Chapter 6

Methodology for Developing the MA Scenarios

Coordinating Lead Authors: Joseph Alcamo, Detlef van Vuuren, Claudia Ringler
Lead Authors: Jacqueline Alder, Elena Bennett, David Lodge, Toshihiko Masui, Tsuneyuki Morita,* Mark Rosegrant, Osvaldo Sala, Kerstin Schulze, Monika Zurek
Contributing Authors: Bas Eickhout, Michael Maerker, Kasper Kok
Review Editors: Antonio Alonso Concheiro, Yuzuru Matsuoka, Allen Hammond

*Deceased.

BOXES

FIGURES

TABLES

*This appears in Appendix A at the end of this volume.

Main Messages

The Millennium Ecosystem Assessment scenarios break new ground in global environmental scenarios by explicitly incorporating both ecosystem dynamics and feedbacks. The goal of the MA is to provide decision-makers and stakeholders with scientific information on the links between ecosystem change and human well-being. Scenarios are used in this context to explore alternative futures on the basis of coherent and internally consistent sets of assumptions. The scenarios are novel in that they incorporate feedbacks between social and ecological systems and consider the connections between global and local socioecological processes.

The approach to scenario development used in the MA combines qualitative storyline development and quantitative modeling. In this way, the scenarios capture the aspects of ecosystem services that are possible to quantify, but also those that are difficult or even impossible to express in quantitative terms. The MA developed scenarios of ecosystem services and human well-being to 2050, with selected results up to 2100. Scenarios were developed in an iterative process of storyline development and modeling. The storylines covered many complex aspects of society and ecosystems that are difficult to quantify, while the models helped ensure the consistency of the storylines and provided important numerical information where quantification was possible.

In the MA, scenarios were partly quantified by using linked global models to ensure integration across future changes in ecosystem services. Available global models do not allow for a comprehensive assessment of the linkages among ecosystem change, ecosystem services, human well-being, and social responses to ecosystem change. To assess ecosystem change for a larger set of services, several global models were linked and run based on a consistent set of scenario drivers to ensure integration across future changes in ecosystem services.

While advances have been made by the MA in scenario development to explore possible futures of the linkages between ecosystem change and society, still further progress is possible. Using quantitative and qualitative tools, the MA scenarios cover a large number of ecological services and drivers of ecosystem change. In the course of developing these scenarios, we also identified areas where analytical tools are relatively weak. For quantification of ecosystem service scenarios, we particularly need models that further disaggregate services to local scales, address cultural and supporting ecosystem services, and consider feedbacks between ecosystem change and human development.

6.1 Introduction

The goal of the Millennium Ecosystem Assessment is to provide decision-makers and stakeholders with scientific information on the links between ecosystem change and human well-being. The MA focuses on ecosystem services (such as food, water, and biodiversity) and on the consequences of changes in ecosystems for human well-being and for other life on Earth. Ecosystem change, on the other hand, is significantly affected by human decisions, often over long time horizons (Carpenter 2002). For example, changes in soils or biodiversity of long-lived organisms can have legacy effects that last for decades or longer. Thus it is crucially important to consider the future when making decisions about the current management of ecosystem services.

The MA developed scenarios to provide decision-makers and stakeholders with scientific information on the links between ecosystem change and human well-being. This chapter describes the methodology used to develop the scenarios. It first provides background information on scenarios in general, followed by an overview of the methodology used in the MA scenario development. The development of the qualitative storylines and the global modeling exercise are then described in detail. Finally, we briefly describe how uncertainty and scale issues were handled in the scenarios. Eight Appendixes provide detailed descriptions of the models we relied on.

6.2 Background to the MA Scenarios

Applied (natural and social) sciences have used many methods for devising an understanding of the future, including predictions, projections, and scenario development. (For an overview of methods, see, e.g., Glenn and Gordon 2005.) Each approach has its own methodology, levels of uncertainty, and tools for estimating probabilities. It should be noted that these terms are often not strictly separated in the literature. The conventional difference, however, is that a prediction is an attempt to produce a most likely description or estimate of the actual evolution of a variable or system in the future. (The term ''forecasting'' is also often used; it is used interchangeably with prediction in this chapter.) Projections differ from predictions in that they involve assumptions concerning, for example, future socioeconomic and technological developments that may not be realized. They are therefore subject to substantial uncertainty. Scenarios are neither predictions nor projections and may be based on a narrative storyline. Scenarios may be derived from projections but often include additional information from other sources.

Over the years, experience with global assessment projects in the ecological and environmental realm has shown that prediction over large time periods is difficult if not impossible, given the complexity of the systems examined and the large uncertainties associated with them—particularly for time horizons beyond 10–20 years. In the case of ecosystems, heterogeneity, non-linear dynamics, and cross-scale interactions of ecosystems contribute to system complexity (Holling 1978; Levin 2000). Furthermore, ecological predictions are contingent on drivers that may be even more difficult to predict, such as human behavior. As a result, people rarely have enough information to produce reliable predictions of ecosystem behavior or environmental change (Sarewitz et al. 2000; Funtowicz and Ravetz 1993). Despite these problems with predicting the future, people need to take decisions with implications for the future. Scenario development offers one approach to dealing with uncertainty.

The MA uses the IPCC definition of scenarios as ''plausible descriptions of how the future may develop, based on a coherent and internally consistent set of assumptions about key relationships and driving forces'' (such as rate of technology changes and prices) (IPCC 2000b). As such, scenarios are used as a systematic method for thinking creatively about complex, uncertain futures for both qualitative and quantitative aspects. Figure 6.1 presents an overview of the additional value created by scenario analysis compared with more deterministic approaches such as predictions.

Scenarios can serve different purposes (see, e.g., Alcamo 2001; van der Heijden 1997). They can be used in an explorative manner or for scientific assessment in order to understand the functioning of an investigated system. For the MA, researchers are interested in exploring hypothesized interactions and linkages between key variables related to ecosystems and human well-being. Scenario outcomes can then form part of planning and decision-making processes and help bridge the gap between the scientific and the policy-making communities. The MA scenarios can also be used in an informative or educational way. Depending on the process used, scenarios can also challenge the assumptions that people have about the future and can illustrate the different views on their outcomes held by participants of the scenario-building exercise.

In general, scenarios contain a description of step-wise changes or a storyline, driving forces, base year, and time steps and horizon (Alcamo 2001). They are often classified by the method used to develop them, their goals and objectives, or their output. One classification of scenarios distinguishes between ''exploratory'' and ''anticipatory'' scenarios. Exploratory scenarios are descriptive and explore trends into the future. Anticipatory scenarios start with a vision of the future that could be optimistic, pessimistic, or neutral and work backwards in time to discern how that particular future might be reached. This type of scenario is sometimes also referred to as a ''normative'' scenario. The MA scenarios were developed using mostly exploratory approaches.

Finally, scenarios can consist of qualitative information, quantitative information, or both. Chapter 2 contains some examples of each of these types of scenarios. Qualitative scenarios, using a narrative text to convey the main scenario messages, can be very helpful when presenting information

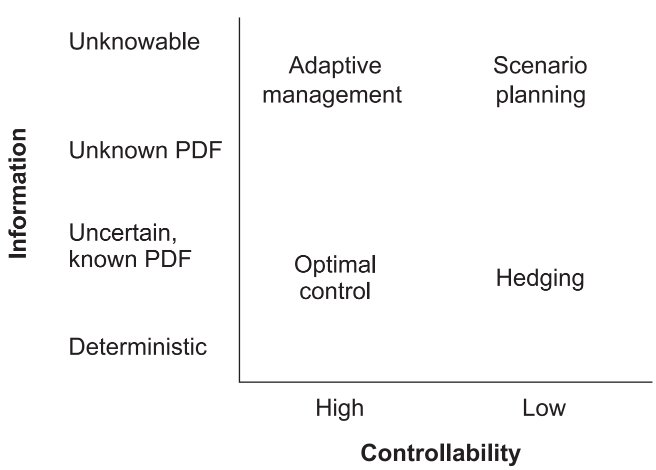


Figure 6.1. Status of Information, from Low to High, versus Degree of Controllability. PDF = probability distribution function. The figure shows the domain of traditional decision tools such as utility optimization and the domain where scenarios may be helpful. (Adapted from Peterson et al. 2003)

to a nonscientific audience. Quantitative scenarios usually rely on modeling tools incorporating quantified information to calculate future developments and changes and are presented in the form of graphs and tables.

Both scenario types can be combined to develop internally consistent storylines assessed through quantification and models, which are then disseminated in a narrative form. (A ''storyline'' is a scenario in written form, and usually takes the form of a story with a very definite message or ''line'' running through it.) This approach was used to develop the MA scenarios. The qualitative scenarios (storylines) provide an understandable way to communicate complex information, have considerable depth, describe comprehensive feedback effects, and incorporate a wide range of views about the future. The quantitative scenarios are used to check the consistency of the qualitative scenarios, to provide relevant numerical information, and to ''enrich'' the qualitative scenarios by showing trends and dynamics not anticipated by the storylines. By ''consistency'' we mean that the storylines do not contain elements that are contradictory according to current knowledge. On the other hand, the goal of developing consistent scenarios should not lead us to omit elements that may look contradictory but in reality are only surprising new connections or results. Often, uncovering these unanticipated connections that challenge current beliefs and assumptions is one of the most powerful results of the scenarios analysis. For example, is a scenario about climate impacts only consistent when it assumes that climate change will lead to global warming? Indeed, there are ''surprising'' yet plausible and consistent scenarios that postulate that climate change will lead to cooling of parts of the lower atmosphere.

Together, the qualitative and quantitative scenarios provide a powerful combination that compensates for some of the deficits of either one on its own. The combination of qualitative with quantitative scenarios has been used in many recent global environmental assessments, such as IPCC's Special Report on Emissions Scenarios (IPCC 2000b), UNEP's Global Environment Outlook (UNEP 2002), the scenarios of the Global Scenario Group (Raskin et al. 1998), and the World Water Vision scenarios (Cosgrove and Rijsberman 2000; Alcamo et al. 2000).

The distinction between qualitative and quantitative scenarios is sometimes blurred, however. Qualitative scenarios can be derived by formalized, almost quantitative methods, while quantitative scenarios can be developed by soliciting numerical estimates from experts or by using semi-quantitative techniques such as fuzzy set theory. Storylines can also be interspersed with numerical data and thereby be viewed as both qualitative and quantitative.

As noted in earlier chapters, the main objective of the MA scenarios is to explore links between future changes in world ecosystems and their services and human well-being. The scenario analysis focuses on the period up to 2050, with selected prospects for 2100.

6.3 Overview of Procedure for Developing the MA Scenarios

This section describes the process used to develop the MA scenarios. The procedure consists of 14 steps organized into three phases (see Box 6.1); the details of the storyline development and the modeling exercise are explained in later sections. In the first phase, the scenario exercise was organized and the main questions and focus of the alternative scenarios were identified. In the second phase, the storylines were written and the scenarios were quantified using an iterative procedure. During the third phase, the results of the scenario analysis were synthesized, and scenarios and their outcomes were reviewed by the stakeholders of the MA, revised, and disseminated. These elements are also indicated in Figure 6.2. While Figure 6.2 suggests that activities were completed once processed, in reality earlier activities were often revised during an iterative process.

Two essential activities within the overall scenario development framework were the formulation of alternative scenario storylines and their quantification. These two elements were designed to be mutually reinforcing. The development of scenario storylines facilitates internal consistency of different assumptions and takes into account a broad range of elements and feedback effects that are either difficult to quantify or for which no modeling capability exists, or both. Based on initial storylines, the quantification process helps to provide insights into those processes where sufficient knowledge exists to allow modeling, and to take into account the interactions among the various drivers and services. During scenario development, several interactions were organized between the storyline development and the modeling exercise in order to increase the consistency of the two approaches.

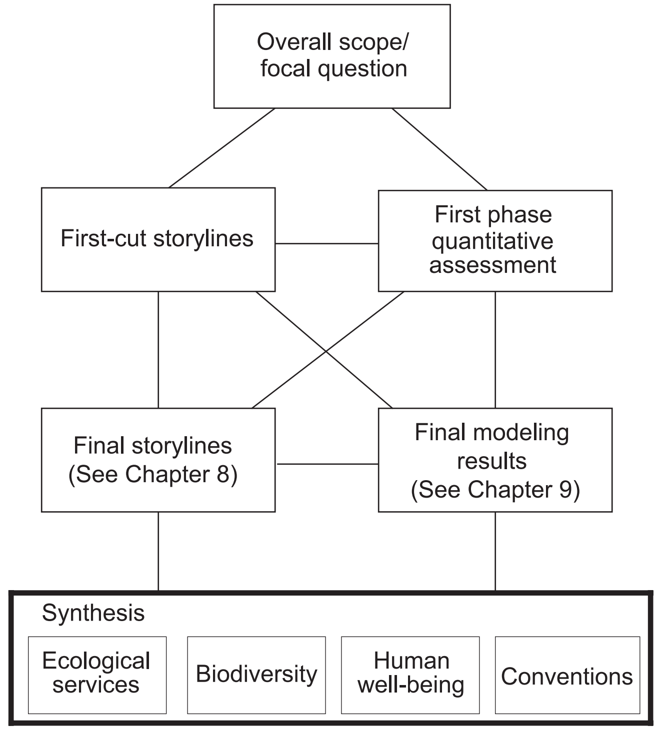


Figure 6.2. Overall Methodology of MA Scenario Development

6.3.1 Organizational Steps

The first phase in the MA scenario development consisted of establishing a scenario guidance team, composed of the chairpersons and secretariat of the Scenarios Working Group, to lead and coordinate the scenario-building process. In addition, a larger panel, composed mainly of scientific experts, was assembled to build the scenarios.

The scenario guidance team conducted a series of interviews with potential users of the scenarios to obtain their input for developing the goals and focus of the scenarios. This was especially important for the MA because the number of potential users is very large and diverse. These interviews also ensured input from stakeholders and users early on in the study. Understanding the needs and desires of users and their outlook on future development helped the team to devise the main focal questions of the scenarios.

Based on the results of the user interviews and discussions with the scenario panel, the objectives, focus, leading themes, and hypotheses of the scenarios were derived by the scenario guidance team and panel (and later confirmed by the MA Assessment Panel). For the MA, the main objective of scenario development was to explore alternative development paths for world ecosystems and their services over the next 50 years and the consequences of these paths for human well-being. Based on these results, the scenario team clarified the focal questions to be addressed by the scenarios (for the rationale behind the choice of questions, see Chapter 5). The main question was:

> *What are the consequences of plausible changes in development paths for ecosystems and their services over the next 50 years and what will be the consequences of those changes for human well-being?*

The key focal question was then defined through a series of more specific questions—that is, what are the consequences

BOX 6.1

MA Procedure for Developing Scenarios

Phase I: Organizational steps

1. Establish a scenario guidance team.
2. Establish a scenario panel.
3. Conduct interviews with scenario end users.
4. Determine the objectives and focus of the scenarios.
5. Devise the focal questions of the scenarios.

Phase II: Scenario storyline development and quantification

6. Construct a zero-order draft of scenario storylines.
7. Organize modeling analyses and begin quantification.
8. Revise zero-order storylines and construct first-order storylines.
9. Quantify scenario elements.
10. Revise storylines based on results of quantifications.
11. Revise model inputs for drivers and re-run the models.

Phase III: Synthesis, review, and dissemination

12. Distribute draft scenarios for general review.
13. Develop final version of the scenarios by incorporating user feedback.
14. Publish and disseminate the scenarios.

for ecosystem services and human well-being of strategies that emphasize:

- economic and human development (e.g., poverty eradication, market liberalization) as the primary means of management?
- local and regional safety and protection, giving far less emphasis to cross-border and global issues?
- development and use of technologies, allowing greater eco-efficiency and adaptive control?
- adaptive management and local learning about the consequences of management interventions for ecosystem services?

Ecosystem services are defined as ''the conditions and processes supported by biodiversity through which ecosystems sustain and fulfill human life, including the provision of goods'' (MA 2003; see also Chapter 1). Ecosystem processes are seldom traded in markets, typically have no market price, and therefore usually do not enter in economic decision-making or cost-benefit analyses even though they are essential for human well-being. The MA considered the following interlinked categories of ecosystem services: provisioning services (food, fresh water, and other biological products), supporting and regulating services (including soil formation, nutrient cycling, waste treatment, and climate regulation), and cultural services.

6.3.2 Scenario Storyline Development and Quantification

Following a review and evaluation of current and past scenario efforts, scenario building blocks for driving forces, ecological management dilemmas, branch points, and so on were mapped out. Storyline outlines were then developed around these building blocks. Additional details on the storyline development are provided later in this chapter.

While the initial storylines were being developed, a team of modelers representing several global models was organized to quantify the scenarios. Five global models covering global change processes or ecosystem provisioning services and two global models describing changes in biodiversity were chosen. Criteria that were used to select these models included global coverage, publications of model structure and/or model application in peer-reviewed literature, relevance in describing the future of ecosystem services, and ability to be adapted to the storylines of the MA. (The Ecopath with Ecosim models used to describe marine ecosystems and their service to global fisheries forms an exception to the rule of global coverage, as no global model for this issue was available.) Although all the models had been developed previously, linkages among models and projections out to 2050 and 2100 did require adjustments for several of them. Test calculations were carried out using preliminary driving force assumptions. These test calculations were helpful in identifying the potential contribution of different models to the analysis and in clarifying the procedures of linking the different models.

After a series of iterations, the zero-order storylines were revised and cross-checked for internal consistency. One measure used to accomplish this was the development of timelines and milestones for the various scenarios.

In the next step, the modeling team, in consultation with the storyline team, developed quantitative driving forces that were considered to be consistent with the storylines. Obviously, there is room for interpretation regarding the consistency of driving forces and the storylines, and multiple sets of driving forces are possible. The driving forces and quantified drivers for the modeling exercise chosen for the MA scenarios are discussed in detail in Chapters 7, 8, and 9. Based on the model outcomes of the quantitative scenarios, the scenario team further elaborated or adapted the storylines. A number of feedback workshops with the MA Board and stakeholder groups were held to improve the focus and details of the storylines.

Based on the results of the first round of quantified scenarios, small adjustments in the specification of drivers and linkages among models were made, new model calculations were carried out with the modeling framework, and the storylines were revised (in other words, there was one iteration between storyline development and quantification). Ideally, a series of iterations between storyline improvement, quantification, and stakeholder feedback sessions would have helped to better harmonize the quantitative and qualitative scenarios, but time constraints limited the number of iterations for the MA. The quantified scenario results are described in detail in Chapter 9, while the scenario storylines can be found in Chapter 8.

6.3.3 Synthesis, Review, and Dissemination

The scenario outcomes were assessed in the context of the focal questions and user needs of the various MA user groups. These results are described in Chapters 11, 12, 13, and 14, based on an analysis of both qualitative and quantitative scenario outcomes. Feedback from the assessment component of the scenario team led to further refinement of the storylines and the provision of additional model details.

The scenarios, consisting of the qualitative storylines and quantitative model calculations, were disseminated for review by interested user groups. This was accomplished through presentations, workshops, the MA review process, and Internet communications. Reviewer comments were then incorporated into the scenarios. Both review and dissemination are considered important elements for the success of the scenario exercise.

6.3.4 Linkages between Different Spatial and Temporal Scales

In order to deal with the multiscale aspects of the relationships between ecosystem services and human well-being, the MA called for a large number of sub-global assessments in addition to the global assessment. Several of the sub-global assessments also developed scenarios. As these were often targeted at specific user groups or addressed very specific questions, it was not always possible to directly link the sub-global assessments to the global assessment. (See also Box 6.2.) Nevertheless, to harmonize the global and sub-global scenario exercises as much as possible, the following steps were taken:

BOX 6.2

A Comparison of Global and Sub-global Scenario Development

One of the goals of both the global and sub-global scenarios was to provide foresight about potential futures for ecosystems, including the provision of ecosystem services and human well-being.

Despite similar goals, sub-global scenario development was somewhat different from global scenario development. The key differences were the extensive use of quantitative models in the global scenarios, greater involvement of decision-makers in the sub-global scenarios, and use of sub-global scenarios directly as a tool for decision-making (versus a broader learning-focused global scenario set).

Because the group of decision-makers at the global scale is more diffuse, involvement of decision-makers in the global scenario development was less intense than it was for the sub-global scenarios. Representatives from the business community, the public sector, and the international conventions were periodically informed of progress in the development of the global scenarios and asked for feedback. The sub-global assessments, because they often focused on issues for which key decision-makers could be identified, had closer contact with their primary intended users. The ultimate result of having decision-makers more involved in scenario development was that the scenarios themselves were built more as a direct tool for engaging people in decision-finding processes. Thus, in most sub-global assessments, scenario development focused on futures over which local decision-makers have at least some direct control.

The global scenarios provide four global storylines from where a look down enriches these stories with regional and local details. The sub-global scenarios provide a large number of local stories from where a look up enriches the stories with regional and global "details." A more complete description of the sub-global scenarios can be found in Chapter 9 of the MA *Multiscale Assessments* volume.

- Representatives of some sub-global assessments participated in the global scenario team and contributed to the scenario development.
- Members of the global scenario guidance team participated at various occasions in meetings of the sub-global scenario assessments, explaining both the preliminary global scenario results and the procedure followed in developing the global scenarios.
- Some of the sub-global assessments used the storylines of the global assessment as background for their work or otherwise linked their scenarios to the global assessment.
- After the storylines and the model runs of the global scenarios were finalized, results and findings of the sub-global assessment were used to illustrate how the scenarios could play out at the local scale. (See Boxes in Chapter 8.)

As well as addressing changes in ecosystems and their services at several spatial scales, the MA also considered different temporal scales. For a more detailed discussion on the general issue of scales in the MA, see the MA conceptual framework report (MA 2003). (See also Chapter 7 of this volume and Chapter 4 in the MA *Multiscale Assessments* volume).

The question of temporal scale was important for the construction of the MA scenarios. Although the global scenarios were primarily developed to the year 2050, scenario results of the quantitative scenario elaboration were also reported for 2020, 2050, and 2100. The 2020 report provided a link between the scenarios and medium-term policy objectives, such as the 2015 Millennium Development Goals. It also linked the global and sub-global scenarios, many of which extend only to approximately 2025. Meanwhile, the results for 2100 impart insight into longer-term trends in ecosystem services. Results for 2100 were only reported for parameters that are determined by strong inertia within the natural system, such as climate change and sea level rise.

While several of the models used within the modeling exercise perform their calculations for 10–40 global regions or countries, a much lower resolution was chosen for reporting. Quantitative results (Chapter 9) are mainly presented for six reporting regions: sub-Saharan Africa, Middle East and North Africa, the Organisation of Economic Co-operation and Development, the former Soviet Union, Latin America, and Asia. (See Figure 6.3 in Appendix A.) These are sometimes aggregated into "rich" or "wealthy" countries and "poorer" countries.

The reasons for using this lower resolution include the amount of information that could be presented within this volume and checked for internal consistency. In addition, some models use a global grid of half-degree latitude and longitude to calculate changes in environmental and ecological parameters. The latter are presented in case they are relevant. Grid-level results should be interpreted as broad-brush visualizations of the geographic patterns underlying the scenarios, not as specific predictions for small regions or even grid cells.

6.4 Building the Qualitative Scenarios: Developing Storylines

Significant emphasis was placed on storyline development. Storylines can be provocative because they challenge the tendency of people to extrapolate from the present into the future. They can be used to highlight key uncertainties and surprises about the future. They can consider nonlinearities and complicated causal links more easily than global models can. Moreover, they can incorporate important ecological processes, which so far have not been satisfactorily considered in existing global models. (See Chapter 3.) Since the MA's goal for scenarios development was to specifically consider the future of ecosystems and their services, storyline development was used to incorporate processes that the models could not fully address. Moreover, the qualitative stories provided the input variables for the global models.

The qualitative storylines were developed through a series of discussions among the scenario development panel alternating with feedback from MA user groups and outside experts. The storyline development followed six steps:

- identification of what the MA user groups wanted to learn from the scenarios,
- development of a set of scenario building blocks,
- determination of a set of basic storylines that reflected the MA goal and responded to user needs,

- development of rich details for the storylines,
- harmonization of the storylines with modeling results, and
- feedback from experts and user groups and its incorporation into the final storylines.

Although these steps are presented in order, the process in reality cycled through some of the steps many times until it was felt that consensus was reached on the storylines.

Key questions about the future and main uncertainties of MA user groups were identified through a series of feedback techniques. Approximately 70 leaders and decision-makers from around the world and in many different decision-making positions were interviewed about their hopes and fears for the future. A formal User Needs survey developed by the MA at the beginning of the assessment was used as additional input. This survey was sent to representatives of the MA user community and contained questions on expected outcomes of the MA process. Synthesis of these surveys led to the formulation of the key questions listed earlier.

In the second step, the scenario team developed a number of scenario building blocks, including the factors differentiating the scenarios. In addition, the scenario team identified possible driving forces of socioecological systems into the future, as well as the main uncertainties of these driving forces and the prospects for being able to steer them. Other scenario building blocks included discussions on ecological dilemmas that decision-makers are likely to face in the near future, possible branching points of scenarios, the occurrence of cross-scale ecological feedback loops, and assumptions that decision-makers hold about the functioning of ecological systems (such as whether ecological systems are fragile or resilient).

A first set of scenario storylines was developed using a number of different development paths to distinguish among them. This was done through a combination of writing, presentations, and discussions within the scenario team and feedback from other working groups within the MA. Once these storylines were developed, they were presented to a wider group of experts, including the MA Board, members of the World Business Council for Sustainable Development, scenario experts from other scenario exercises, and several decision-maker communities. Feedback from this exercise led to further refinement of the storylines.

As the results of the quantified scenarios became available, they were compared with the qualitative storylines. This led to further discussions about the logical pathways to the final sequence of events in the scenarios. These discussions were encouraged by the structure of the scenario team, which included both storyline-writers and members of the modeling teams. As a result of these discussions, storylines and model driving forces were adjusted. These discussions also led to new interpretations of the storylines into model parameters.

6.5 Building the Quantitative Scenarios: The Global Modeling Exercise

6.5.1 Organization of the Global Modeling Exercise

As noted in previous sections, the storyline development was complemented by building quantitative scenarios using a linked set of global models. The purpose of the modeling exercise was both to test the consistency of the storylines as developed in the first round and to elaborate and illustrate the scenarios in numerical form. This ''quantification of the scenarios'' had five main steps:

- Assembling several global models to assess possible future changes in the world's ecosystems and their services. These models are briefly described in Box 6.3 and in the Appendixes. In addition, several models were used to describe certain aspects of changes in biodiversity.
- Specifying a consistent set of model inputs based on the scenario storylines.
- Running the models with the specified model inputs.
- Soft-linking the models by using the output from one model as input to another (we use the term soft-link as the models were not run simultaneously).
- Compiling and analyzing model outputs about changes in future ecosystem services and implications for human well-being. The models were used to analyze the future state of indicators for ''provisioning,'' ''regulating,'' and ''supporting'' ecosystem services. These indicators are listed in Table 6.1. The analysis of modeling results is presented in Chapter 9.

6.5.2 Specifying a Consistent Set of Model Inputs

The first version of the storylines of the MA scenarios (and in particular, tables containing their main characteristics) formed the basis of the main model assumptions for the quantitative exercise. Over several workshops, the storylines were translated into a consistent set of model assumptions that closely corresponded to the ''indirect drivers'' of ecosystem services. These included:

- *population development,* including total population and age distribution in different regions;
- *economic development* as represented by assumed growth in per capita GDP per region and changes in economic structure;
- *technology development,* covering many model inputs such as the rate of improvement in the efficiency of domestic water use or the rate of increase in crop yields;
- *human behavior,* covering model parameters such as the willingness of people to invest time or money in energy conservation or water conservation; and
- *institutional factors,* such as the existence and strength of institutions to promote education, international trade, and international technology transfer. The latter are represented directly (trade barriers, for instance, and import tariffs) or indirectly (income elasticity for education) in the models, based on the storylines.

For each of these factors, trends were developed for model inputs that corresponded to the qualitative statements of the storylines. For example, statements in the storylines about ''high'' or ''low'' mortality were interpreted such that the trend in mortality would be in the upper or lower 20% of the probabilistic demographic projections. (See also Chapter 9.) Another example is that the scenario with the highest level of agricultural intensification was assumed to have the fastest rate of improvement of crop yield

BOX 6.3
Models Used in MA Global Modeling Exercise

The models in the global modeling exercise include:

- The IMPACT model of the International Food Policy Research Institute in the United States, which computes food supply, demand, trade, and international food prices for countries and regions (Rosegrant et al. 2002).
- The WaterGAP model of the University of Kassel in Germany, which computes global water use and availability on a watershed scale (Alcamo et al. 2003a, 2003b).
- The AIM global change integrated model of the National Institute for Environment Studies in Japan, which computes land cover and other indicators of global change worldwide, with an emphasis on Asia (Kainuma et al. 2002).
- The IMAGE 2.2 global change model of the National Institute of Public Health and the Environment in the Netherlands, which computes climate and global land cover on a grid scale and several other indicators of global change (IMAGE-team 2001).
- The Ecopath with Ecosim model of the University of British Columbia in Canada, which computes dynamic changes in selected marine ecosystems as a function of fishing efforts (Pauly et al. 2000).

and largest expansion of irrigation development. An overview of model inputs is provided in Chapter 9.

6.5.3 Soft-linking the Models

To achieve greater consistency between the calculations of the different models, they were "soft-linked" in the sense that output files from one model were used as inputs to other models. (See Figure 6.4.) The time interval of data that were exchanged between the models was usually one year. The following model linkages were included:

- Computations of regional food supply, demand, and trade from the IMPACT model were aggregated to the 17 IMAGE world regions and the 12 IMAGE animal and crop types. These data were then used as input to the IMAGE land cover model that computed on a global grid the changes in agricultural land that are consistent with the agricultural production computed in IMPACT. In addition, IMAGE was used to calculate the amount of grassland needed for the livestock production computed in IMPACT. Two iterations were done between IMPACT and IMAGE to increase the consistency of the information on agricultural production, availability of land, and climate change. (First, preliminary runs were used as a basis for discussion between the two groups on the consistency of trends under each of the four scenarios for agricultural production, yields changes, and impacts on total land use in each region; for the final runs, an additional iteration was done, providing information from IMAGE to IMPACT on yield changes resulting from climate change and use of marginal lands.) The linkage between IMPACT and IMAGE was done for 2000, 2020, 2050, and 2100.

Table 6.1. Global Modeling Output

Ecosystem Service	Indicator	Model Used to Calculate Indicator
Direct drivers of ecosystem change		
Climate change	temperature change, precipitation change	IMAGE
Changes in land use and land cover	areas per land cover and land use type	IMAGE
Technology adaptation and use	water use efficiency, energy efficiency, area and numbers growth, crop yield growth, and changes in livestock carcass weight	IMPACT, IMAGE, WaterGAP
Exogenous inputs	fertilizer use, irrigation, wage rates	IMPACT, IMAGE
Air pollution emissions	sulfur and NO_x emissions	AIM, IMAGE
Provisioning services		
Food	total meat, fish, and crop production; consumption; trade, food prices	IMPACT
Food	potential food production, crop area, pasture area, and area for biofuels	IMAGE, AIM
Fish	stock	Ecopath/Ecosim
Fuelwood	biofuel supply	IMAGE, AIM
Fresh water	annual renewable water resources, water withdrawals and consumption, return flows	WaterGAP, AIM
Regulating services		
Climate regulation	net carbon flux	IMAGE
Erosion	erosion risk	IMAGE
Supporting services		
Primary production	primary production	IMAGE, AIM
Food security	calorie availability, food prices, share of malnourished pre-school children in developing countries	IMPACT
Water security	water stress	WaterGAP, AIM
Input to biodiversity calculations		
Terrestrial biodiversity	land use area, climate change, nitrogen and sulfur deposition	IMAGE
Aquatic biodiversity	river discharge	WaterGAP
	climate change	IMAGE

- Changes in irrigated areas computed in IMPACT were allocated to a global grid in the WaterGAP model and then used to compute regional irrigation water requirements. These irrigation water requirements were then added to water withdrawals from the domestic and in-

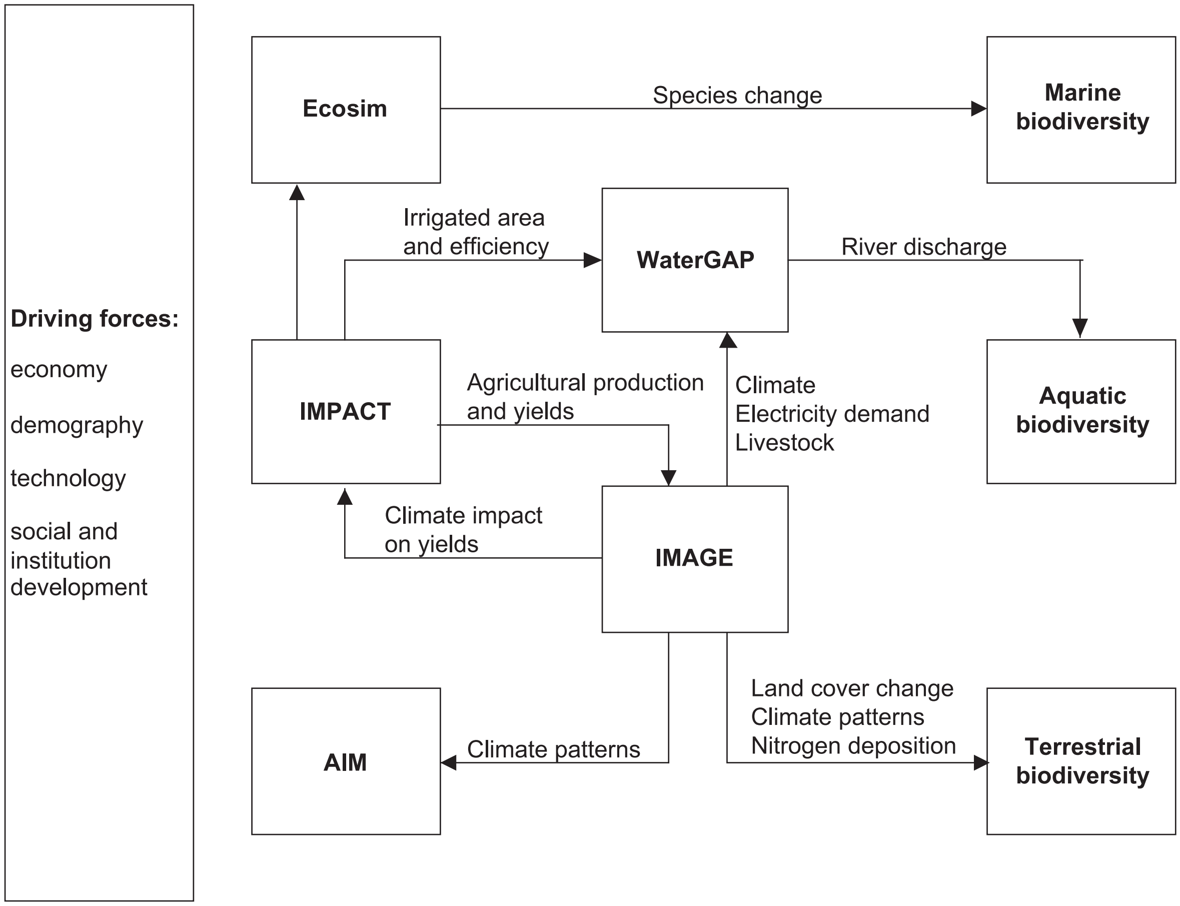


Figure 6.4. Linkages between Models

dustrial sectors (changes for these sectors were calculated by WaterGAP) and compared with local water availability. From this comparison, WaterGAP estimated water stress on a global grid.

- Changes in temperature and precipitation were calculated in IMAGE based on trends in greenhouse gas emissions from energy and land use. These climate change calculations were used in WaterGAP to compute changes in water availability and in IMPACT to estimate changes in crop yield.
- The IMAGE model was used to compute changes in electricity use and livestock production, the latter obtained from IMPACT, which were used by WaterGAP to estimate future water requirements in the electricity and livestock sectors.
- The model for Freshwater Biodiversity used inputs of river discharge from WaterGAP and climate from IMAGE.
- The calculations of changes in terrestrial biodiversity relied on calculations of land cover changes, nitrogen deposition, and climate from IMAGE. Calculations were done on the basis of annual IMAGE output data.
- The AIM modeling team used the same drivers in terms of population, economic growth, and technology development, but no linkages were made between the AIM model and outputs of other models.

Linkages between models are seldom straightforward, and usually require the upscaling (aggregation) or downscaling of various data. The IMPACT model, for instance, uses a more detailed regional disaggregation level than the IMAGE model. In almost all cases, however, regional scaling was possible by combining regions (upscaling) or by assuming proportional changes (downscaling). The models were not recalibrated on the basis of the new input parameters provided by the other models, but in most cases the models had been calibrated using comparable international databases. The new linkages therefore did not lead to major inconsistencies in assumptions between the models.

6.5.4 Modeling Changes in Biodiversity

Currently, there are no global models that describe changes in biodiversity on the basis of global scenarios. For the MA analysis, several smaller models or algorithms were developed on the basis of linkages between global change parameters and species diversity to describe elements of biodiversity change. Outcomes from these tools were then used for a more elaborate discussion of the possible impacts of the different scenarios for global biodiversity. The methods used are discussed in detail in Chapter 10.

6.5.4.1 Terrestrial Biodiversity

The possible future changes in terrestrial biodiversity under the four MA scenarios were explored on the basis of the assessment of changes in native habitat cover over time, climate change, and changes in nitrogen deposition. A review of global threats to biodiversity identified land use change, climate change, the introduction of alien species, nitrogen deposition, and carbon fertilization as major driving forces for extinction (Sala et al. 2000). Simple and well-established existing relationships between these threats and species diversity were used to explore the possible impacts under the MA scenarios. For land use change, for instance, the species-area relationship was used to describe potential loss of plant diversity.

A second important cause of potential change in future global biodiversity is climate change. The potential impacts of climate change were explored using several tools that provide insight into changes in biomes and plant diversity as a result of climate change. More qualitative assessments were made for the impacts of nitrogen and invasive species. Finally, changes in local biodiversity were directly estimated on the basis of the land cover change scenarios.

6.5.4.2 Aquatic and Marine Biodiversity

Oberdorff et al. (1995) developed a global model to describe the diversity of fresh waters as a function of river discharge, net primary production per area of the watershed, watershed area, and fish species richness of the continent. As river discharge can be used as a measure of the size of the freshwater habitat, Oberdorff's model is, in fact, an approximation or expression of the species-area curve for freshwater biodiversity. In our exercise, we updated the fish species numbers and discharge data in Oberdorff's model and used it to describe changes in fish biodiversity as a function of changes in drivers that affect river discharge.

For marine biodiversity, several studies are available on the impacts of fisheries on the marine diversity for different trophic levels. However, to date no global model has been developed. Instead, we applied several regional models to different seas around the world using the MA storylines to specify their main assumptions. The results of these localized case studies served to indicate possible changes in global biodiversity. In addition, a qualitative discussion based on expert knowledge of the impacts of other pressures, including climate change, on marine biodiversity added to the interpretation of model results.

6.5.5 Comments on the Modeling Approach

The approach of using global models to quantify the scenarios has certain disadvantages that should be made explicit. The outcomes of global modeling exercises are highly uncertain, and their assumptions, drivers, and equation systems are often difficult to explain to a nontechnical audience. Furthermore, the models brought together in the MA global modeling exercise were developed independently and were therefore not fully compatible. For example, they have different spatial and temporal resolutions.

The advantages of using global models as part of the scenario building process outweigh the disadvantages, however. Although the model results are uncertain, the models themselves have been published in the scientific literature and have undergone peer review. They have also been found useful for linking science with policy issues in earlier international policy-relevant applications. The models used in the MA exercise provide insights into the trends of many different types of ecosystem services, including global food production, the status of global freshwater resources, and global land cover. In combination, they provide a unique opportunity to generate globally comprehensive, rich, and detailed information for enriching the MA storylines.

While more than 20 indicators were computed in the linked modeling system, coverage of global ecosystem services and feedback effects remained limited. As noted, we tried to make up for this deficit by developing qualitative storylines, which in text form can describe additional indicators and aspects of ecosystem services. At the same time, the modeling exercise addressed some of the deficits of the storylines. For example, model calculations can be used to interlink outcomes for various ecosystem services and to explore the consistency of the storyline assumptions. As part of an overall approach, the storyline-writing and modeling exercise complement each other.

6.6 Discussion of Uncertainty and Scenarios

6.6.1 Using the Scenario Approach to Explore Uncertainty

As explained in the introduction, the main reason to use a scenario approach to explore the future development of ecosystem services is that the systems under study are too complex and the uncertainties too large to use alternative approaches, such as prediction. (See also Chapter 3.) Therefore scenario analysis is used as a tool to address the uncertainty of the future. The MA scenario analysis provides concrete information about plausible future development paths of ecosystem services and their relation to human well-being. The range of scenarios exemplifies the range of possible futures and in so doing helps stakeholders and decision-makers to design robust strategies to preserve ecosystem services for human well-being.

The high level of uncertainty about the future of ecosystem services also implies that is not possible to distinguish between the probability of one scenario versus another. In scenario analysis we sometimes have an intuitive sense that one scenario is more probable than another, but for the MA and most scenario exercises it is not fruitful to dwell on their relative probabilities. With regards to the MA scenarios, other scenarios are also possible, and it is highly unlikely that any of the four scenarios developed for the MA would materialize as described. In other words, the four scenarios are only a small subset of limitless plausible futures. They were selected because they sampled broadly over the space of possible futures, they illustrated points about ecosystem services and human well-being that the MA was charged to address, and they enabled us to answer the focal questions posed by the MA Scenarios Working Group.

6.6.2 Communicating Uncertainties of the Scenarios

Despite the uncertainty of the future, the scenarios contain statements that we intuitively judge as more likely than others. To communicate this certainty/uncertainty we use the expressions shown in Figure 6.5. This scheme was developed for handling uncertainty in assessments of the Intergovernmental Panel on Climate Change (Moss and Schneider 2000).

Associated with each statement of confidence is a quantitative confidence level or range of probability. According to this scale, a confidence level of 1.0 implies that we are absolutely certain that a statement is true, whereas a level of 0.0 implies that we are absolutely certain that the statement is false. It should be noted, however, that in this volume confidence levels are typically not estimated numerically. Instead, they are based on the subjective judgments of the scientists. Also, it is unusual to make statements that do not have at least *medium certainty* (unless they are high-risk events).

Another way to communicate uncertainty is shown in Figure 6.6, which describes a set of expressions for describing the state of knowledge about models and parameters used for constructing the MA scenarios. These expressions can be used to supplement the five-point scale of Figure 6.5 in order to explain why a model outcome is associated with high, medium, or low confidence. These expressions are used, for example, in the Appendix of this chapter to describe the uncertainties of different aspects of the models used in the global modeling exercise. They are also used extensively in Chapter 9 to explain estimates of future changes in ecosystem services.

6.6.3 Sensitivity Analysis

In some cases, formal sensitivity analysis was used as part of the global modeling exercise to estimate the uncertainty of calculations. For example, the MA population scenarios were selected from a stochastic calculation of population projections. (See Chapter 7.) Another example is the assessment of the uncertainty of climate change on water availability. (See Chapter 9.) A third example is the use of Monte-Carlo analysis as part of the calculation of changes in terrestrial biodiversity. (See Chapter 10.)

(1.00) "Very certain" (0.975)
(0.975) "High certainty" (0.83)
(0.83) "Medium certainty" (0.67)
(0.67) "Low certainty" (0.525)
(0.525) "Very uncertain" (0.5)

Figure 6.5. Scale for Assessing State of Knowledge and Statement Confidence (Moss and Schneider 2000)

Level of Agreement			
	High	Established but incomplete	Well-established
	Low	Speculative	Competing explanations
		Low	High
		Amount of evidence (theory, observations, model outputs)	

Figure 6.6. Scheme for Describing "State of Knowledge" or Uncertainty of Statements from Models or Theories (Moss and Schneider 2003)

6.7 Summary

The goal of the MA is to provide decision-makers and stakeholders with scientific information about linkages between ecosystem change and human well-being. Several MA scenarios were developed to explore alternative futures on the basis of coherent and internally consistent sets of assumptions. Scenario development was chosen instead of other approaches, such as predictions, as scenarios are better suited to deal with the large inherent uncertainties of the complex relationships between ecological and human systems and within each of these systems.

An important aspect of the MA scenarios is that they need to take into account ecosystem dynamics and ecosystem feedbacks. As earlier global scenarios have been generated for other purposes, incorporation of realistic ecosystem dynamics is a novel aspect of the MA scenarios.

The MA developed scenarios of ecosystems services and human well-being from 2000–50 with selected outlooks to 2100. The MA scenarios were developed by first defining qualitative storylines, followed by quantification of selected storyline drivers and parameters in an iterative process. The development of scenario storylines allowed the process to focus on internal consistency of different assumptions and also to take into account a broad range of elements and feedback effects that often cannot be quantified. Based on initial storylines, the quantification process helped to provide insights into processes where sufficient knowledge exists to allow for modeling and to take into account the interactions among the various drivers and ecosystem services.

APPENDIXES: Descriptions of Models

Appendix 6.1 The IMAGE 2.2 Model

The IMAGE modeling framework—the Integrated Model to Assess the Global Environment—was originally developed to study the causes and impacts of climate change within an integrated context. At the moment, however, IMAGE 2.2 is used to study a whole range of environmental and global change problems, in particular in the realm of land use change, atmospheric pollution, and climate change. The model and its sub-models have been described in detail in several publications (see, in particular, Alcamo et al. 1998; IMAGE-team 2001).

Model Structure and Data

In general terms, the IMAGE 2.2 framework describes global environmental change in terms of its cause-response chain. Appendix Figure 6.1 provides an overview of the different parts of the model.

The cause-response chains start with the main driving forces—population and macroeconomic changes—that determine energy and food consumption and production. Cooperation with a macroeconomic modeling team (CPB 1999) working on a general equilibrium model ensures in several cases an economic underpinning of assumptions made. Next, a detailed description of the energy and food consumption and production are developed using the TIMER Global Energy Model and the AEM Food Demand and Trade model (for the MA, the latter was replaced by a link to the IMPACT model). Both models account for various substitution processes, technology development, and trade.

The changes in production and demand for food and biofuels (the latter are calculated in the energy model) have implications for land use, which is modeled in IMAGE on a 0.5 by 0.5 degree grid. Changes in both energy consumption and land use patterns give rise to emissions that are used to calculate changes in atmospheric concentration of greenhouse gases and some atmospheric pollutants such as nitrogen and sulfur oxides. Changes in concentration of greenhouse gases, ozone precursors, and species involved in aerosol formation comprise the basis for calculating climatic change. Next, changes in climate are calculated as global mean changes that are downscaled to the 0.5 by 0.5 degree grids using patterns generated by general circulation models.

The Land-Cover Model of IMAGE simulates the change in land use and land cover in each region driven by demands for food (including crops, feed, and grass for animal agriculture), timber, and biofuels, in addition to changes in climate. The model distinguishes 14 natural and forest land cover types and 5 humanmade types. A crop module based on the FAO agro-ecological zones approach computes the spatially explicit yields of the different crop groups and grass and the areas used for their production, as determined by climate and soil quality (Alcamo et al. 1998). In case expansion of agricultural land is required, a rule-based "suitability map" determines which grid cells are selected. Conditions that enhance the suitability of a grid cell for agricultural expansion are its potential crop yield (which changes over time as a result of climate change and technology development), its proximity to other agricultural areas, and its proximity to water bodies.

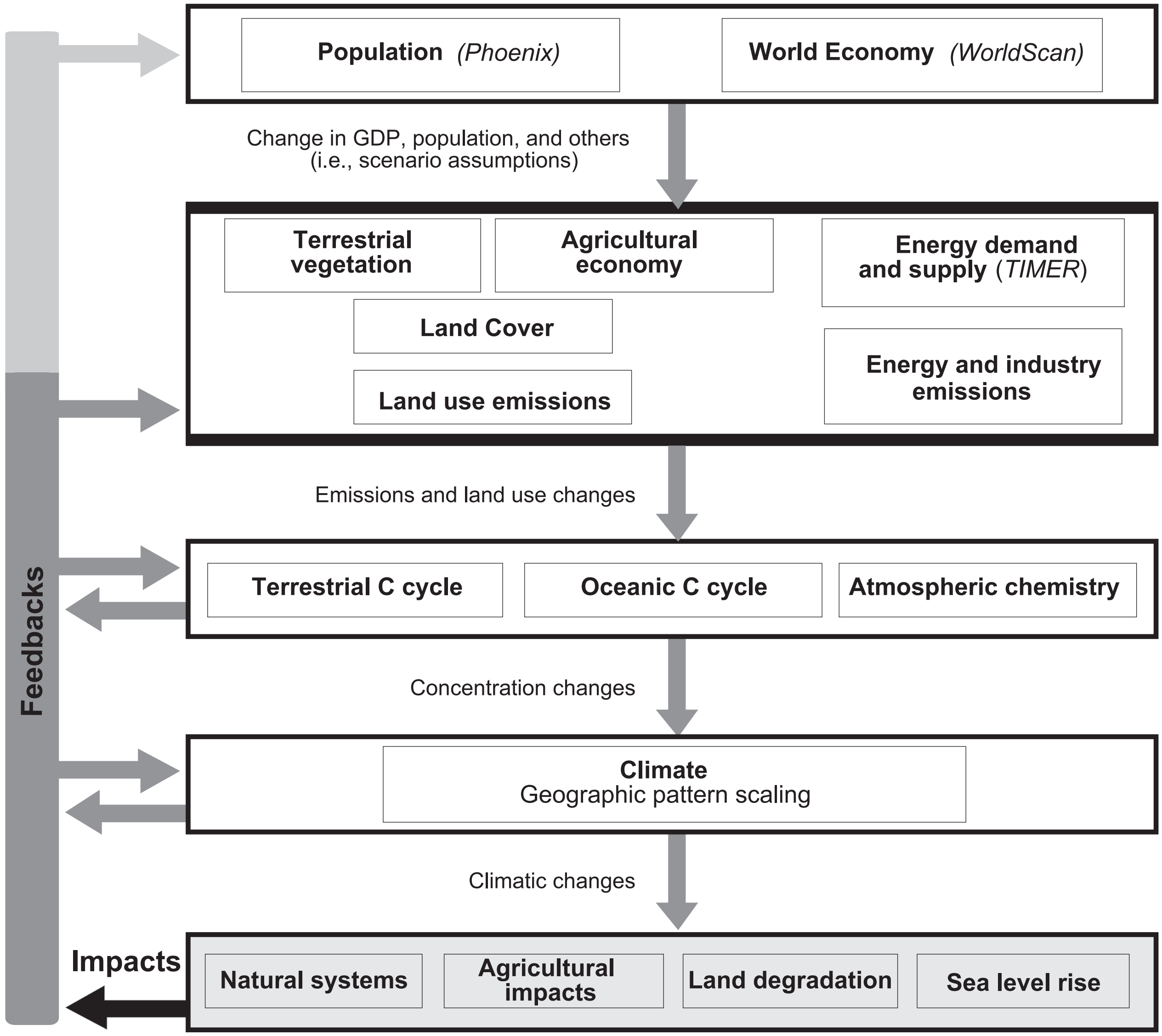
The Land-Cover Model also includes a modified version of the BIOME model (Prentice et al. 1992) to compute changes in potential vegetation (the equilibrium vegetation that should eventually develop under a given climate). The shifts in vegetation zones, however, do not occur instantaneously. In IMAGE 2.2, such dynamic adaptation is modeled explicitly according to the algorithms developed by Van Minnen et al. (2000). An important aspect of IMAGE is that it accounts for significant feedbacks within the system, such as temperature, precipitation, and atmospheric CO_2 feedbacks on the selection of crop types and the migration of ecosystems. This allows for calculating changes in crop and grass yields and, as a consequence, the location of different types of agriculture, changes in net primary productivity, and migration of natural ecosystems.

Application

The IMAGE model has been applied in several assessment studies worldwide, including work for IPCC and analyses for UNEP's Global Environment Outlook (UNEP 2002). For instance, the IMAGE team was one of the six models that took part in the development of the scenarios of IPCC's Special Report on Emission Scenarios (IPCC 2000a; de Vries et al. 2000; Kram et al. 2000). The model has also been used for a large number of studies that aim to identify strategies that could mitigate climate change, mostly focusing on the role of technology or relevant timing of action (e.g., van Vuuren and de Vries 2001). IMAGE also contributed to European projects, including the regularly published *State of the Environment* report on Europe of the EU/European Environment Agency and work for the Directorate-General for the Environment of the European Commission. Recently, the geographic scale of IMAGE was further disaggregated to the country level in Europe, using the model in a large project for land use change scenarios in Europe. In addition, on a project basis the capabilities of the model to describe the nitrogen cycle are improved. In recent years, the links to biodiversity modeling have also been improving.

Uncertainty

As a global Integrated Assessment Model, the focus of IMAGE is on large-scale, mostly first-order drivers of global environmental change. This obviously introduces some important limitations to its results, and in particular how to interpret their accuracy and uncertainty. An important method to handle some of the uncertainties is by using a scenario approach. A large number of relationships and model drivers that are currently not known or that depend on human decisions are varied in these scenarios to explore



Appendix Figure 6.1. Structure of IMAGE 2.2 Model. Phoenix, WorldScan, and TIMER are submodels of the IMAGE 2.2 model.

the uncertainties involved in them (see IMAGE-team 2001). For the energy model, in 2001 a separate project was performed to evaluate the uncertainties in the energy model using both quantitative and qualitative techniques. Through this analysis we identified that the model's most important uncertainties had to do with assumptions for technological improvement in the energy system and how human activities are translated into a demand for energy (including human lifestyles, economic sector change, and energy efficiency).

The carbon cycle model has also been used in a sensitivity analysis to assess uncertainties in carbon cycle modeling in general (Leemans et al. 2002). Finally, a main uncertainty in IMAGE's climate model has to do with the ''climate sensitivity'' (that is, the response of global temperature computed by the model to changes in atmospheric greenhouse gas concentrations) and the regional patterns of changed temperature and precipitation. IMAGE 2.2 has actually been set up in such a way that these variables can be easily varied on the basis of more scientifically detailed models, and a separate CD-ROM has been published indicating the uncertainties in these relationships in detail. To summarize, in terms of the scheme discussed in this chapter on the certainty of different theories, most of IMAGE would need to go into the category of established but incomplete knowledge.

Appendix Tables 6.1 and 6.2 give an overview of the main sources of uncertainty in the IMAGE model.

Appendix 6.2 The IMPACT Model

IMPACT—the International Model for Policy Analysis of Agricultural Commodities and Trade—was developed in the early 1990s as a response to concerns about a lack of vision and consensus regarding the actions required to feed the world in the future, reduce poverty, and protect the natural resource base.

Model Structure and Data

IMPACT is a representation of a competitive world agricultural market for 32 crop and livestock commodities, includ-

Appendix Table 6.1. Overview of Major Uncertainties in the IMAGE Model

	Model Component		
Uncertainty	**Energy and Related Emissions**	**Land Use and Land Cover**	**Environmental System and Climate Change**
Model structure	integration in larger economy, feedbacks dynamic formulation in energy model (learning by doing, multinomial logit)	rule-based algorithm for allocating land use	scheme for allocating carbon pools in the carbon cycle model
Parameter	resource assumptions learning parameters	biome model parameter setting CO_2 fertilization	climate sensitivity climate change patterns multipliers in carbon model (impact of climate and carbon cycle)
Driving force	population assumptions economic assumptions assumptions on technology change lifestyle, material intensity, diets environmental policies agricultural production levels (from IMPACT)		
Initial condition	emissions in base year (1995) historic energy use	initial land use / land cover maps historic land use data (FAO)	climate in base year (average global values and maps)
Model operation			downscaling method

Appendix Table 6.2. Level of Confidence in Different Types of Scenario Calculations from IMAGE

Level of Agreement	High	**Established but incomplete** climate impacts on agriculture and biomes carbon cycle	**Well-established** energy modeling and scenarios
	Low	**Speculative** grid-level changes in driving forces impacts of land degradation	**Competing explanations** global climate change—including estimates of uncertainty local climate change land use change
		Low	**High**
		Amount of Evidence (theory, observation, model outputs)	

ing all cereals, soybeans, roots and tubers, meats, milk, eggs, oils, oilcakes and meals, sugar and sweeteners, fruits and vegetables, and fish. It is specified as a set of 43 country or regional sub-models, within each of which supply, demand, and prices for agricultural commodities are determined. The country and regional agricultural sub-models are linked through trade, a specification that highlights the interdependence of countries and commodities in global agricultural markets.

The model uses a system of supply and demand elasticities incorporated into a series of linear and nonlinear equations to approximate the underlying production and demand functions. World agricultural commodity prices are determined annually at levels that clear international markets. Demand is a function of prices, income, and population growth. Growth in crop production in each country is determined by crop prices and the rate of productivity growth. (See Appendix Figure 6.2.) The model is written in the General Algebraic Modeling System programming language and makes use of the Gauss-Seidel algorithm. This procedure minimizes the sum of net trade at the international level and seeks a world market price for a commodity that satisfies market-clearing conditions.

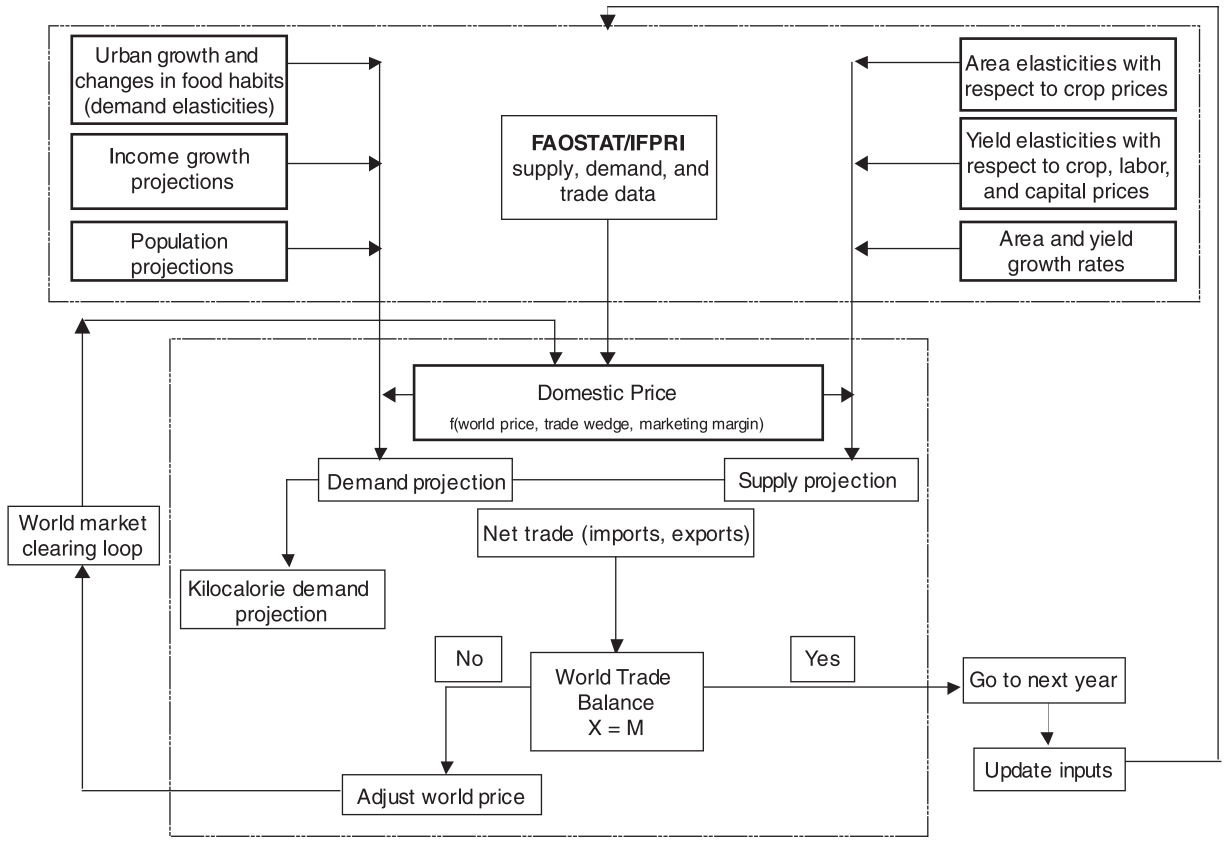
IMPACT generates annual projections for crop area, yield, and production; demand for food, feed, and other uses; and prices and trade. It also generates projections for livestock numbers, yield, production, demand, prices, and trade. The current base year is 1997 (three-year average of 1996–98) and the model incorporates data from FAOSTAT (FAO 2000); commodity, income, and population data and projections from the World Bank (World Bank 1998, 2000a, 2000b) and the UN (UN 1998); a system of supply and demand elasticities from literature reviews and expert estimates; and rates for malnutrition from ACC/SCN (1996)/WHO (1997) and calorie-child malnutrition relationships developed by Smith and Haddad (2000). For MA purposes, the projections period was updated from 1997–2025 to 2100. Additional updates on drivers and parameters are described in Chapter 9.

Application

IMPACT has been applied to a wide variety of contexts for medium- and long-term policy analysis of global food markets. Applications include commodity-specific analyses (for example, for roots and tubers (Scott et al. 2000), for livestock (Delgado et al. 1999), and for fisheries (Delgado et al. 2003)) and regional analyses (for example, on the consequences of the Asian financial crisis (Rosegrant and Ringler 2000)). In 2002 a separate IMPACT-WATER model was developed that incorporates the implications of water availability and nonagricultural water demands on food security and global food markets (Rosegrant et al. 2002).

Uncertainty

As IMPACT does not contain equations with known statistical properties, formal uncertainty tests cannot be carried



Appendix Figure 6.2. Structure of IMPACT Model

out. However, the robustness of results has been tested and the sensitivity of results with respect to the various drivers in the model have been carried out through numerous scenario analyses, as described in Rosegrant et al. (2001) and the other IMPACT publications cited in this assessment. The drivers associated with uncertainty that have important implications for model outcomes include population and income growth, as well as drivers affecting area and yield and livestock numbers and slaughtered weight growth.

Appendix Tables 6.3 and 6.4 summarize the points related to uncertainty in the model, based on the level of agreement and amount of evidence.

Appendix 6.3 The WaterGAP Model

The principal instrument used for the global analysis of water withdrawals, availability, and stress is the WaterGAP model—Water Global Assessment and Prognosis—developed at the Center for Environmental Systems Research of the University of Kassel in cooperation with the National Institute of Public Health and the Environment of the Netherlands. WaterGAP is currently the only model with global coverage that computes both water use and availability on the river basin scale.

Model Structure and Data

The aim of WaterGAP is to provide a basis both for an assessment of current water resources and water use and for an integrated perspective of the impacts of global change on the water sector. WaterGAP has two main components, a global hydrology model and a global water use model. (See Appendix Figure 6.3.)

The global hydrology model simulates the characteristic macroscale behavior of the terrestrial water cycle to estimate water availability; in this context, we define ''water availability'' as the total river discharge, which is the combined surface runoff and groundwater recharge. The model calculates discharge based on the computation of daily water balances of the soil and canopy. A water balance is also performed for open waters, and river flow is routed via a global flow routing scheme. In a standard global run, the discharge of approximately 10,500 rivers is computed. The global hydrology model provides a testable method for taking into account the effects of climate and land cover on runoff.

The global water use model consists of three main submodels that compute water use for households, industry, and irrigation in 150 countries. Beside the water withdrawal (total volume of water that is abstracted from surface or groundwater sources), the consumptive water use (water that is actually used and not returned to the water cycle as return flow) is quantified. Both water availability and water use computations cover the entire land surface of the globe except Antarctica (spatial resolution 0.5°—that is, 66,896 grid cells). A global drainage direction map with a 0.5° spatial resolution allows for drainage basins to be chosen flexibly; this permits the analysis of the water resources situation in all large drainage basins worldwide. For a more detailed

Appendix Table 6.3. Overview of Major Uncertainties in the IMPACT Model

Model Component	Uncertainty
Model structure	based on partial equilibrium theory (equilibrium between demand and supply of all commodities and production factors) underlying sources of growth in area/numbers and productivity structure of supply and demand functions and underlying elasticities, complementary and substitution of factor inputs.
Parameters	**Input parameters** base year (three-year centered moving averages for) area, yield, production, numbers for 32 agricultural commodities and 43 countries and regions elasticities underlying the country and regional demand and supply functions commodity prices driving forces **Output parameters** annual levels of food supply, demand, trade, international food prices, calorie availability, and share and number of malnourished children
Driving force	**Economic and demographic drivers** income growth (GDP) population growth **Technological, management, and infrastructural drivers** productivity growth (including management research, conventional plant breeding) area and irrigated area growth livestock feed ratios **Policy drivers** including commodity price policy as defined by taxes and subsidies on commodities, drivers affecting child malnutrition, and food demand preferences
Initial condition	baseline—three-year average centered on 1997 of all input parameters and assumptions for driving forces
Model operation	—

description of the model, see Alcamo et al. (2000, 2003a, 2003b), Alcamo (2001), and Döll et al. (2003).

Application

Results from the model have been used in many national and international studies, including the World Water Assessment, the International Dialogue on Climate and Water, UNEP's Global Environmental Outlook, and the World Water Vision scenarios disseminated by the World Water Commission.

Uncertainty

Appendix Tables 6.5 and 6.6 summarize some of the most important sources of uncertainty in WaterGAP calculations.

Appendix Table 6.4. Level of Confidence in Different Types of Scenario Calculations from IMPACT

Level of Agreement/ Assessment		Amount of Evidence (theory, observations, model outputs): Low	High
	High	**Established but incomplete** projections of area projections of irrigated area, yield projections of livestock numbers, production number of malnourished children calorie availability	**Well-established** changes in consumption patterns and food demand
	Low	**Speculative**	**Competing explanations** projections of commodity prices commodity trade

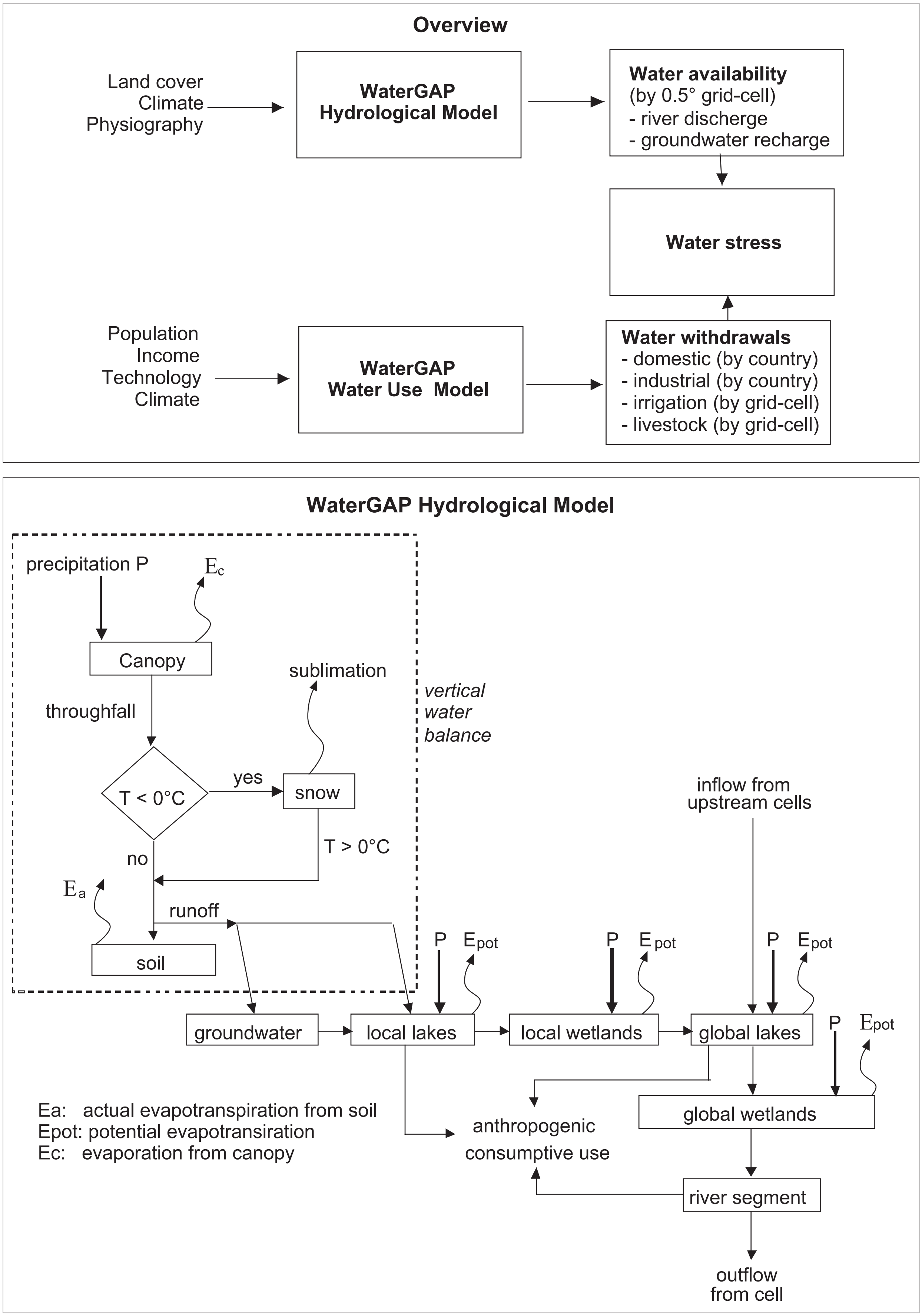
Alcamo et al. (2003b) found that the magnitude of uncertainty of model calculations was very spatially dependent.

Appendix 6.4 The Asia-Pacific Integrated Model

AIM—the Asia-Pacific Integrated Model—is a large-scale computer simulation model developed by the National Institute for Environmental Studies in collaboration with Kyoto University and several research institutes in the Asia-Pacific region. AIM assesses policy options for stabilizing global climate, especially in the Asia-Pacific region, with objectives of reducing greenhouse gas emissions and avoiding the impacts of climate change. Modelers and policymakers have recognized that climate change problems have to be solved in conjunction with other policy objectives, such as economic development and environmental conservation. The AIM model has thus been extended to take into account a range of environmental problems, such as ecosystem degradation and waste disposal, in a comprehensive way.

Model Structure and Data

AIM/Water estimates country-wise water use (withdrawal and consumption in agricultural, industrial, and domestic sector), country-wise renewable water resource, spatial distribution of water use and renewable water resources with resolution of 2.5° × 2.5°, and basin-wise water stress index. Appendix Figure 6.4 presents an overview over the main components of the AIM/Water sub-model. Future scenarios of population, GDP, technological improvements, and historical trends of population with access to water supply are the basic inputs used in the estimation of water use. The country-wise water use is then disaggregated to grid cells in proportion to the spatial densities of population and crop-



Appendix Figure 6.3. Structure of WaterGAP Model. Top: overview of main components. Bottom: WaterGAP hydrological model. (Döll et al. 2003)

Appendix Table 6.5. Overview of Major Uncertainties in WaterGAP Model

Model Component	Uncertainty
Model structure	evapotranspiration river transport time snowmelt mechanism
Parameters	watershed calibration parameter parameter for allocating total discharge to surface and sub-surface flow
Driving force	local precipitation inputs, frequency of rain days
Initial condition	current direction of flows in flat and wetland areas grid resolution of current water withdrawals
Model operation	downscaling method for country-scale domestic and industrial withdrawals; interpolation of climate data

Appendix Table 6.6. Level of Confidence in Different Types of Scenario Calculations from WaterGAP

Level of Agreement		Amount of Evidence (theory, observations, model outputs): Low	Amount of Evidence (theory, observations, model outputs): High
	High	**Established but incomplete** water stress annual withdrawals in developing countries annual water availability in areas without long-term hydrologic gauges	**Well-established** annual withdrawals in industrialized countries annual water availability where there are long-term hydrologic gauges (about 50% of the area of Earth)
	Low	**Speculative** return flows	**Competing explanations** water quality freshwater biodiversity (WaterGAP contributes to these calculations)

land. The change in renewable water resource is estimated by considering future climate change as input data. In order to obtain a water stress index, water withdrawal and renewable water resources are compared in each river basin. See also Harasawa et al. (2002) for a more detailed description.

AIM/Agriculture estimates potential crop productivity of rice, wheat, and maize with the spatial resolution of 0.5° × 0.5°. Climatic factors are then taken as inputs to simulate net accumulation of biomass through photosynthesis and respiration. They include monthly temperature, cloudiness, precipitation, vapor pressure, and wind speed. The physical and chemical properties of soil such as soil texture and soil slope are also considered in estimating suitability for agriculture (Takahashi et al. 1997).

AIM/Ecosystem is a global computable general equilibrium model. The model structure is shown in Appendix Figure 6.5. It is an economic model with 15 regions and 15 sectors. The model has been developed for the period 1997–2100 with recursive dynamics. Prices and activities are calculated in order to balance demand and supply for all commodities and production factors. AIM/Ecosystem model is linked to AIM/Agriculture model in terms of land productivity changes resulting from climate change. The main drivers of these dynamics are population, production investment, and technology improvement. In this model, various environmental issues such as deforestation and air pollution are included. These interact with the economy through provision of resources and maintenance and degradation of the environment. This model thus consistently estimates economic activities such as GDP and primary energy supply, the related environmental load such as air pollution, and environmental protection activities such as investments in desulfurization technologies (Masui et al. forthcoming).

Application

The AIM model has been used in the development of one of the marker scenarios for IPCC/SRES. The extended version was used for UNEP's GEO3 report. Long-term scenarios of environmental factors quantified using AIM/Water, AIM/Agriculture, and AIM/Ecosystem have been used for the MA.

Uncertainty

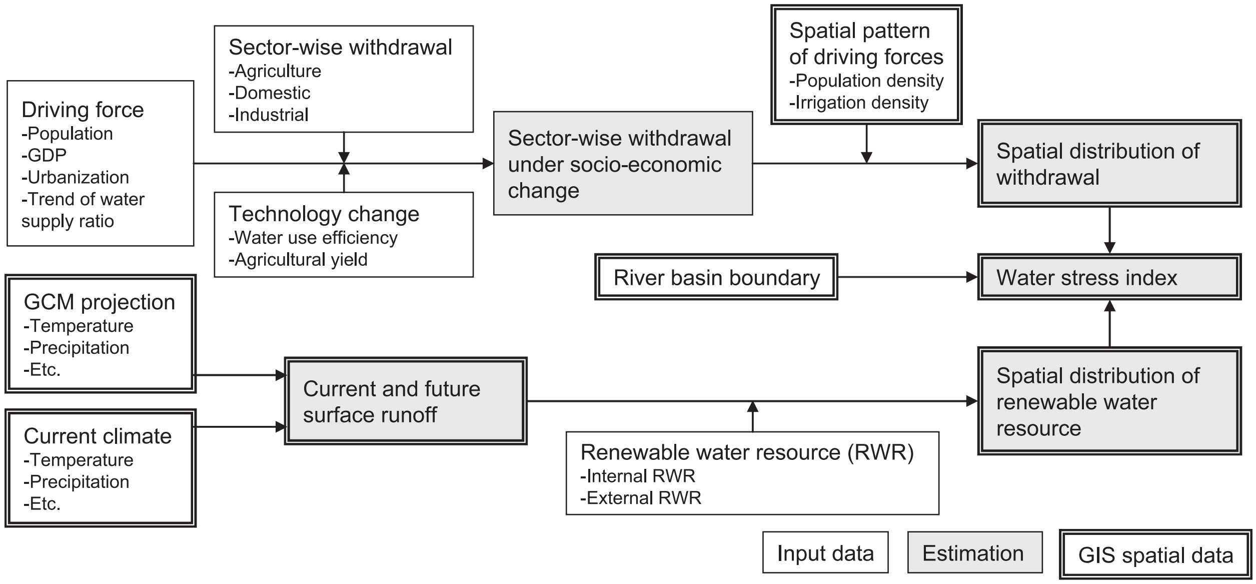
The AIM models are based on a deterministic framework. The time scale of each model is more than 100 years. This long-term framework stresses theoretical consistency. It is preferable to models that use past trends because those are not suitable for studying long-term dynamics. Our approach to uncertainty is not to evaluate each parameter or function individually but to assess the robust options or policies derived from the various simulation results.

Appendix Tables 6.7 and 6.8 summarize the uncertainties in each model.

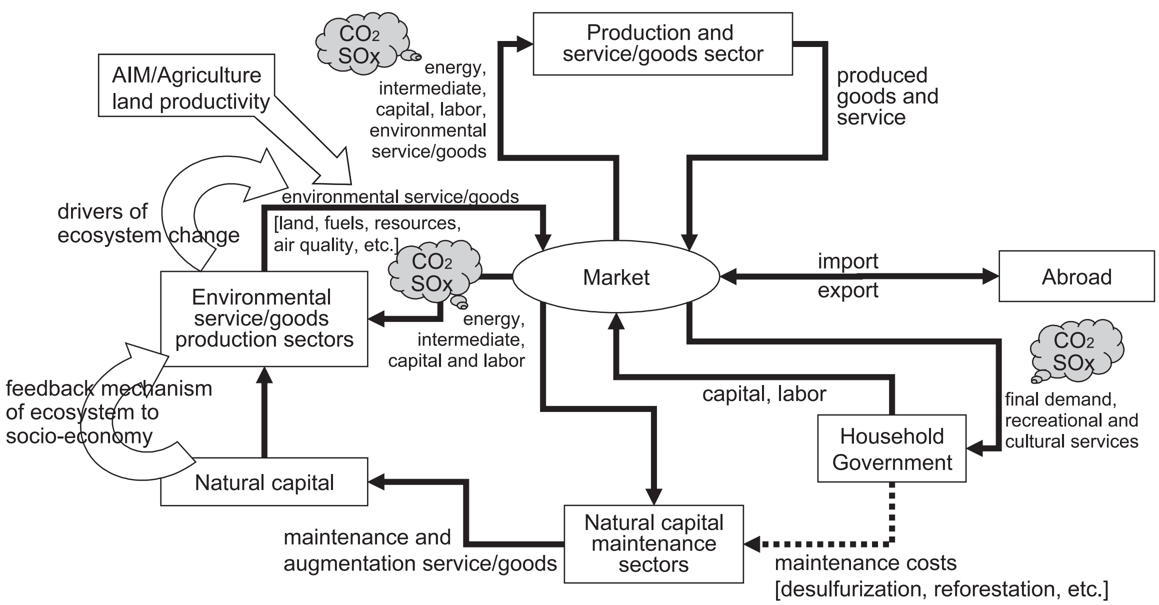
An option or sets of options related to the elements in this table are introduced to the models and simulated under the different scenarios. When the options always produce similar results even in different scenarios, they are regarded as robust.

Appendix 6.5 Ecopath with Ecosim

EwE—Ecopath with Ecosim—is an ecological modeling software suite for personal computers; some components of EwE have been under development for nearly two decades. The approach is thoroughly documented in the scientific literature, with over 100 ecosystems models developed to date (see www.ecopath.org). EwE uses two main components: Ecopath, a static, mass-balanced snapshot of the system, and Ecosim, a time dynamic simulation module for policy exploration that is based on an Ecopath model.



Appendix Figure 6.4. Structure of AIM/Water Model



Appendix Figure 6.5. Structure of AIM/Ecosystem Model

Model Structure and Data

The foundation of the marine fisheries calculations is an Ecopath model (Christensen and Pauly 1992; Pauly et al. 2000). The model creates a static, mass-balanced snapshot of the resources in an ecosystem and their trophic interactions, represented by trophically linked biomass "pools." The biomass pools consist of a single species or of species groups representing ecological guilds. Pools may be further split into ontogenetic (juvenile/adult) groups that can then be linked together in Ecosim.

Ecopath data requirements of biomass estimates, total mortality estimates, consumption estimates, diet compositions, and fishery catches are relatively simple and are generally available from stock assessment, ecological studies, or the literature. The parameterization of Ecopath is based on satisfying two key equations: the production of fish and the conservation of matter. In general, Ecopath requires input of three of the following four parameters: biomass, production/biomass ratio (or total mortality), consumption/biomass ratio, and ecotrophic efficiency for each of the functional groups in a model. Christensen and Walters (2004) detail the methods used and the capabilities and pitfalls of this approach.

Ecosim has a dynamic simulation capability at the ecosystem level, with key initial parameters from the base Ecopath model. (See Appendix Figures 6.6 and 6.7.) The key computational aspects are:

- use of mass-balance results (from Ecopath) for parameter estimation;

Appendix Table 6.7. Overview of Major Uncertainties in AIM Model

	Uncertainty	
	AIM/Water	
Model Component	**Water Withdrawal Model**	**Renewable Water Resource Model**
Model structure	assumption that the spatial pattern of population and land use will not change in future	choice of method for estimating potential evapotranspiration
Parameter	assumption regarding water use efficiency improvement in each sector	assumption of the model parameter for relating actual and potential evapotranspiration
	assumption of the model parameter for estimating urbanization ratio	
Driving force	population	climate projected by GCM
	increasing trend in population with access to water	
	degree of economic activity	
Initial condition	error in the estimated sectoral water withdrawal in the base year	error in the estimated renewable water resource in the base year
		error in the observed climate data
Model operation		procedure to develop climate scenario from GCM result
	AIM/Agriculture	
Model structure	choice of method for estimating photosynthesis ratio	
Parameter	assumption of the model parameter which describes crop growth characteristics	
Driving force	future climate projected by GCM	
Initial condition	error in the observed climate data	
	error in the soil data	
Model operation	procedure to develop climate scenario from GCM result	
	AIM/Ecosystem	
Model structure	based on the general equilibrium theory (equilibrium between demand and supply of all commodities and production factors)	
	investment function in each period	
	structures of production function and demand function: especially elasticity of substitution among the inputs	
Parameter	change of preference	
	relationship between cost and performance in pollution reduction	
Driving force	technology assumption and population projection	
Initial condition	disaggregation of economic data into more detailed subsectors (inputs to each power generation such as thermal power, nuclear, and hydro power)	
	environmental investment and stock of environmental equipment besides the stock of production equipment	
Model operation	nonlinearity in demand and production functions	

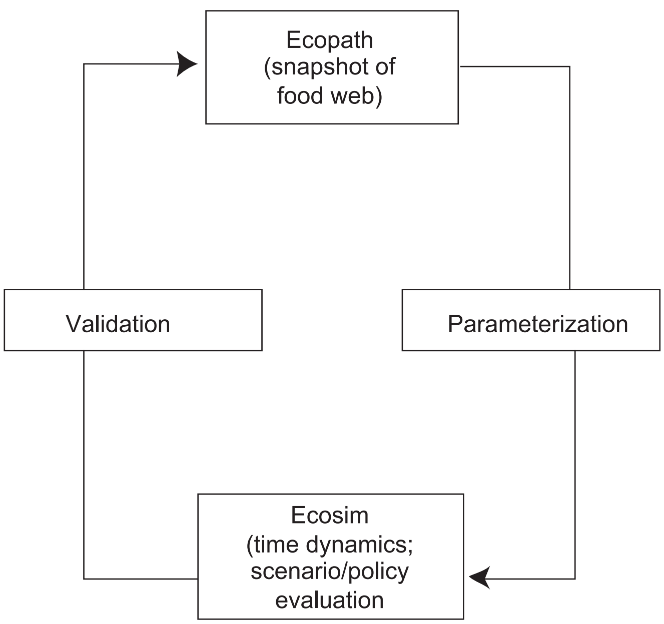
- variable speed splitting, which enables efficient modeling of the dynamics of both ''fast'' (phytoplankton) and ''slow'' groups (whales);
- the effects of micro-scale behaviors on macro-scale rates: top-down versus bottom-up control explicitly incorporated; and
- inclusion of biomass and size structure dynamics for key ecosystem groups, using a mix of differential and difference equations.

Ecosim uses a system of differential equations that express biomass flux rates among pools as a function of time varying biomass and harvest rates (Walters et al. 1997, 2000). Predator-prey interactions are moderated by prey behavior to limit exposure to predation, such that biomass flux patterns incorporate bottom-up as well as top-down control (Walters 2000). Repeated simulations in Ecosim allow for the fitting of predicted biomasses to time series data. Ecosim can thus incorporate time series data on: relative abundance indices (such as survey data or catch per unit effort data), absolute abundance estimates, catches, fleet effort, fishing rates, and total mortality estimates.

Ecosim can be used in optimization and gaming modes. In the latter, it can explore policy options by ''sketching'' fishing rates over time, with the results (catches, economic

Appendix Table 6.8. Level of Confidence in Different Types of Scenario Calculations from AIM

		Amount of Evidence (theory, observation, model outputs): Low	Amount of Evidence (theory, observation, model outputs): High
Level of Agreement	High	**Established but incomplete** pollution reduction water demand water stress	**Well-established** economic activity (based on general equilibrium theory) production function
	Low	**Speculative** —	**Competing explanations** impact on agricultural products (from economic model) renewable water resource



Appendix Figure 6.6. Structure of Ecopath with Ecosim (EwE) Model

performance indicators, biomass changes) examined for each sketch. Formal optimization methods can be used to search for fishing policies that would maximize a particular policy goal or ''objective function'' for management. The objective function represents a weighted sum of the four objectives: economic, social, legal, and ecological. Assigning alternative weights to these components is a way to look at conflict or trade-off with one another in terms of policy choice. The goal function for policy optimization is defined by the user in Ecosim, based on an evaluation of four weighted policy objectives:

- maximize fisheries rent,
- maximize social benefits,
- maximize mandated rebuilding of species, and
- maximize ecosystem structure or ''health.''

The fishing policy search routine described estimates time series of relative fleet sizes that would maximize a multi-criterion objective function. In Ecosim, the relative fleet sizes are used to calculate relative fishing mortality rates by each fleet type, assuming the mix of fishing rates over biomass groups remains constant for each fleet type (that is, reducing a fleet type by some percentage results in the same percentage decrease in the fishing rates that it causes on all the groups that it catches). However, density-dependent catchability effects can be entered, and if so reductions in biomass for a group may result in the fishing rate remaining high despite reductions in total effort by any or all fleets that harvest it. Despite this caveat, the basic philosophy in the fishing policy search is that future management will be based on control of relative fishing efforts by fleet type rather than on multispecies quota systems.

Application

Ecopath with Ecosim has been applied to a number of marine ecosystems throughout the world and at varying spatial scales—from small estuary and coral reef systems to large regional studies such as the North Atlantic. For the MA, three well-documented and peer-reviewed EwE models were used: Gulf of Thailand, Central North Pacific, and North Benguela. (See Appendix Box 6.1.) For each one, the narrative storylines of the MA scenarios were interpreted in terms of specific model parameters (mostly the objective function specifying focus on profits, conservation of jobs, or ecosystem management). The landings, value of the landings (see Chapter 9), and the diversity of the landings (see Chapter 10) were used to investigate the differences between the various scenarios for each ecosystem.

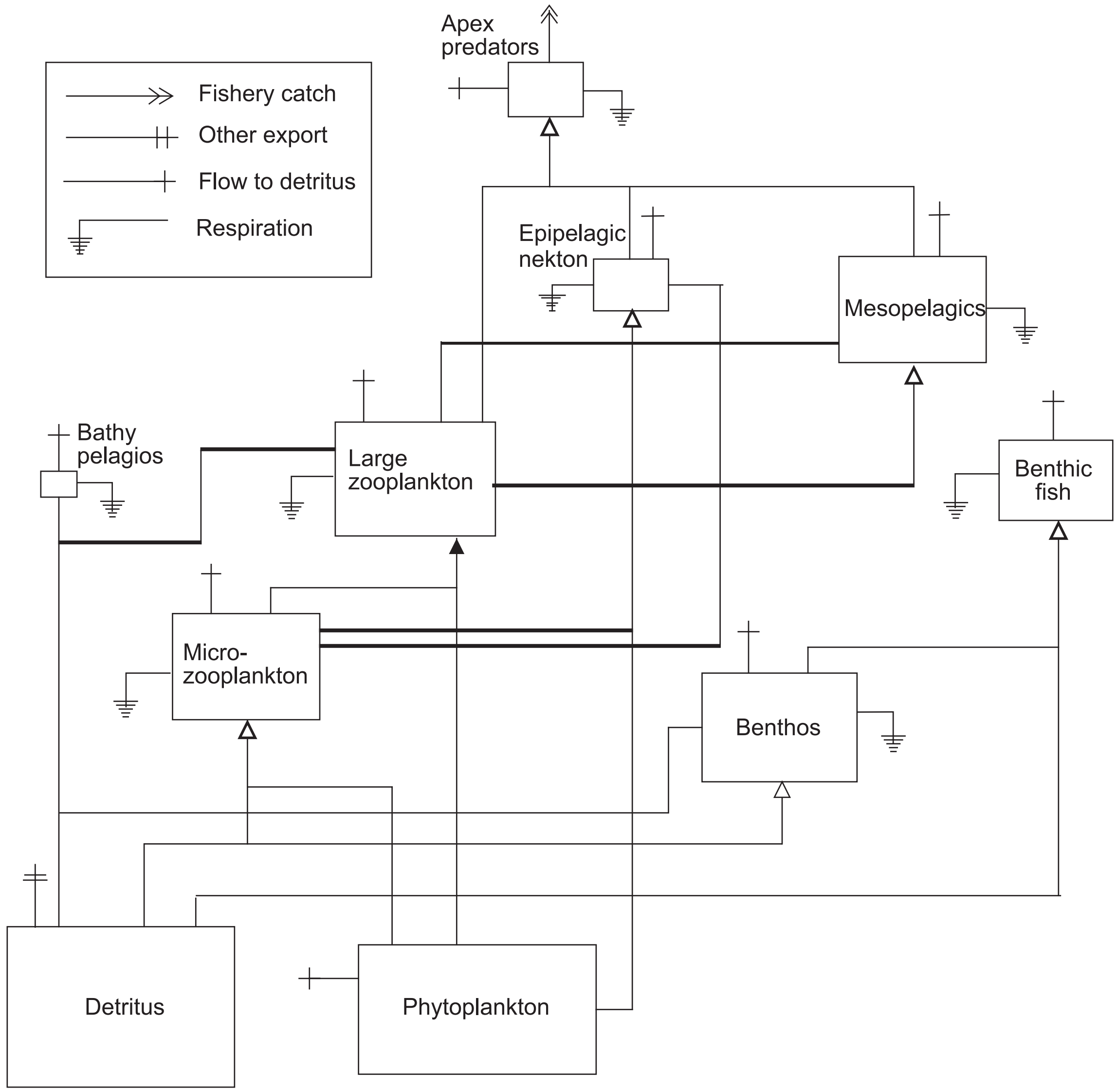
Uncertainty

EwE models include routines to explicitly deal with uncertainty in input parameters and with the way this uncertainty may affect results from the simulation modeling. Parameterization for this is as a rule straightforward. The biggest problem in the analysis is usually centered on the state of the knowledge of how exploitation has affected the ecosystem resources over time. It is, for instance, difficult to evaluate if a certain catch history is caused by light exploitation of a large stock or heavy exploitation of a small stock. In order to evaluate this, it is necessary to have information about the population histories in a given ecosystem, and such information is often not accessible, especially for tropical areas.

Appendix Tables 6.9 and 6.10 sum up the uncertainties of the EwE models.

Appendix 6.6 Terrestrial Biodiversity Model

The concept of biodiversity has several dimensions. First of all, it is used for different conceptual levels—genetic diversity, species diversity, and ecosystem diversity. In addition, it refers to both richness and levels of abundance. And finally, the term can be applied both at the local and the



Appendix Figure 6.7. Structure of Ecopath Model

global level. These aspects relate in a different way to ecological services, as discussed in Chapter 10. In the context of the MA, the main focus was on the analysis of species diversity. Chapter 4 provides an overview of the different available methods to assess changes in biodiversity and their strengths and weaknesses.

Model Structure and Data

The assessment applied in Chapter 10 covers four different causes of biodiversity loss: loss of habitat, climate change, nitrogen deposition, and introduction of alien species. For the quantitative analysis, the basis of the analysis is formed by the species-area relationship, defined as $S = c A^{z,}$ where S is the number of species in an area, A is the habitat area, and c and z are constants. This SAR is applied to about 60 biomes defined by the combination of the biomes defined in IMAGE 2.2 and the realms defined in the biodiversity ecoregion map of Olson et al. (2001). Within the analysis, data on vascular plants were used as an example of possible changes in biodiversity. Data on the c value of the SAR (which represents the intrinsic diversity of each system for a unity size) for vascular plants were obtained by comparing the global land cover map of the IMAGE 2.2 model to a map on diversity of vascular plants (Barthlott 1999). For the z-value of the SAR, a large range of different values was used, as explained in detail in Chapter 10.

The analysis focuses on both global and local changes in biodiversity. For the three different drivers of loss used in the quantitative analysis, the following analysis was performed:

- biodiversity loss from land use change—the SAR was applied directly on the basis of the changes in the IMAGE land use maps;
- biodiversity loss from climate change—three different methods to describe impacts from climate change were applied (a process-oriented model, a method related to species ranges, and the biome description applied in IMAGE 2.2); and
- biodiversity loss from nitrogen deposition—the method describing risks of nitrogen deposition based on critical loads as described by Bouwman et al. (2002) was used.

APPENDIX BOX 6.1

The Three Ecopath with Ecosim Models Used

Gulf of Thailand

The Gulf of Thailand is located in the South China Sea. It is a shallow, tropical coastal shelf system that has been heavily exploited since the 1960s. Prior to the early 1960s, fishing in the area was primarily small scale, with minimal impact on the ecosystem. A trawl fishery was introduced in 1963, however, and since then the area has been subjected to intense, steadily increasing fishing pressure (Pauly and Chuenpagdee 2003). The system has changed from a highly diverse ecosystem with a number of large, long-lived species (such as sharks and rays) to one that is now dominated by small, short-lived species that support a high-value invertebrate fishery. Shrimp and squid caught primarily by trawl gear are economically the dominant fisheries in the Gulf of Thailand. The bycatch of the trawl fishery is used for animal feed. The Gulf of Thailand model is well established and detailed in an FAO technical report (FAO/FISHCODE 2001).

Central North Pacific

The area of Central North Pacific that is modeled is focused on epipelagic waters from 0N to 40N latitude and between 150W and 130E longitude (Cox et al. 2002). Tuna fishing is the major economic activity in the area after tourism in the Hawaiian Islands. The tuna fishery is divided into deepwater longline fisheries that target large-sized bigeye, yellowfin, and albacore tuna and surface fleets that target all ages/sizes of skipjack tuna, small sizes of bigeye, yellowfin, and albacore using a range of gear including purse seine, large-mesh gillnet (driftnet), small-mesh gillnet, handline, pole-and-line, and troll (Cox et al. 2000). Recent assessments of the tuna fisheries indicate that top predators such as blue marlin (*Makaira spp.)* and swordfish (*Xiphias gladius*) declined since the 1950s while small tunas, their prey, have increased. The Central North Pacific model is described in detail in Cox et al. (2000).

North Benguela

The North Benguela Current is an upwelling system off the west coast of Southern Africa. This system is highly productive, resulting in a rich living marine resource system that supports small, medium, and large pelagic fisheries (Heymans et al 2004). The system undergoes dramatic changes due to climatic and physical changes and therefore the marine life production can be quite variable. Sardine or anchovy used to be the dominant small pelagics; both species, however, have been at very low abundance for years, as indicated by surveys in the late 1990s (Boyer and Hampton 2001). The North Benguela ecosystem model is now used by the Namibian Fisheries Research Institute and is described in detail in Heymans et al. (2004).

Appendix Table 6.9. Overview of Major Uncertainties in Ecopath with Ecosim (EwE) Model

Model Component	Uncertainty
Model structure	**Ecopath:**
	mass balance based on the estimation of the biomass and food consumption of the state variables (species or groups of species) of an aquatic ecosystem, with the master equation: Production = catches + predation mortality + biomass accumulation + net migration + other mortality; with *P*roduction = *B*iomass * P/B ratio.
	Ecosim:
	Ebiomass dynamics expressed through a series of coupled differential equations derived from the Ecopath master equation:
	$dB_i / dt = g_i \sum_j Q_{ji} - \sum_j Q_{ij} I_i - (M_i + F_i + e_i)B_i$
Parameter	biomass by species (group) (usually from fisheries surveys)
	catch rate (t · km^{-2} year $^{-1}$) by species group
	the P/B ratio is equivalent to total mortality
	net migration rate and biomass accumulation rate (often set to zero)
	assimilation rate
	diet composition (obtained from predators' stomach contents)
Driving force	fishing mortality of fishing effort
	forcing functions expressing environmental variables
Initial condition	the system (Ecopath model) is initially set to equilibrium (but can include net migration rate and biomass accumulation rate not equal to zero)
Model operation	**Ecopath:**
	used to obtain "snapshot" representation of the food web and biomass in an ecosystem
	Ecosim:
	optimization or gaming modes, policies explored by "sketching" fishing rates over time and with the results (catches, economic performance indicators, biomass changes) examined for each simulation (with or without previous fitting of biomass or the time series)

Uncertainty and Limitations

In the overall methodology, several major assumptions had to be made:

- We assume that the SAR can be applied independently for each ecoregion-biome combination, thus assuming that the overlap in numbers of species is minimum relative to the number of species that are endemic to each ecoregion-biome combination.
- We assume that diversity loss will occur as a result of the transformation of natural vegetation into a human-dominated land cover unit, so we assume that human-dominated vegetation has a diversity of zero endemic species for the purposes of the SAR calculations.
- In our calculations, we have not assumed any extinction rate with time, but simply assume that at some point the number of species will reach the level as indicated by the SAR. This means that our results should not be interpreted in terms of a direct loss of number of species, but in terms of species that are "committed" to extinction.

The method to estimate impacts from climate change is a simplification of the response at the level of individual species that will occur in reality.

Appendix Table 6.10. Level of Confidence in Different Types of Scenario Calculations from Ecopath with Ecosim

		Amount of Evidence (theory, observation, model outputs): Low	Amount of Evidence (theory, observation, model outputs): High
Level of Agreement	High	**Established but incomplete** Ecopath: diet composition and biomass Ecosim: dynamics of depleted groups	**Well-established** Ecopath: food consumption rate, P/B ratios Ecosim: dynamics of abundant groups
Level of Agreement	Low	**Speculative** Ecopath: treatment of lower trophic levels, especially microbial groups Ecosim: trophic versus environment forcing	**Competing explanations** Ecopath: n.a. Ecosim: trophic mediation (control of interaction of two species by third species)

The method is dependent on several uncertainties in data, including the value of z and the number of ecoregions that is defined. In Chapter 10, an extensive uncertainty analysis is performed with regard to these aspects. Appendix Table 6.11 gives a brief overview of the uncertainties of the model.

Appendix Table 6.11. Overview of Major Uncertainties in the Terrestrial Biodiversity Model

Model Component	Uncertainty
Model structure	use of species-area curve
	assumption of irreversibility of species loss
	fraction of species remaining after conversion of natural area into agricultural land
	BIOME model to describe impacts of climate change
	use of critical loads to describe loss of biodiversity for nitrogen deposition
Parameter	value of z (determining biodiversity loss for reduction of habitat), scale of analysis (provincial, island, continental)
	biodiversity loss multiplier for areas affected by climate change
	biodiversity loss multiplier as a function of nitrogen deposition (excess of critical load)
Driving force	land use change (from IMAGE)
	climate change and biome response (from IMAGE)
	nitrogen deposition (from IMAGE)
Initial condition	number of species per habitat type
	land use maps and biome map for start year
Model operation	number of separate biomes and the amount of overlap in species numbers between biomes

Appendix 6.7 Freshwater Biodiversity Model

Freshwater ecosystems have been underrepresented in past global studies of biodiversity. No global quantitative models to forecast the response of freshwater biodiversity to environmental drivers exist. Thus we adapted a previously published descriptive model (Oberdorff et al. 1995) on the relationship between the number of fish species to river size (as measured by volume of water discharged at the river mouth). While fishes are only one component of freshwater biodiversity, they are frequently of great ecological importance and of great value to humans in fisheries. They were the only group of freshwater biota for which near-global data exist. Likewise, because analogous statistical relationships are not quantified for other freshwater habitats (such as lakes and wetlands), we were limited in our quantitative effort to rivers.

Model Structure and Data

Using the statistical approach of Oberdorff et al. (1995), we constructed a regression model relating the number of fish species (taken from Oberdorff et al. 1995 and FishBase) to river discharge for 237 rivers worldwide. Baseline river discharge data from the WaterGAP model correlated strongly with data used by Oberdorff et al. (1995). Thus, for our scenarios we used river discharge output from WaterGAP for both baseline and future conditions. In brief, WaterGAP provided future river discharge that was then used as the dependent variable in a simple regression model to predict the future number of fish species.

Applications

While variations on this statistical model have been used successfully to predict current patterns of riverine fishes among rivers (Oberdorff et al. 1995; Guegan et al. 1998; Hawkins et al. 2003), there has been no previous application of the approach to future scenarios.

Uncertainty and Limitations

For reasons of model structure and data limitation, output applies only to rivers and fishes; lakes and wetlands and other aquatic taxa are not addressed with this quantitative model. Because the data for fish species in each river do not distinguish endemic species from species that also occur in other rivers, the scenario estimates are for river-specific losses of species, not global extinctions. Because other considerations (for example, the pace of evolution, the rate at which species might migrate, and the prevalence of human introductions of species) dictate that the model should not be used to make quantitative forecasts of increases in fish species number, quantitative scenarios are only possible where river discharge declines in scenarios.

Because the independent variable in the regression model (river discharge) is an output from WaterGAP, values of future discharge are subject to all the uncertainties described for WaterGAP. Appendix Table 6.12 summarizes the main sources of uncertainty.

Appendix Table 6.12. Overview of Major Uncertainties in the Freshwater Biodiversity Model

Model Component	Uncertainty
Model structure	assumption of log-linearity between number of fish species and river discharge
Parameter	uncertain coefficients of statistical model
Driving force	uncertainty of river discharge (see WaterGAP description)
Initial condition	uncertain current relationship between number of fish species and river discharge
Model operation	inclusion of only river discharge as independent variable

The model also assumes that all other features of the riverine habitat that are important biologically remain constant. This assumption is most certainly violated, but the magnitude of the consequences of any violation is impossible to ascertain. Violations would include changes in other aspects of river flow besides mean annual discharge (the timing and duration of low and high flows are also important to fishes), and the variety of other drivers (eutrophication, acidification, temperature, xenochemicals, habitat structure, other species in the food web, and so on) that would interact strongly with discharge. Finally, lag times of unknown duration would characterize the pace at which fish species numbers would equilibrate to lower discharge.

While the magnitude of error in scenarios is impossible to quantify, there are strong reasons to expect that the directions of errors are likely to produce underestimates of species loss (once species number equilibrates with reduced discharge levels). Reductions in species number are likely to be greater then predicted by the species-discharge model because interactions between discharge and other habitat features will change conditions away from those to which local species are adapted. Thus the species-discharge model will provide a conservative index of river-specific extirpation of fish species, as a function of the drivers that affect discharge (climate and water withdrawals).

Appendix 6.8 Multiscale Scenario Development in the Sub-global Assessments

As part of the MA's sub-global assessments, a number of scenario exercises were carried out in order to develop scenarios at regional scales. The number of sub-global assessments was limited by the available human and financial resources. Assessments were carried out in over 15 locations. (See Appendix Figure 6.8.) They have yielded scientific insights and policy-relevant information and prove the potential of the multiscale design of the MA.

Multiscale Design

Three of the sub-global assessments are themselves multiscalar. The SAfMA, PtMA, and CARSEA sub-global assessments contained nested assessments. Appendix Figure 6.8 depicts the designs of these three nested assessments. Each has opted for a slightly different design. In SAfMA, scenarios were developed for the Southern African Development Community region, for two large basins (particularly the Gariep basin) within SADC, and for a number of local small watersheds within these basins. The design was strictly hierarchical, although scenarios were developed independently. In Portugal, the design is not completely hierarchical and an attempt will be made to scale the national scenarios down to a very small community and to a single farm directly. National scenarios for PtMA are themselves downscaled from the global scenarios. In the Caribbean Sea assessment, scenarios were developed independently in two separate nested assessments. A link will be attempted after the scenarios have been fully developed.

Advantages of Multiscale Scenarios

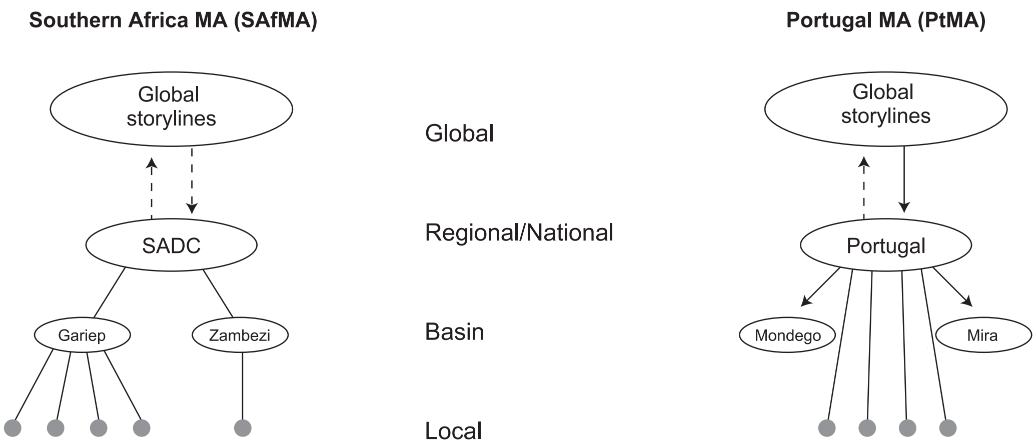
The advantages of generating multiscale scenarios are:

- *Global and local scenarios are linked.* A single approach for developing both global and local scenarios simultaneously produces a higher level of consistency and integration than if they were independently developed.
- *Different purposes to develop scenarios can be "merged."* Local adaptive management strategies can be compared with regional and global explorations of future changes in ecosystems and human well-being.
- *The audience for scenario results can be increased.* Scenarios can be effective tools for integrating and communicating complex information about ecosystem services and other subjects. Producing both global and local scenarios at the same time can in principle broaden the audience of MA results to include local indigenous people (through theater plays), local decision-makers (through models), and the national or international public (through newspapers) or policy-makers (through combined stories and models).

When to Focus on Single-Scale Scenarios?

Large amounts of resources—time and money—are required for multiscale scenario development, especially if it involves a high degree of stakeholder participation or an iterative process between stakeholders, scenarios writers, and modelers. When adequate resources are not available, it might be sufficient to develop scenarios at a single scale. Despite the advantages of multiscale scenarios, there are a number of situations in which the full development of multiscale scenarios might not prove to have a large added value. For example:

- *The importance of a local issue can be decoupled from issues at the global scale.* In the sub-global assessment in the Kristianstad wetlands in Sweden, recent flooding events put the question of coastal protection high on the local agenda. The main issue was whether dikes should be raised or natural area put aside as a flooding area.
- *The national government is dominant in the management of national resources.* Because China is very large and has many nationalities, the national government is dominant in the organization of national resources. Hence the sub-



Appendix Figure 6.8. Multiscale Design of the Sub-global Assessments in Southern Africa and Portugal

global assessment in western China accounted mostly for national rather than global actors in its analyses.

References

ACC/SCN (United Nations Administrative Committee on Coordination–Subcommittee on Nutrition), 1996: *Update on the Nutrition Situation*. ACC/SCN, Geneva.

Alcamo, J., P. Döll, T. Henrichs, F. Kaspar, B. Lehner, T. Rösch, and S. Siebert, 2003a: Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrological Sciences*. **48(3),** 317–337.

Alcamo, J., P. Döll, T. Henrichs, F. Kaspar, B. Lehner, T. Rösch, and S. Siebert, 2003b: Global estimation of water withdrawals and availability under current and ''business as usual'' conditions. *Hydrological Sciences*. **48(3),** 339–348.

Alcamo, J., 2001: *Scenarios as tools for international assessments,* Expert's corner report Prospects and Scenarios No. 5, European Environment Agency. Copenhagen, 31 pp.

Alcamo, J., T. Henrichs, and T. Rösch, 2000: *World Water in 2025—Global modeling and scenario analysis for the World Water Commission on Water for the 21st Century*. Report A0002, Center for Environmental Systems Research, University of Kassel, 48pp.

Alcamo, J., R. Leemans, and E. Kreileman (eds.), 1998: *Global change scenarios of the 21st century. Results from the IMAGE 2.1 model*. Pergamon & Elseviers Science, London, 296 pp.

Barthlott, W., N. Biedinger, G. Braun, F. Feig, G. Kier, and J. Mutke, 1999: Terminological and methodological aspects of the mapping and analysis of global biodiversity. Acta Botatica Fennica, **162,** 103–110.

Bouwman, A.F., D.P. van Vuuren, R.G. Derwent, and M. Posch, 2002: A global analysis of acidification and eutrophication of terrestrial ecosystems. *Water, Air and Soil Pollution*. **141,** 349–382.

Boyer, D. C. and I. Hampton, 2001: An overview of the living marine resources of Namibia. *South African Journal of Marine Science,* **23,** 5–35

Carpenter, S.R., 2002: Ecological futures: building an ecology of the long now. *Ecology,* **83(8),** 2069–2083.

Christensen, V. and C. Walters, 2004: Ecopath and Ecosim: methods, capabilities and limitations. In: *Methods for assessing the impact of fisheries on marine ecosystems of the North Atlantic*. Pauly, D. and T.J. Pitcher (eds.), Fisheries Centre Research Report, **8(2),** 79–105.

Christensen, V. and D. Pauly, 1992: Ecopath II—a software for balancing steady-state ecosystem models and calculating network characteristics. *Ecological Modelling*, **61(3/4),** 169–185.

Cosgrove, W., and F. Rijsberman, 2000: *World Water Vision: Making water everybody's business*. Earthscan Publications, Ltd., London, 108 pp.

Cox, S. P., S. J. D. Martell, C. J. Walters, T. E. Essington, J. F. Kitchell, C. Boggs, and I. Kaplan, 2002: Reconstructing ecosystem dynamics in the central Pacific Ocean, 1952–1998. 1. Estimating population biomass and recruitment of tunas and billfishes. *Canadian Journal of Fisheries and Aquatic Sciences,* **59,** 1724–1735.

CPB (Centraal Planbureau), 1999: *WorldScan: The Core Version*. CPB Netherlands Bureau for Economic Policy Analysis, The Hague, 137 pp.

de Vries, B., J. Bollen, L. Bouwman, M. den Elzen, M. Janssen, and E. Kreileman, 2000: Greenhouse gas emissions in an equity-, environment- and service-oriented world: an IMAGE-based scenario for the 21st century. *Technological Forecasting and Social Change,* **63,** 137–174.

Delgado, C., N. Wada, M. Rosegrant, S. Meijer, and M. Ahmed, 2003: *Fish to2020: Supply and demand in changing global markets*. International Food Policy Research Institute and WorldFish Center, Malaysia, 226 pp.

Delgado C., M. Rosegrant, H. Steinfeld, S. Ehui, and C. Courbois, 1999: *Livestock to 2020 the next revolution*. Food, Agriculture and the Environment Discussion Paper 28, IFPRI, Washington DC.

Döll, P., F. Kaspar, and B. Lehner, 2003: A global hydrological model for deriving water availability indicators: model tuning and validation. *Journal of Hydrology,* **270,** 105–134.

FAO (Food and Agriculture Organization of the United Nations), 2000: FAOSTAT Statistics Database. [online] Rome. Cited May, 2004. Available at http//www.fao.org/FAOSTAT.

FAO/FISHCODE, 2001: *Report of a bio-economic modeling workshop and a policy dialogue meeting on the Thai demersal fisheries in the Gulf of Thailand,* 31 May–9 June 2000, Hua Hin, Thailand, FI:GCP/INT/648/NOR: Field Report F-16 (En), Rome, FAO, 104 pp.

Funtowicz, S. O. and J. R. Ravetz, 1993: Science for the post-normal age. *Futures,* **25(7),** 739–755.

Glenn, J., T. Gordon (eds.) 2005: Futures research methodology. Version 2.0. AC/UNU Millennium Project. United Nations University Press.

Guegan, J.F., S. Lek., T. Oberdorff, 1998: Energy availability and habitat heterogeneity predict global riverine fish diversity. *Nature,* **391(6665),** 382–384

Harasawa, H., Y. Matsuoka, K. Takahashi, Y. Hijioka, Y. Shimada, Y. Munesue, and M. Lal, 2002: Potential impacts of global climate change, In: *Climate Policy Assessment—Asia-Pacific Integrated Modeling,* Kainuma, M., Matsuoka, Y., and Morita, T. (eds.). Springer, Tokyo, pp. 37–54.

Hawkins, B.A., Field, R., Cornell, H.V., 2003: Energy, water, and broad-scale geographic patterns of species richness. *Ecology,* **84(12),** 3105–3117.

Heymans, J.J., L.T. Shannon, and A. Jarre, 2004: Changes in the Northern Benguela ecosystem over three decades: 1970s, 1980s and 1990s. *Ecological Modelling,* **172(2–4),** 175–196.

Holling, C. S., (ed.), 1978: *Adaptive Environmental Assessment and Management*. John Wiley & Sons, London, 377 pp.

IMAGE-team, 2001: The IMAGE 2.2 implementation of the SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st century [CD-ROM], RIVM CD-ROM publication 481508018, National Institute for Public Health and the Environment, Bilthoven, the Netherlands.

IPCC (Intergovernmental Panel on Climate Change), 2000a: Special Report on Emission Scenarios. A Special Report of IPCC Working Group III. Edited by N. Nakićenović and R. Swart. *Cambridge University Press,* Cambridge, United Kingdom.

IPCC, 2000b: *Special Report on Emissions Scenarios*. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

Kainuma, M., Y. Matsuoka, and T. Morita, 2002: Climate Policy Assessment. Springer, Tokyo, 432 pp.

Kram, T., T. Morita, K. Riahi, R.A. Roehrl, S, van Rooien, A. Sankowski, and B. De Vries, 2000: Global and Regional Greenhouse Gas Emissions Scenarios. *Technological Forecasting and Social Change,* **63(2–3**), 335–372.

Leemans, R., B. Eickhout, B. Strengers, L. Bouwman, and M. Schaeffer, 2002: The consequences of uncertainties in land use, climate and vegetation responses on the terrestrial carbon. In: *Land Use/Cover Change Effects on the Terrestrial Carbon Cycle in the Asia-Pacific Region,* Science in China, Vol. 45, J.G. Canadell, G. Zhou, I. Noble (eds.), pp. 126–141.

Levin, S. A., 2000: *Fragile dominion: complexity and the commons,* Perseus Publishing, Reading, MA, 256 pp.

MA (Millennium Ecosystem Assessment), 2003: *Ecosystems and Human Well-Being: A Framework for Assessment.* Island Press, Washington, DC.

Masui, T., Y. Hijioka, K. Takahashi, J. Fujino, Y. Matsuoka, H. Harasawa, and T. Morita, Analysis of economic instruments for global natural conservation, forthcoming.

Moss, R.H. and S.H. Schneider, 2000: Uncertainties in IPCC TAR. Recommendation to Lead Authors for more consistent Assessment and Reporting. In: *Guidance papers on the cross cutting issues of the Third Assessment Report of IPCC,* R. Pachuari, T. Taniguchi, and K. Tanaka (eds.), Geneva, Switzerland, World Meteorological Organization, 33–51.

Oberdorff T., J.F. Guégan, and B. Hugueny, 1995: Global scale patterns of fish species richness in rivers. *Ecography,* **18,** 345–352.

Olson, D. M., E. Dinerstein, E.D. Wikramanayake, N.D. Burgess, G.V.N. Powelle, E.C. Underwood, J.A. D'amico, I. Itoua, H.E. Strand, J.C. Morrison, C.J. Loucks, T.F. Allnutt, T.H. Ricketts, Y. Kura, J.F. Lamoreux, W.W. Wettengel, P. Hedao, K.R. Kassem, 2001: Terrestrial ecoregions of the world: A new map of life on Earth. *BioScience,* **51(11),** 933–938.

Pauly, D. and R. Chuenpagdee, 2003: Development of fisheries in the Gulf of Thailand large marine ecosystem: Analysis of an unplanned experiment. In: *Large Marine Ecosystems of the World: Change and Sustainability,* G. Hempel and K. Sherman (eds.) Elsevier Science.

Pauly, D., V. Christensen, and C. Walters, 2000: Ecopath, Ecosim, and Ecospace as tools for evaluating ecosystem impact of fisheries. *ICES Journal of Marine Science,* **57(3),** 697–706.

Peterson, G.D., Cumming, G.C., and S.R. Carpenter, 2003: Scenario Planning, a tool for conservation in an uncertain world. *Conservation Biology,* **17,** 358–366

Prentice, I.C., W. Cramer, S.P. Harrison, R. Leemans, R. A. Monserud, and A. M. Solomon, 1992: A global biome model based on plant physiology and dominance, soil properties and climate. *Journal of Biogeography,* **19,** 117–134

Raskin, P., G. Gallopin, P. Gutman, A. Hammond, and R. Swart, 1998: Bending the curve: toward global sustainability. Stockholm Environment Institute. Lilla Nygatan 1. Box 2142, S-103, Stockholm, Sweden.

Rosegrant, M.W., X. Cai, and S. Cline, 2002: *World Water and Food to 2025: Dealing with Scarcity.* International Food Policy Research Institute, Washington, DC, 310 pp.

Rosegrant, M.W., M. Paisner, S. Meijer, and J. Witcover, 2001: *Global Food Projections to 2020: Emerging Trends and Alternative Futures.* International Food Policy Research Institute. Washington, DC, 206 pp.

Rosegrant, M.W. and C. Ringler, 2000: Asian economic crisis and the long-term global food situation. *Food Policy* **25(3),** 243–254.

Sala, O.E., F.S. Chapin III, J.J. Armesto, R. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L.F. Huenneke, R.B. Jackson, A. Kinzig, R. Leemans, D. Lodge, H.A. Mooney, M. Oesterheld, N.L. Poff, M.T. Sykes, B.H. Walker, M. Walker, and D.H. Wall, 2000: Global biodiversity scenarios for the year 2100. *Science,* **287,** 1770–1774.

Sarewitz, D., R.A. Pielke Jr., and R. Byerly Jr., 2000: *Prediction—Science, Decision Making, and the Future of Nature.* Island Press, Washington DC, 405 pp.

Scott, G.J., M.W. Rosegrant, and C. Ringler, 2000: *Roots and Tubers for the 21st century: Trends, projections, and policy options.* 2020 Vision for Food, Agriculture, and the Environment Discussion Paper No. 31. International Food Policy Research Institute, Washington, DC, 2pp.

Smith, L. and L. Haddad, 2000: *Explaining Child Malnutrition in Developing Countries: A Cross-Country Analysis.* Research Report 111. International Food Policy Research Institute, Washington, DC, 112 pp.

Takahashi, K., H. Harasawa, Y. and Matsuoka, 1997: Climate change impact on global crop production, *Journal of global environmental engineering,* **3,** 145–161.

UN (United Nations), 1998: *World Population Prospects: 1998 Revisions.* United Nations, New York.

UNEP (United Nations Environment Programme), 2002: *Global Environmental Outlook 3, Past, present and future perspectives.* UNEP and Earthscan Publications Ltd, 446 pp.

Van der Heijden, K., 1996: *Scenarios: The Art of Strategic Conversation.* Wiley, NY.

Van Minnen, J., R. Leemans, and F. Ihle, 2000: Defining the importance of including transient ecosystem responses to simulate C-cycle dynamics in a global change model. *Global Change Biology,* **6,** 595–612.

Van Vuuren, D.P. and H.J.M. De Vries, 2001: Mitigation scenarios in a world oriented at sustainable development: the role of technology efficiency and timing. *Climate Policy,* **1,** 189–210.

Walters, C. J., J.F. Kitchell, V. Christensen, and D. Pauly, 2000: Representing density dependent consequences of life history strategies in aquatic ecosystems: EcoSim II. *Ecosystems,* **3,** 70–83.

Walters, C., V. Christensen, and D. Pauly, 1997: Structuring dynamic models of exploited ecosystems from trophic mass-balance models of marine ecosystems. *Reviews in Fish Biology and Fisheries,* **7(2),** 139–172.

WHO (World Health Organization), 1997: *WHO Global Database on Child Growth and Malnutrition.* Program of Nutrition. WHO Document WHO/NUT/97.4. World Health Organization, Geneva.

World Bank, 2000a: World Development Indicators [CD-Rom] The World Bank, Washington, DC.

World Bank, 2000b: *Global Commodity Markets: A Comprehensive Review and Price Forecast.* Developments Prospects Group, Commodities Team. The World Bank, Washington DC.

World Bank, 1998: World Development Indicators [CD-Rom] The World Bank, Washington, DC.