there is a mixture of C_3 and C_4 species because of known species differences in the effect of CO_2 on water use efficiency (Mooney *et al.*, 1991; Jackson *et al.*, 1994). For example, changes in atmospheric CO_2 may change the competitive balance between species that differ in rooting depth, photosynthetic pathway or woodiness Mooney *et al.*, 1999). Therefore, we assigned the maximum impact factor of elevated CO_2 to grasslands and savannas, which are water-limited biomes with a mixture of contrasting plant functional types. Based on the same reasoning, we assigned smallest impact factors to arctic, alpine, boreal forest and tropical forest.

Increased nitrogen (N) deposition should have the largest impact on biodiversity in those biomes that are most N-limited by giving a competitive advantage to plant species with high maximum growth rates which then exclude the slower growing species (Tilman, 1993). Consequently, we assigned the largest impact factor to temperate forests, boreal forests, arctic and alpine. Biodiversity in deserts and tropical forests may respond least to N deposition because plant growth is strongly limited by water and phosphorus, respectively (Vitousek *et al.*, 1997). Grasslands, savannas, and Mediterranean systems received intermediate impact factors since N and other factors limit plant growth.

A given change in climate is expected to have the largest proportional impact on biodiversity in those biomes characteristic of extreme climates, although biodiversity in all biomes will likely be sensitive to climate. Small changes in temperature or precipitation in arctic, alpine, desert, and boreal forest will result in large changes in species composition and biodiversity. Similarly, we assume that biomes where climate less strongly limits the activity of organisms will experience changes in the distribution of organisms, but the overall effect on diversity may be less pronounced than in extreme environments.

Biotic introductions (i.e., the successful establishment of exotic species) vary according to environmental conditions and biogeographic considerations. Invasions have occurred least frequently in arctic and alpine ecosystems, due to their severe environment (Drake *et al.*, 1989) and the broad longitudinal distribution of much of the high-latitude flora and fauna. In the tropics, we also expect a small proportional change in the diversity of intact ecosystems because of the high initial diversity and because abiotic and biotic factors characteristic of this biome, including its high diversity, minimize the probability of successful establishment by invaders in undisturbed communities (Rejmánek, 1996). Conversely, we expect greatest impact of biotic exchange in biomes such as Mediterranean and southern temperate forests that have long been isolated and exhibit extensive convergent evolution. Other biomes are intermediate in their connectedness. There is wide variation within most biomes in the successful establishment of biotic introductions, depending on the original diversity and isolation from similar habitats. For example, islands typically have low diversity and are more prone to biotic invasions (Vitousek *et al.*, 1995).

When averaged across biomes, land-use change is the driver that is expected to have the largest global impact on biodiversity by the year 2100 (Fig.6), mostly because of its devastating effects on habitat availability and consequent species extinctions. Climate change will be the second most important driver of biodiversity change, mostly as a result of the expected warming at high latitudes. Changes in atmospheric CO_2, biotic exchange, and nitrogen deposition will also have substantial effects on future biodiversity, with their relative importance being regionally variable. In this global analysis, we consider only proportional changes in diversity and give no weighting to the area, species diversity, or economic value of biomes.

There are large differences among biomes in the causes of future change in biodiversity (Fig. 7). Biomes like tropical and southern temperate forest show large changes mostly due to changes in land use with relatively small effects due to other drivers. Arctic ecosystems are also influenced largely by a single factor (climate change). In contrast, Mediterranean ecosystems, savannas, and grasslands are substantially affected by most drivers. Finally, biomes such as the northern temperate forests and deserts show contributions by all the drivers but most of them are moderate.

In order to estimate the total change in biodiversity for each biome, we provide three alternative scenarios of biodiversity, based on alternative assumptions of the interactions among causes of biodiversity change. In all scenarios, we project that grasslands and Mediterranean ecosystems will experience large biodiversity loss because of their sensitivity to all drivers of biodiversity change, particularly land-use change (Fig. 7 and 8). Projected biodiversity changes in other biomes differ dramatically among our three scenarios.

If we assume that diversity will respond to global changes, without any interaction among these drivers of change, we project that Mediterranean and grassland ecosystems would be most sensitive to change (Fig. 7 and 8). In contrast, arctic, alpine, and desert ecosystems would show only moderate changes in biodiversity for reasons that are specific to each biome. The range of changes among biomes projected by this scenario is relatively small with the least change biome showing only a 60% of the maximum.

If we assume that diversity in each biome will be determined only by the factor that has greatest impact on diversity, then we project that tropical and southern temperate forests would experience substantial changes in diversity due to land-use change and the arctic due to climate change (Fig. 7 and 8). In this scenario, deserts and alpine would show least diversity changes, because there is no single driver to which biodiversity in these biomes is extremely sensitive.

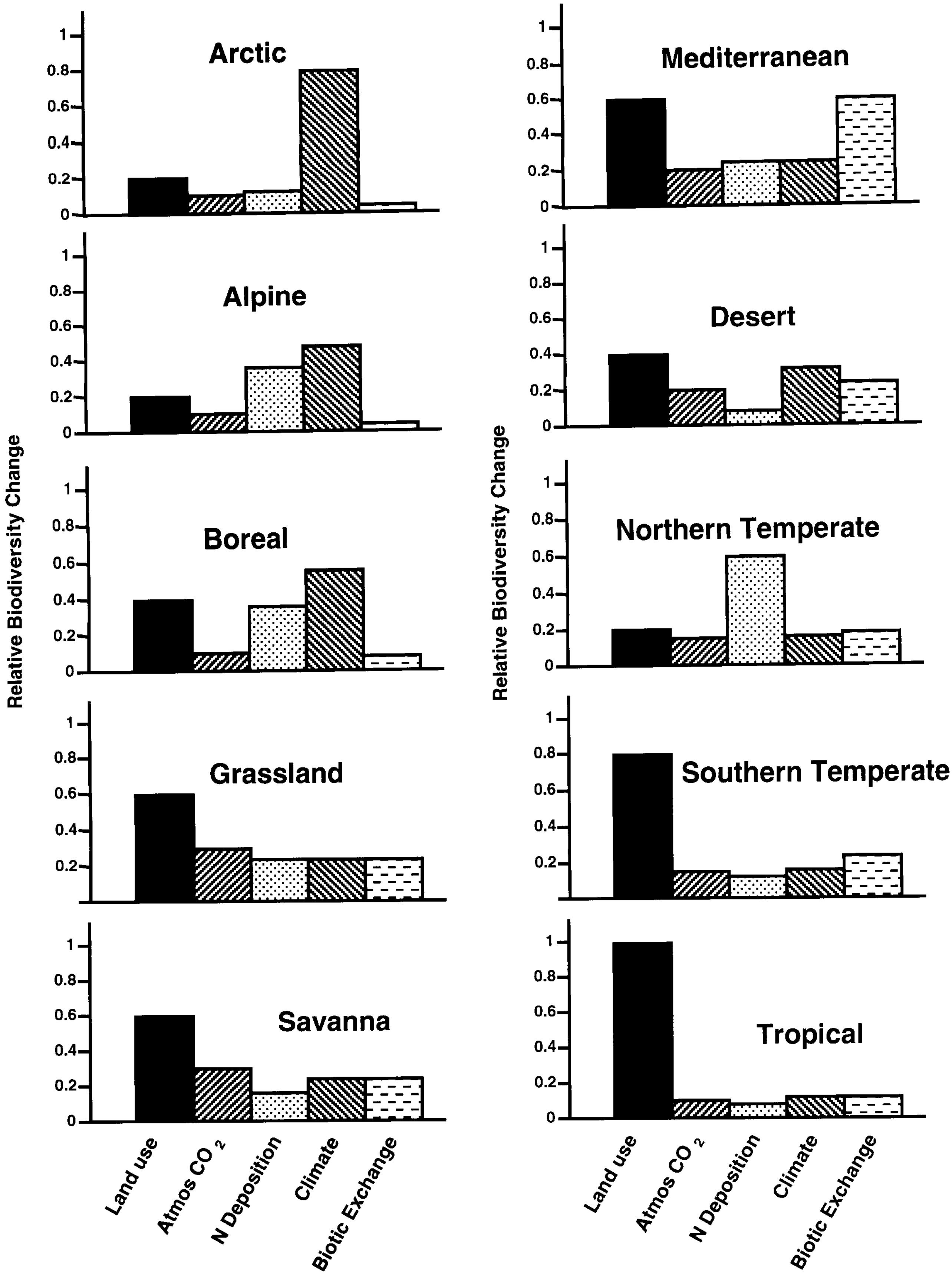

Figure 7. The effect of each driver on biodiversity change for each biome calculated as the product of the expected change of each driver times its impact for each biome.

If there are synergistic interactions among all causes of biodiversity change, we project that Mediterranean and grassland ecosystems would suffer greatest biodiversity change because diversity in these biomes is sensitive to all global-change drivers (Fig. 7 and 8). In this scenario, tropical forest, arctic, and alpine ecosystems would show least biodiversity change, because there are several drivers of change to which these biomes are relatively insensitive. In contrast to the no-interaction scenario, in this case, the range of expected change is quite broad encompassing two orders of magnitude, highlighting the effect that synergistic interactions may have in amplifying differences among biomes.

3.4 Discussion and conclusions

This analysis highlights the sensitivity of biodiversity change to our assumptions about interactions among causes of biodiversity change. Which assumptions are most plausible? There is clear evidence for nonlinearities and synergistic interactions among many of the global change drivers. Invasions of exotic species are promoted by human disturbance and changes in climate variability (interaction of biotic exchange, land-use, and climate change). Elevated CO_2 has greatest effect on species composition in presence of nitrogen deposition (interaction of CO_2 and nitrogen deposition). Synergistic interactions may decrease in importance at extreme values of individual drivers of biodiversity change. For example, where land use has been severe and extensive such as in forest clearing followed by seeding of an exotic crop species, further damage to biodiversity by other drivers may not be possible. In cases like that, biodiversity change responds only to the driver with the highest impact. The strength of interactions among drivers in their effects on biodiversity is virtually unknown. We hypothesize that future changes in biodiversity will be intermediate between scenarios that consider synergistic interactions or no interactions, but realistic projections of future biodiversity change require improved understanding about interactions among drivers of biodiversity change.

Other uncertainties in our analysis include the magnitude and regional variation in the future changes in drivers, as thoroughly analyzed by IPCC (Houghton *et al.*, 1996). This reflects future policies governing (1) the intensity and aerial extent of land-use change, (2) the protection of biodiversity per unit of land-use change, and (3) changes in atmospheric composition. Uncertainties in future climate and vegetation reflect these same policy uncertainties (Houghton *et al.*, 1996). As a result of the large policy-related uncertainties in drivers, we emphasize that we have presented scenarios rather than predictions of biodiversity change.

We expect large regional variation in biodiversity change within each. For example, diversity in islands, streams, and lakes is particularly vulnerable to biotic exchange because geographic isolation has led to local adaptation and often a low biodiversity (Vitousek *et al.*, 1995). Hot spots of diversity such as riparian corridors often coincide with hot spots of development, leading to large biodiversity loss.

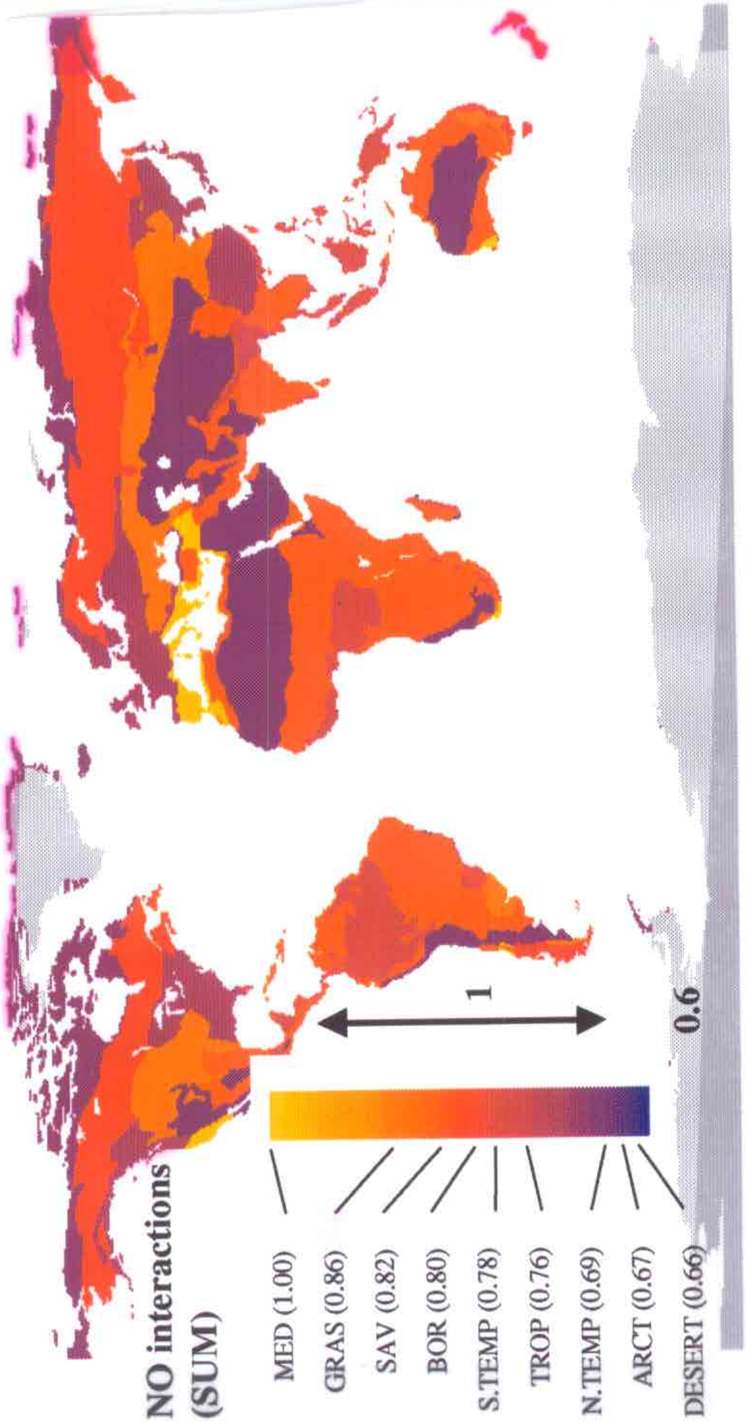

Figure 8a. Maps of scenario A of the expected change in biodiversity for the year 2100. Scenario A assumes that there are no interactions among drivers of biodiversity change, and consequently total change is calculated as the sum of the effects of each driver which in turn result from multiplying the expected change in the driver for a particular biome (Table 7) times the impact of the driver which is also a biome specific characteristic (Table 8). *The different colors represent the expected change in biodiversity from moderate to maximum for the different biomes of the world ranked according to the total expected change. The numbers in parenthesis represent the total change in biodiversity relative to the maximum value projected for each scenario. The biomes are MED Mediterranean ecosystems, GRAS Grasslands, SAV Savannas, BOR Boreal forest, S. TEMP Southern temperate forest, TROP Tropical forest, N.TEMP Northern temperate forest, ARCT Arctic ecosystems, DESERT Desert.*

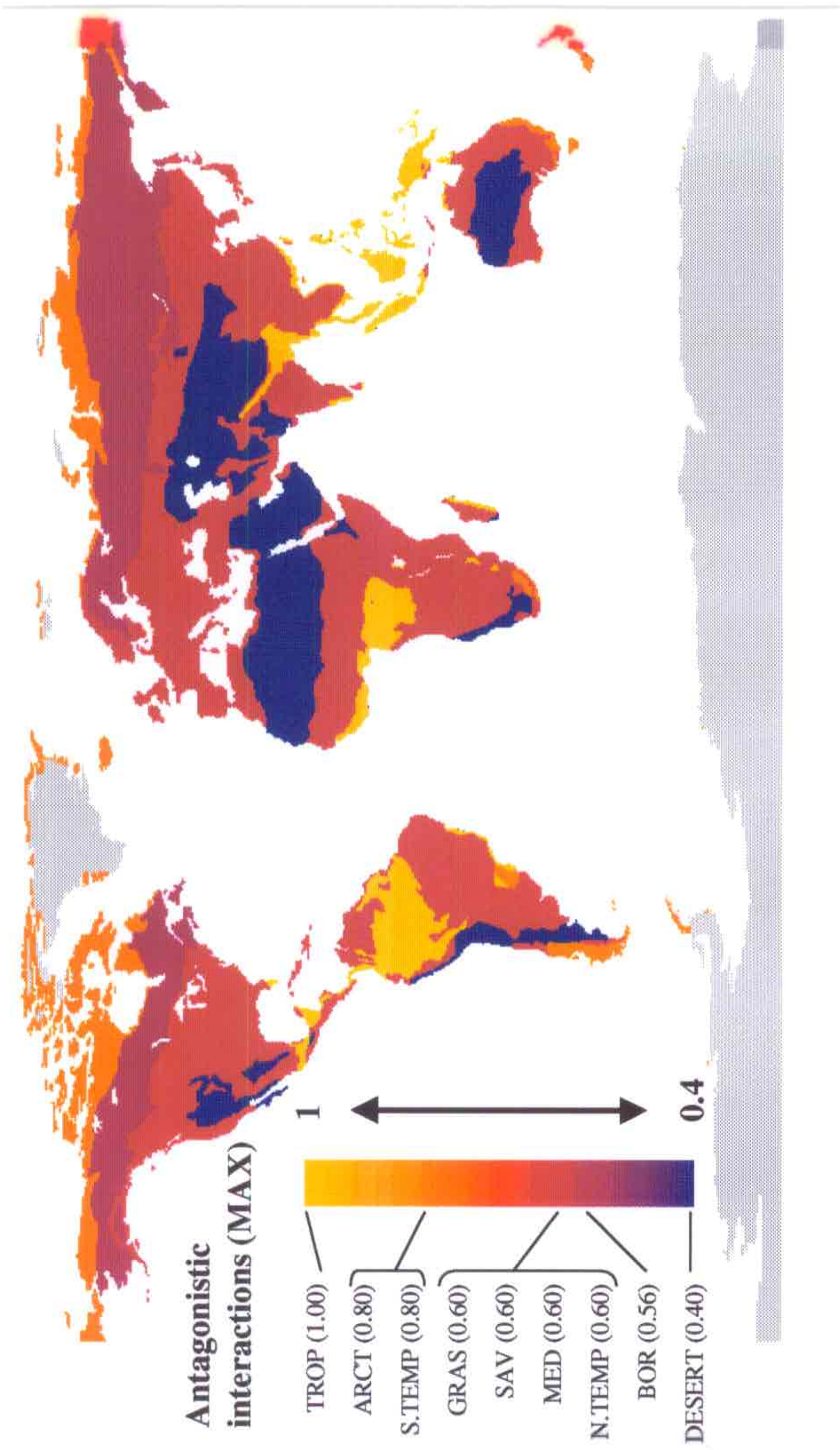

Figure 8b. Maps of scenario B of the expected change in biodiversity for the year 2100. Scenario B assumes that total biodiversity change equals the change resulting from the driver that is expected to have the largest effect and is calculated as the maximum of the effects of all the drivers. (For explanation, see caption Figure 8a)

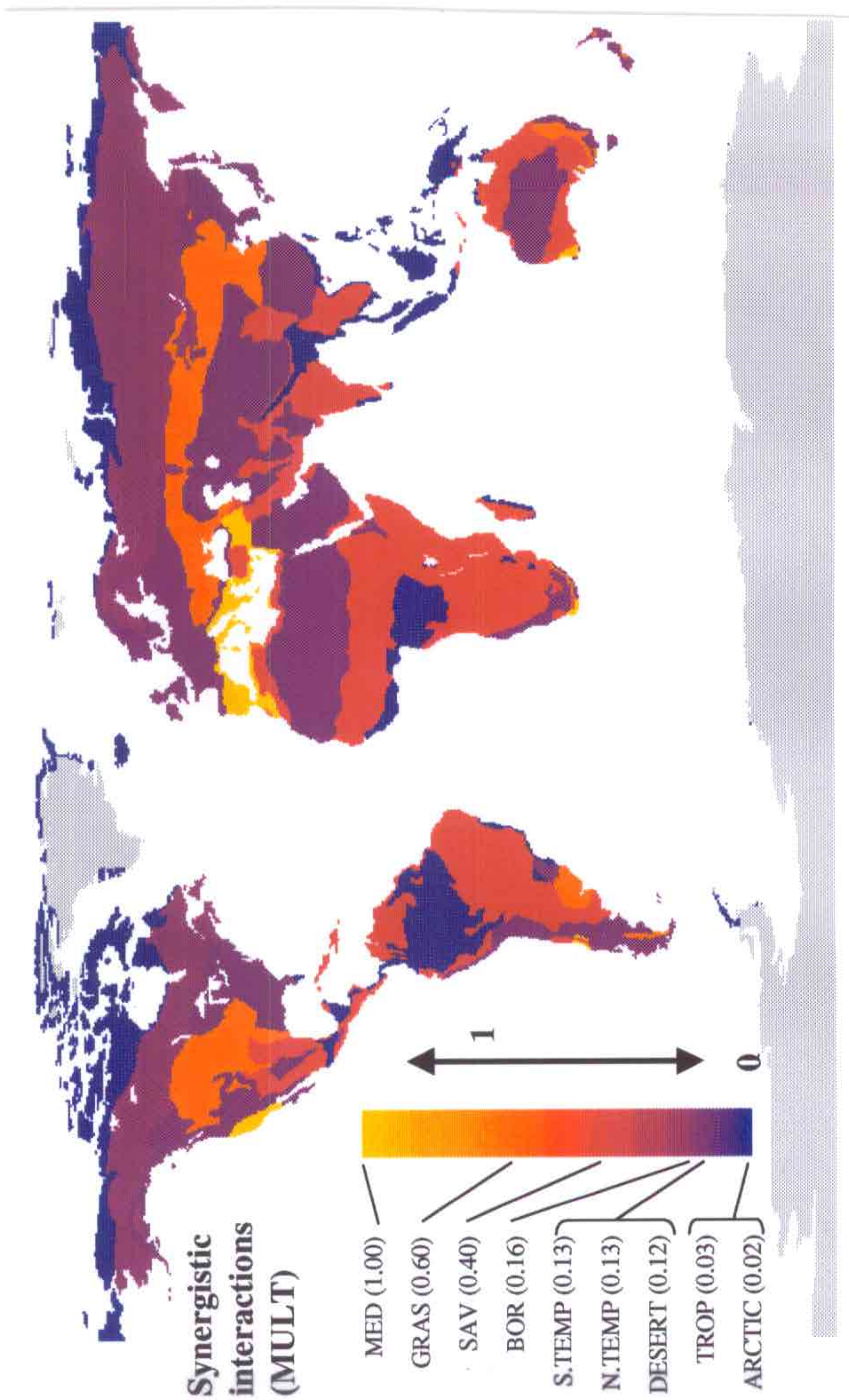

Figure 8c. Maps of scenario C of the expected change in biodiversity for the year 2100. Scenario C assumes synergistic interactions among the drivers, and consequently the total change is calculated as the product of the changes resulting from the action of each driver. (For explanation, see caption Figure 8a)

Within-biome variation in climate may cause greatest biodiversity change near climatically determined boundaries of organism distribution. Other specific local patterns of biodiversity change are less predictable than general trends at larger scales and may reflect interactions among drivers of biodiversity change that are locally important or a consequence of local "surprises". An initial analysis of the causes of regional variation in diversity loss within each biome is being published separately (Sala *et al.*, 1999).

Our analysis suggests that biodiversity in all biomes is sensitive to global changes in environment and land use and that realistic projections of biodiversity change will require an integrated effort by climatologists, ecologists, social scientists, and policy makers to improve scenarios of future changes in the Earth System. Refinement of these scenarios to the point that they are useful to policy makers will require quantitative regional analyses and study of the interactions among factors to which local biodiversity is most sensitive.

Appendix A: Project description of the 'Scenarios of Future Biodiversity: Causes, Patterns and Consequences' workshop

Problem Statement

It is becoming increasingly clear that biotic change is not simply a consequence of global environmental change but that biotic change is also an important driver of global change through massive increases in both invasions and extinctions. The Intergovernmental Panel on Climate Change (IPCC) has developed scenarios of change in climate, atmospheric composition, and land use. These scenarios have had considerable impact on national and international policy and in guiding research. However, biological diversity is changing simultaneously with these other global changes. Because of the recent rapid changes in biodiversity, it seems equally critical to develop scenarios of future change in biodiversity to guide researchers in understanding its ecological consequences and to guide policy makers in carrying out the agreements reached in the Global Biodiversity Convention. No such biodiversity scenarios are available for any biome.

Research on global change and on biodiversity have generally engaged two different scientific communities, working largely independently. These two areas are, however, related. Changes in land use, atmospheric composition, and climate directly affect biodiversity and ecological complexity, which in turn affects ecosystem functioning. During the past several years SCOPE spearheaded an effort to develop a conceptual framework for understanding the relationship between biodiversity and ecosystem functioning.

There have also been regional analyses of the current status of biodiversity and of relationship between biodiversity and ecosystem functioning for the major terrestrial biomes. However, there has been no attempt to predict future patterns of biodiversity. We include in our definition of biodiversity changes in diversity ranging from genetic diversity within species to species diversity, to landscape diversity.

The purpose of this workshop is to develop future scenarios of biodiversity at all scales for the next century, based on currently available IPCC scenarios of climate, atmospheric composition, vegetation, and land-use change. Perhaps the most important goal of the proposed workshop is to describe the ecosystem consequences of the scenarios of biodiversity change in terms that are useful to ecologists, managers, and policy makers, so that this information can be used to guide policies influencing land development, reserve design, etc.

Proposed activities and timetable

The workshop will consist of a 4-day meeting in which we discuss and refine scenarios of biodiversity change that have been prepared in advance by each participant. Each participant will be supplied with summaries of currently published IPCC scenarios of changes in climate, atmospheric composition, and land use for the next century. These scenarios include best-case, worst-case, and business-as-usual scenarios. We will also supply maps of natural vegetation composition under current climate and vegetation that is projected to be in equilibrium with a 2X CO_2 world. This information will be sent to participants in late March prior to the meeting. We assume that there will be active discussion at the meeting about pitfalls and insights into how these scenarios can be made as credible as possible. We will ask each person to provide a written chapter by September following the meeting.

There will be two major sections to the workshop and the final product: (1) a summary of the major drivers of changes in biodiversity and (2) a biome-by-biome analysis of the probable changes in biodiversity and their consequences for ecosystem functioning. In dealing with consequences we will encourage participants to consider both ecological consequences for functioning of natural communities and economic and social consequences for human society.

An interesting feature of the scenarios will be the capability to identify vulnerable ecosystems around the world, i.e., areas where relatively small changes in ecological conditions and biodiversity may lead to large changes in ecosystem functioning and to recognize areas that are important for conservation because they are particularly rich in diversity. This can be done by the biome-scale scenarios of complexity change with an estimation of the implications of such change for ecosystem functioning. The initial estimation of vulnerable areas will be based on the SCOPE synthesis of ecosystem consequences of biodiversity change.

Anticipated results and beneficiaries

The final product will be a book published by a major publisher (tentatively Springer-Verlag). We also anticipate writing a summary report for the general public and policy makers that would be published perhaps by the Ecological Society/Pew Foundation project to develop summaries of major ecological issues for policy makers. We expect that the work will be used by ecologists and resource planners who are concerned about current and future trends in biodiversity.

Summary of topics and invited participants

Causes of altered biodiversity

- Climate and vegetation distribution: Martin Sykes (martin@planteco.lu.se)
- Land-use change: Rik Leemans (rik.leemans@rivm.nl)and Tony Janetos (ajanetos@leda.hq.nasa.gov)
- Drivers of landscape change: Monica Turner (mgt@macc.wisc.edu)

- Landscape fragmentation and species loss: Frank Davis (fd@geog.ucsb.edu) and Ian Noble (noble@rsbs-central.anu.edu.au)
- Paleo-ecological perspectives on diversity change: Margaret Davis (mbdavis@ecology.umn.edu) and Jim Clark (jimclark@sun1.botany.duke.edu)

Biome scenarios of biodiversity change in the next 50-100 yr

- Tundra: Marilyn Walker (mwalker@taimyr.Colorado.EDU) and Terry Chapin
- (fschapin@garnet.berkeley.edu)
- Boreal forest: John Bryant (ffjpb@aurora.alaska.edu)
- Temperate forest: Steward Pickett (STAPickett@aol.com), Hank Shugart
- (hhs@amazon.evsc.virginia.edu), and Juan Armesto (jarmesto@abello.seci.uchile.cl)
- Grassland: Osvaldo Sala (osala@cnea.edu.ar), Bill Lauenroth
- (billl@bouteloua.cnr.colostate.edu), and David Tilman (tilman@lter.umn.edu)
- Tropical forest: Gary Hartshorn and Rudolfo Dirzo
- Savanna: Brian Walker (wls@cbr.dwe.csiro.au)
- Islands: Peter Vitousek (vitousek@leland.Stanford.EDU)
- Deserts: Jim Brown (brown@bootes.unm.edu) and Laura Huenneke (lhuennek@nmsu.edu)
- Tropical agriculture: Mike Swift (tsbf@cgnet.com)
- Temperate agriculture: Phil Robertson (robertson@kbs.msu.edu)
- Shrublands: Hal Mooney (hmooney@jasper.stanford.edu)
- Soil biology: Elvira Cuevas (ecuevas@oikos.ivic.ve) and Diana Freckman
- (freckman@nrel.colostate.edu)
- Lakes : David Lodge (david.m.lodge.1@nd.edu)
- Streams: Scott Cooper (scooper@lifesci.lscf.ucsb.edu)
- Coastal marine: Jane Lubchenco (lubchenj@cgrb.ORST.EDU) and Juan Carlos Castilla
- Pelagic marine: Ed Houde
- Benthic marine: Mike Rex (rex@umbsky.cc.umb.edu)
- Estuaries: James Carlton (james.t.carlton@williams.edu)
- Mangroves: Ernesto Medina (ermedina@oikos.ivic.ve)

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