Chapter 13

Lessons Learned for Scenario Analysis

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FIGURES

Main Messages

The Millennium Ecosystem Assessment scenarios build on earlier scenarios and modeling efforts and also extend scenario analysis to include ecosystem services and their consequences for human well-being, which has not been done before. The main objectives of the MA scenarios are to assess future changes in world ecosystems and resulting ecosystem services over the next 50 years and beyond, to assess the consequences of these changes for human well-being, and to inform decisions-makers at various scales about these potential developments and possible response strategies and policies to adapt to or mitigate these changes. These objectives are reflected in the overall approach and are an integral part of the four narrative and quantitative scenarios about alternative futures.

MA scenarios further refine and extend a number of recent methodological improvements in the scenario formulation process. These include integration across social, economic, environmental, and ecosystems dimensions; disaggregation across multiple scales of global patterns down to regional and in some cases also place-specific developments; multiple futures across four alternative scenarios to reflect deep uncertainties of long-range outcomes; and quantification of key variables linked to ecosystem conditions and ecosystem services along alternative narrative storylines. In addition, the MA scenarios make four important new contributions: They extend the integrated assessment approaches to include ecosystem services and their consequences on human well-being. They model explicitly changes in biodiversity as an integral part of scenario development. They assess interactions and trade-offs among ecosystem services. And they assess possible replacement of some ecosystem services by other services and the emergence of new ways of providing these services, such as through technological change.

MA scenarios establish another important precedent in adopting the long time horizon of 50 years, and for some variables, a century. Many salient but slow trends in ecosystems will only become visible over this long time period, but decisions influencing these trends have already been taken or will be taken in the immediate future. Integrated scenarios, which portray human activities together with ecosystem dynamics, are the main tool available for the assessment of alternative futures and possible response strategies. Increasingly, long time horizons and global perspectives are required to understand complex interactions between human and ecological systems.

The MA scenarios provide rich and useful images of broad patterns of possible futures at the global scale and at the level of major world regions. However, the models are not able to perform detailed analyses of local processes and impacts. One possible remedy and a crucial improvement for similar future assessments in terms of usability for several stakeholders would be to "soft-link" sector- and region-specific models by using the global scenario framework and outputs of global models to drive them. A particularly useful feature of the present effort is that scenarios provide the information about the socioeconomic and technological development patterns that is necessary for the assessment of the viability and effectiveness of various instruments and response strategies currently available or that might become available in the future to different stakeholder groups.

A key goal of the MA scenarios is to help decision-makers gain a better understanding of the intended and unintended effects of various policy measures for maintaining ecosystem services and human well-being simultaneously. Human activities have become an important co-determinant of Earth systems, and decisions made now and in the immediate future will have consequences across both temporal and spatial scales. Alternative futures described in the MA scenarios are subject to human choices, both those already made and those to be made in the future. Multiple dynamics of change characterize human activities and ecological systems. Bringing these interactions to the foreground is one of the main goals of the MA scenarios.

While basic human conditions generally improve across three scenarios and decline for some people in one scenario, they all portray, to a varying extent, perilous paths of ecosystems change. This illustrates complex linkages and feedbacks of ecosystem service changes on human well-being. While material elements of human well-being generally increase, loss of ecosystem services leads to higher inequalities in some of the scenarios and even degradation of some aspects of human well-being in others. Degradation and loss of some ecosystem services also affects the trade-offs and relations between provisioning and regulating functions of ecosystems. This is one central and important development pattern shared by all four scenarios.

The paths of the four scenarios are fundamentally different. Each scenario includes inherent path-dependencies and irreversibilities that are the results of the long response times and cumulative nature of many changes that affect ecosystem services and human well-being. The scenarios do not converge, though the possibility exists that decisions could be made in one scenario to make it evolve (or branch out) into an alternative future resembling one of the other MA scenarios. They differ with respect to many of the drivers of global change identified by the MA. In particular, the scenarios differ with respect to whether the world becomes more or less interconnected and whether environmental management is reactive or proactive.

Land use changes are perhaps the most critical aspect of anthropogenic global change in influencing the future of ecosystems and their services. Nevertheless, indirect effects on future ecosystem services, which can potentially result from other global changes (climate change, biodiversity loss), will also be of importance and superimposed on effects of land use changes. In the four MA scenarios, land use changes will directly determine many of the provisioning and regulating functions of ecosystems. These will depend on the future changes in biodiversity, desertification, or wetlands—all a function of land use changes. Land use patterns are in turn directly dependent on some of the main scenario driving forces, such as demographic, economic, and technological changes.

The models used to quantify the MA scenarios were unable to explore or elaborate on the evolutionary path-dependencies among anthropogenic system and ecosystem development, possible emergence of thresholds, and the specific dynamics caused by bifurcations. The current quantitative methodological approaches are not well suited for assessment of cross-scale phenomena such as place-specific developments in relation to regional and global ones. Extending the scenario development to more than one set of integrated models might better encompass some of the deep uncertainties associated with alternative futures and the resulting ecosystem services. Since the qualitative development of the MA scenarios was able to address path-dependencies, thresholds, and bifurcation dynamics, the storylines should be consulted for additional depth and richness about path-dependencies, thresholds, and cross-scale feedback.

Important lessons learned in the development of the MA scenarios could help improve the development of global storylines in any future assessments:

- Development of regional and more place-specific scenarios would help inform and create better global scenarios. Regional scenarios can use more accurate local information to develop scenarios and might represent system dynamics more accurately. They can also pinpoint specific variables of interest.

- Better communication and interaction with policy-makers would help inform the development of the storylines by indicating the key variables that are of interest to decision-makers. This would be useful both for understanding which are the most pressing questions of policy-makers as well as for communicating results to policy-makers at the end of the process. Having more policy-makers and decision-makers within the working group may be one way to improve this communication.

- Improved communication and interaction across scientific disciplines would improve future scenarios. Differences among disciplines' core beliefs about how the world functions were also often the critical issues that policy-makers wanted to have addressed in the scenarios. Better interdisciplinary communication prior to initiation of future assessments might make an exceedingly complex process a bit easier.

13.1 Introduction

The main objectives of the MA scenarios are to assess changes in ecosystems and their services over the next 50 years and beyond, to assess the consequences of these changes for human well-being, and to inform diverse decisions-makers about these potential developments and how they can affect them through response strategies and policies. These objectives, as stated in Chapter 5, are reflected in the overall approach used to develop the new MA scenarios. The objectives are an integral part of the basic assumptions about the future of the main driving forces of the four scenarios.

The scenarios do not attempt to describe all possible futures that can be imagined. The MA scenario paths were developed to provide plausible answers to the major uncertainties and focal questions about the future of socioecological systems. (See Chapter 5.) In addition, the scenarios systematically follow through a number of assumptions and management approaches currently discussed by decision-makers around the world. The quantification of changes in ecosystem services across the four scenarios are based on an integrated modeling framework, which uses an existing set of models, but with new linkages designed explicitly to reflect the main objectives of the MA scenarios. A brief summary of the four scenarios and their main characteristics is given in the SDM. Chapters 8, 9, 10, and 11 synthesize a wide range of social, economic, environmental, and policy implications of changes in ecosystem services on human well-being, and include an assessment of possible policy responses to these changes.

The MA scenarios have been conceived and developed to provide insights into a broad range of potential future ecosystem changes. The objective was to portray plausible developments that are internally consistent rather than those that may be considered to be desirable or undesirable. The idea of what is "negative" or "positive" in any given scenario is inherently dependent on the eye of the beholder and thus highly subjective. Therefore, great attention was given in previous chapters to presenting both positive and negative aspects in the scenarios. Uniting only "positive" or "negative" features in a scenario would result in homogeneous and "unidimensional" futures that may not be plausible and consistent.

The overall objectives, scenario formulations, and development of the MA scenarios are new. However, our approach builds on previous scenarios and modeling efforts in the literature. The new and innovative element is the focus on ecosystem services and human well-being. The MA scenarios distinguish between provisioning, regulating, supporting, and cultural ecosystem services (MA 2003). Access to ecosystem services is one of several factors affecting human well-being, which is considered along a multidimensional continuum—from extreme deprivation or poverty to a high attainment of experience of well-being—and has five major components: material well-being, health, good social relations, security, and freedom and choice (MA 2003, Chapter 3). Human well-being is context-dependent, reflecting factors such as age, culture, geography, and ecology.

Many insights were gained in the process of developing scenarios that focus on ecosystem services and human well-being. In the models used to quantify the MA scenarios, land use changes were perhaps the most critical aspect of anthropogenic global change in influencing the future of ecosystems and their services. As a first approximation, the results of MA scenarios modeling exercises suggest that land use changes directly determine many of the provisioning and regulating functions of ecosystems. These will depend on future changes in biodiversity, desertification, or wetlands, all a function of land use changes. Land use patterns are in turn directly dependent on some of the main scenario driving forces such as demographic, economic, and technological change. Another important finding across all scenarios is that indirect effects on future ecosystem services that might result from other global changes, such as those of climate, will be of secondary importance compared with land use changes. In the scenarios, the global changes generally tend to amplify effects, especially the adverse consequences of changes in ecosystem services.

The MA scenarios also have important weaknesses that point to potential areas for future improvements. Many needed improvements relate to our ability to quantify the future of ecosystem services. These include improving capabilities for modeling ecosystem services and human well-being, especially for supporting and cultural ecosystem services; consideration of the consequences of a larger range of driving forces; and more-explicit treatment of the deep uncertainties associated with alternative futures, especially those related to quantifying ecosystem services.

Perhaps the most important deficiency in the new scenarios is that the current models are not well suited for the assessment of cross-scale phenomena such as place-specific developments in relation to regional and global ones. This means that the models are not able to sufficiently explore the evolutionary path-dependencies among anthropogenic systems and ecosystem developments or the possible emergence of resilience or irreversibilities. However, many of the cross-scale feedbacks and many other scenario characteristics that could not be captured by models were treated in greater detail in the narrative storylines. Extending scenario development to more than one set of integrated models might be another way to better encompass some of the deep uncertainties associated with alternative futures and the resulting ecosystem services.

13.2 New Contributions of the MA Scenarios

The MA scenarios make a number of new contributions to the method of scenario analysis for exploring (inherently unknown) alternative futures, to the process of how scenarios are developed, and to the inclusion of an integrated assessment of ecosystem services and human well-being.

13.2.1 An Analytical Typology of the MA Scenarios

The MA was developed in the context of major advances in the methodology of scenario analysis. Figure 13.1 shows a typology for assessment based on the distinction made by Rayner and Malone between descriptive social science research, based on an analysis of mostly quantitative energy and material flows, and interpretive social science, focused on the values, meaning, and motivations of human agents (Rayner and Malone 1988; see also Robinson and Timmerman 1993). The figure further distinguishes between more global and more local analysis and attempts to indicate typical forms of analysis that correspond to the four quadrants identified. The distinctions among the quadrants shown in Figure 13.1 underlie many of the problems of interdisciplinary communication and analysis in the sciences. It is well known that it is difficult to combine, for example, interpretive place-based analysis of human motivations with, say, a quantitative analysis of energy systems and emissions. Much of the early work in the climate field, whether global or local, was located on the descriptive side of the typology.

It is particularly noteworthy therefore, that recent developments in scenario analysis are beginning to bridge this difficult gap (Morita and Robinson 2001; Swart et al. 2004; see also Chapter 2). Over the past decade, the global scenario analysis community has begun to combine the primarily qualitative and narrative-based scenario analyses undertaken by Royal Dutch/Shell and other companies (Wack 1985a, 1985b; Schwartz 1992) with global modeling work in the form of analyses that bring together the development of detailed narrative storylines with their ''quantification'' in various global models (Raskin et al. 1998; Nakićenović et al. 2000). For example, the Special Report on Emissions Scenarios work (Nakićenović et al. 2000), undertaken for the Intergovernmental Panel on Climate Change, cut across the interpretive/descriptive divide, though it still focused mainly on the global and regional level.

	Local	Global
Interpretive	place-based case studies	global storylines
Descriptive	regional science	global modeling

Figure 13.1. Analytical Typology of Scenarios Analysis. This figure illustrates local and global scenarios exercises and exercises that are more based on interpretive, qualitative, or descriptive modeling-based approaches.

As shown in Figure 13.2, the MA scenarios work also cuts across the divide between interpretive and descriptive research by combining narrative storylines and quantitative modeling. However, it also begins to reach across the global/local gap, with a stronger focus on local analysis of ecosystem effects. This was mainly accomplished by incorporating information from a few of the sub-global assessments in the global scenario effort and vice versa. Also, a few methodological steps were explored to link or nest the development of the local, regional, and global scenarios. Linking and nesting different scale scenario exercises is a field that needs further exploration in the future. In this way, the MA work contributes to the trend toward more integrated and more interdisciplinary work on the relationships among human and natural systems.

Figure 13.2 demonstrates the place of the MA analysis along two axes describing the geographical scale of work and the degree to which the scenarios are based on interpretive, qualitative storylines or grounded in model-based descriptions. The MA scenarios combine the storyline approach with a modeling exercise. (See Chapter 6.) The four scenarios presented in this volume are primarily global scenarios, but the MA did go one step in the direction of developing multiscale scenarios (MA *Multiscale Assessments,* Chapter 10).

13.2.2 Contributions to the Process of Scenario Development

The MA further refined and extended a number of recent methodological improvements in the scenario formulation process. They include integration across social, economic, environmental, and ecosystems dimensions; disaggregation across multiple scales of global patterns down to regional and in some cases also place-specific developments; multiple futures across four alternative scenarios to reflect deep uncertainties of long-range outcomes; and quantification of key variables linked to ecosystem conditions and ecosystem services along alternative narrative storylines (See Chapter 2).

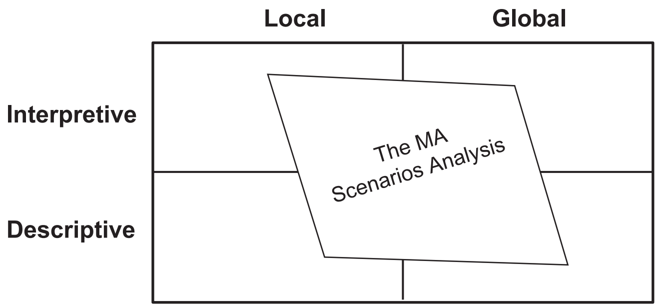

Figure 13.2. Placing of MA Scenarios Analysis in Analytical Typology. For a description of the typology see Figure 13.1.

Integration across dimensions is needed because multiple anthropogenic stresses have an impact on the environment via direct driving forces such as pollution, climate and hydrological change, resource extraction, and land use changes, and they play an important role in co-determining future evolution of ecosystems. These changes in direct drivers result from long causal chains of indirect drivers such as population, economic, and technological patterns, that are, in turn, conditioned by such ultimate drivers as human values, culture, interest, power, and institutions. To capture this nexus of interactions and emergent systems properties, a systemic framework is required that includes the key driving forces, possible consequences of their unfolding or collapse, and feedbacks. (See Chapter 1.) MA scenarios achieve this by introducing these integrative elements:

- formulation of extensive narrative stories, or storylines, of four alternative sets of main driving forces to 2050 and beyond to provide a context for unfolding ultimate drivers and impacts on ecosystem services and human well-being;
- quantification of the narrative storylines by extended integrated assessment models that include quantitative assessment of biodiversity, water, and fisheries; and
- qualitative assessment of possible trade-offs among ecosystem services and substitutions by other services, the implications for human well-being, and possible policy responses.

Many of these integrative elements are present in other scenarios in the literature, but the emphasis on and integration of ecosystem services and human well-being is new.

Disaggregation across multiple scales is essential because multiple interactions between anthropogenic and ecological systems occur within and across scales from global and regional to local and place-specific levels. These different spatial scales are often associated with characteristically different temporal scales and provide mutually enhancing perspectives into possible futures. Many of the relevant global processes operate over very long time periods ranging from decades to centuries, and their impacts on human well-being are usually indirect and complex but fundamental, in some cases even threatening human existence itself. In contrast, place-specific and local processes are usually much more direct in the ways that they affect human well-being, such as health, air and water quality, or nutrition.

Scientific capabilities to model links across temporal and spatial scales are very modest. Often such attempts are reduced to disaggregating global development into a (small) number of global regions. Narrative storylines are richer in the sense that they can provide apparently seamless connections across multitudes of scales, but compared with numerical and analytical models they are not quantitative and do not provide reproducibility under varying assumptions about main driving forces. In Chapter 2, the hope was expressed that perhaps future scenario-building techniques and models would evolve to allow seamless views across scales and levels of analysis, representing each spatial unit as an interacting component of an integrated global system. The MA scenarios provide a first step in this direction by providing, for example, quantitative links between different scales of land use patterns, climate change, and biodiversity. Another method of bridging across scales is more anecdotal and is provided in Chapter 10, where some place-specific, scenario-dependent developments of marine biodiversity are briefly described for places such as the Gulf of Thailand and the North Pacific.

Multiple futures are fundamental to any scenario enterprise, because prediction of complex and evolving systems is not possible. They are required for indicating the range of plausible futures and for encompassing some of the deep uncertainties associated with the evolution of complex systems. Examples of deep uncertainties are nonlinear responses of complex systems, emerging properties and path-dependencies, and generally unpredictable behavior that emerges due to branching points, bifurcations, and complex temporal and spatial dynamics. Complex systems are inherently unpredictable, especially when human response strategies that have yet to be defined are involved.

The overall time horizon of the four MA scenarios is to 2050 and beyond. Such long time horizons are required to encompass fundamental changes in anthropogenic and ecological systems and their interactions. It is likely that they will unfold in unexpected ways and will embody important surprises. Such surprises could include unexpected emergent properties, path-dependencies, and the crossing of critical thresholds, leading to irreversibilities. Given the modest modeling techniques available today, development of a rich set of alternative scenarios is the main method used to encompass these different possibilities and the associated uncertainties. This approach is also followed in the four MA scenarios. In addition to the quantitative formulation of many of the alternative scenario characteristics with an extended integrated assessment modeling framework, the MA scenarios also have elaborate narratives that extend across a multitude of levels and scales. They provide the background information about the main driving forces, the associated fundamental drivers, and their consequences. In this way, they link various analytical and numerical methods that are not (yet) an integral part of the IAM used to quantify the four scenarios.

The long time horizon for the scenarios of 2050 and beyond extend the state-of-the-art in scenario building. Such long time horizons were used first in the scenarios for assessing anthropogenic climate change, its impacts, and possible response strategies. The time horizon of a century or more was imposed by long-time constants in the climate system response to anthropogenic forcing, such as the emissions of greenhouse gases, aerosols, and particulate matter. In contrast, most of the economic scenarios, whether global, regional, or national, are associated with relatively short time horizons of a decade or two at most; this does not allow for fundamental changes in economic system, but it does capture the accumulation of more gradual and incremental changes based on current trends and tendencies. Demographic scenarios are usually somewhere in between due to the large inertia associated with population momentum and slow cumulative changes arising from migration patterns or the emergence of pandemics. Fundamental technological, institutional, and infrastructure changes can also take many decades or centuries, so that scenarios of the possible emergence and diffusion of new technologies usually have time horizons of 50 years or more. Integrated climate scenarios that included possible human response strategies were the first applications of integrated scenarios with time horizons of century or more.

The MA scenarios establish another important precedent in adopting a similarly long time horizon so as to encompass alternative future developments of ecosystem services and human well-being. This is important not merely because some of the ecosystem services such as biodiversity may significantly decrease over these longer time horizons, threatening at least some aspects of human well-being, but also because these futures are subject to human choices that have not yet been made. It is difficult to separate all complex interactions that co-determine changes in human well-being components related to biodiversity.

So far it is not possible to quantify all these interactions, but an innovative part of the MA is a first attempt in this direction. Decision-makers and various stakeholders need to understand how policies and other measures can influence and affect future provision of ecosystem services and human well-being. Human activities have become an important co-determinant of Earth systems, and decisions made now and in the immediate future will have consequences across both temporal and spatial scales. Integrated scenarios are the main tool available for the assessment of alternative future developments and possible response strategies. Increasingly, long time horizons and global perspectives are required to understand complex interactions between human and natural systems.

The combination of narrative storylines and their quantification in integrated scenarios of alternative futures is the main method for capturing complexity and uncertainty and transcending limits of conventional deterministic models of change. (See Chapter 2.) MA scenarios address a highly complex set of interactions between human and natural systems, a scientific challenge that is compounded by the cumulative and long-term character of the phenomena. While the world of many decades from now is indeterminate, scenarios offer a structured means of organizing information and gleaning insight into the possibilities. Scenarios can draw on both science and imagination to articulate a spectrum of plausible visions of the future and pathways of development. Some characteristics of the MA scenarios are assumed to evolve gradually and continuously from current social, economic, and environmental patterns and trends; others deviate in fundamental ways. A long-term view of a multiplicity of future possibilities is required in order to be able to consider the ultimate risks of maintaining adequate ecosystem services, assess critical interactions with other aspects of human and environmental systems, and guide policy responses.

The development of methods to effectively blend quantitative and qualitative insights is at the frontier of scenarios research today. The narrative storylines give voice to important qualitative factors shaping development such as values, behavior, and institutions, providing a broader perspective than is possible by analytical and numerical modeling alone. (See Chapter 2.) Storylines are rich in detail, texture, metaphors, and possible insights, while quantitative analysis offers structure, discipline, rigor, and reproducibility. The most relevant recent efforts are those that have sought to balance these attributes. They provide important insights into how current tendencies and trends might become amplified in different future worlds across the four storylines and provide a multitude of different details across scales and systems. They are embedded in extensive assessment of the main driving forces and their future developments across scenarios in the literature. (See Chapter 7.)

13.2.3 Ecosystem Services and Human Well-being Development Paths across Scenarios

The MA scenarios make four important new contributions to the contents of global environmental scenarios exercises compared with the literature:

- extending the integrated assessment approaches to include ecosystem services and their consequences on human well-being;
- modeling changes in biodiversity as an integral part of scenario development;
- assessing the interactions and trade-offs among ecosystem services; and
- assessing the possible replacement of some ecosystem services by others and the emergence of new ways of provisioning of these services, such as through technological change.

Perhaps the most important new contribution of MA scenarios to global scenario analysis is the extension of integrated assessment and modeling of alternative futures to explicitly include ecosystems and their services and human well-being. The vast body of environmental scenarios literature deals primarily with climate-related issues. The first integrated assessment models and frameworks were developed to link driving forces to possible climate change consequences, including impacts of climate changes, and various response strategies, including mitigation and adaptation.

Figures 13.3 and 13.4 compare the MA modeling system to that of the IPCC, which is an integrated assessment of

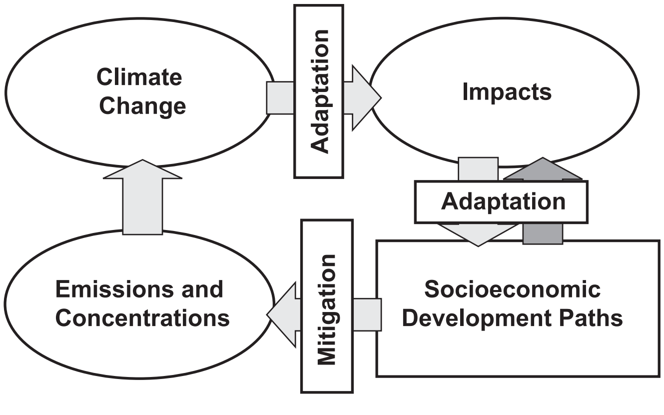

Figure 13.3. Integrated Assessment Framework of Intergovernmental Panel on Climate Change (IPCC 2001)

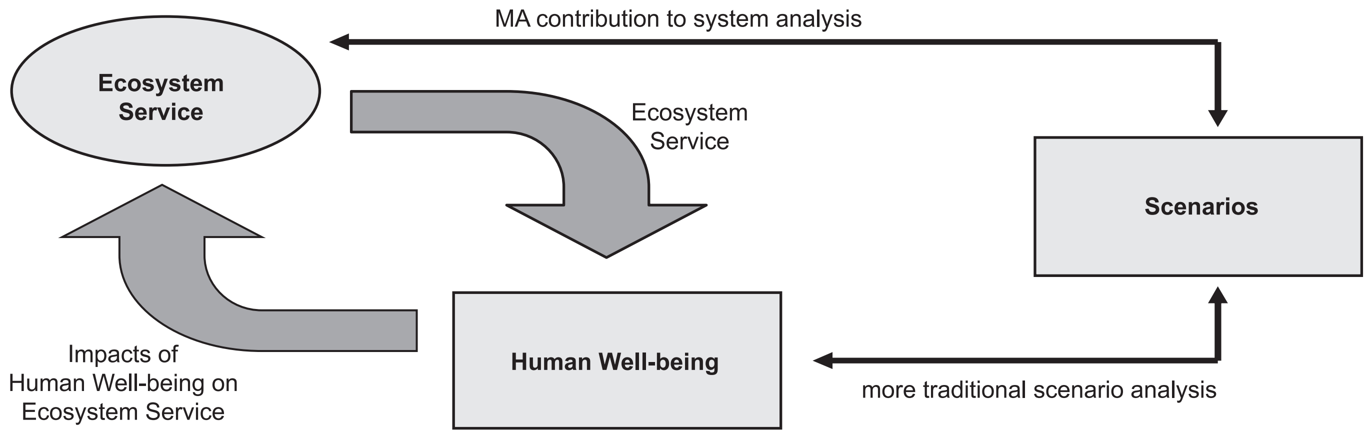

Figure 13.4. Approach and Contributions of MA to Focus of Scenarios Development

climate change that takes account of the human drivers of, and responses to, changes in the physical climate system. The MA scenarios add a new element by exploring feedbacks from the responses to environmental change to the drivers that affect this change. Prior to the MA, the majority of scenario exercises explored changes in socioeconomic systems and their impacts on the variable of interest (such as climate change or water supply and quality). This approach was enhanced in the MA scenarios by focusing on parallel changes in ecosystem services and human systems and their impacts on one another. Figure 13.4 demonstrates this new approach to integrating across the various driving forces and simultaneously describing the feedback loops within the socioecological system.

In some sense, there is a symmetry between integrated approaches to assess future climate change and the MA approach to assessing future ecosystem changes. MA scenarios extend the state-of-the-art by including both an integrated treatment of climate and ecosystems change as well as the resulting changes in ecosystem services and human well-being. However, they do not explicitly deal with the ethical dimension of the social developments suggested by some of the scenario features. For example, the scenarios do not provide details on possible implications for equity or lifestyle changes, but they directly address changes in human well-being that result from changes in ecosystem services. While the perspective of services is not new in itself, the explicit inclusion of a multitude of ecosystem services in MA scenarios is unique in scenario analysis. Assessing multiple ecosystem services is a formidable task because ecosystem services do not act in isolation; they interact with one another and with anthropogenic systems in complex and usually unpredictable ways.

Technology and institutions also play a role in the provision of ecosystem services; the nature of the interaction between ecosystems, technology, and institutions is not always entirely clear, however. The MA scenarios also address the issue of the extent to which alternative services, derived from new technologies, institutions, and other human activities, offer new solutions to improve the efficiency, accessibility, affordability, and quality of the provision of ecosystem services.

It may be easy to replace some services with others or to improve their provision through technological or institutional advances. More often, however, ecosystem services may not be easily substitutable by other services. Thus the degree to which the provision of ecosystem services can be improved and pressure on ecosystems reduced by technologically generated alternatives is highly uncertain. It will depend on what services are demanded in the future, what new technologies are available, and what other ecosystem services are (purposefully or accidentally) traded off by the substitution processes. (See Chapter 12.)

It is true that future technologies may offer feats that are impossible or prohibitively expensive today. The costs of many technologies are likely to decrease, making their widespread diffusion possible and affordable. However, some technologies may have unpleasant and unexpected negative effects and cause unanticipated interactions among ecosystem services. Similarly, currently unknown ecosystem services, or those considered to be less important, may be found to be fundamental to people or the future maintenance of ecosystems. These are some of the dimensions of ecosystem change that are addressed across the four MA scenarios.

While an important step forward, the MA scenarios work is incomplete. Particularly the quantitative analyses of ecosystem services and human well-being were driven by the underlying scenario analysis, with no explicit modeling feedbacks from those analyses back to the underlying anthropogenic driving forces. In other words, while in the quantitative models changes in ecosystems affect ecosystem services and human well-being, changes in ecosystem services and human well-being do not lead to further changes in the anthropogenic drivers of change. These feedbacks were, however, included in the narrative analysis of the interaction between human well-being and ecosystem services outcomes.

While incomplete, the inclusion of ecosystem effects in the MA represents a major step forward. It points the way toward a truly integrated assessment of possible future relationships among human and natural systems.

The MA scenarios develop four different futures, each plausible in its own right, and detail the resulting changes in ecosystem services and their consequences for human well-being. While basic human conditions generally improve across all four scenarios, the scenarios nevertheless all result in perilous paths of ecosystem changes. Global population increases in all four scenarios, as does the affluence of an average person, but this generally occurs at the cost of ecosystems degradation and consequently also lower per capita ecosystem services.

The individual development paths of the scenarios are fundamentally different and do not converge. They differ with respect to the paths of many of the drivers of global change. In particular, the scenarios differ with respect to whether the world becomes more or less interconnected and whether environmental management is reactive or proactive. Global Orchestration is connected and reactive, Order from Strength is disconnected and reactive, Adapting Mosaic is disconnected and proactive, and TechnoGarden is connected and proactive.

These basic differences are explored in more detail in the full storylines. The scenarios differ with regard to institutions, technology, social organization, and ecological change. None of these four development paths leads to a full transition to sustainability, even though the two proactive scenarios include response to ecosystem change. TechnoGarden follows a ''technology strategy'' to deal with these threats, while Adapting Mosaic takes a more institutional and behavioral path. A complementary mixture of these two different strategies is required for the sustainability transition and a future where the loss of ecosystem services is avoided both through substitutions by other services or through human change itself. In contrast, the two reactive scenarios put more emphasis on material human well-being but take different strategies toward this goal. Global Orchestration is a world where globalization of economic activities is fairly successful and results in the highest economic growth rates of all four scenarios. Order from Strength is a fragmented world where economic and material interests are focused on more local and regional solutions.

This rudimentary and ''caricature-like'' brief description of the scenarios illustrates the fundamentally different nature of their development paths. Chapters 8 and 9 provide a rich qualitative and quantitative image of these four futures. Despite this detail, each scenario represents a kind of ''pure'' strategy. In reality, elements of each described possible world will be presented in some aspects of the future development but not others. Therefore, it should be noted that the scenarios jointly give the full range of heterogeneity of future developments. Some combinations of them are a real possibility, especially at the more local and regional level. Even though they portray divergent development paths, they jointly hold the full richness of future ecosystem services and human well-being.

One common finding is that all these different possibilities lead to a general decrease of regulating and supporting ecosystem services per capita while ecosystem managers try to maintain provisioning services. However, the chosen development paths all lead to different outcomes for the five components of human well-being. Global Orchestration leads to the greatest improvement in human well-being. TechnoGarden improves all but one element of human well-being. Adapting Mosaic significantly improves human well-being in the South with little change in the North. In Order from Strength, human well-being is decreased.

While basic human conditions generally improve across three scenarios and decline in one scenario, they all result, to a varying extent, in perilous paths of ecosystem changes and lower per capita ecosystem services. This illustrates the complex linkages and feedbacks of ecosystem service changes with human well-being. While material elements of human well-being generally increase, loss of ecosystem services leads to higher inequalities in some of the scenarios and even degradation of some aspects of human well-being in others. Degradation and loss of some ecosystem services also affects the relationship between provisioning and regulating functions of ecosystem services.

The Global Orchestration scenario has the highest rates of economic development associated with lowest population increase. This leads to a high capacity to both invest in the future and respond to potential threats. However, this carries an environmental price as it leads to the highest rates of global change, including the highest rates of forest land disappearance and the highest levels of energy consumption. Nevertheless, the overall improvement of human well-being is the highest with this scenario, particularly in the currently developing countries. This may be because increases in wealth and equity lead to a high capacity to respond to changing circumstances and offset some loss of ecosystem services.

But the key uncertainty of the Global Orchestration path is whether or not the impressive rates of economic development and human well-being can be sustained if all externalities are accounted for. It remains unclear whether this development path is only achieved at the cost of endangering the biosphere and other planetary systems irrespective of apparent improvement of human well-being, thus undermining economic systems in the long term. Full consideration of the feedbacks from ecosystems to human systems in the quantitative models might reduce the level of economic development and the relative improvement of human well-being.

The Order from Strength development path comes close to disaster. It is the world with the highest population growth, some of the highest adverse environmental impacts, and the lowest rates of economic development. The income disparities in this possible future are similar to those that prevail today. Ecosystem services are seriously eroded. Society lacks the economic or technological capacities to adapt or respond to these threats to human well-being. For example, while high trade boundaries reduce the chance of invasive species, the risk of adverse impacts on human well-being when invasions do occur is high due to low social capacity for adaptation.

There is an utter disregard, under Order from Strength, for human interference in the biophysical processes and a general erosion of the main pillars of sustainability: environment, equity, and development. The consequences are the second highest demand for energy services (after Global

Orchestration) associated with the highest greenhouse gas emissions for all scenarios, the highest levels of water abstraction, and the lowest per capita incomes. It is not surprising that the incidence of disease, poverty, loss of security and freedom, and other adverse human conditions are most prevalent in this scenario.

The Adapting Mosaic development path is the most proactive about emerging challenges. It sets parallels between the adaptive development of humans and ecosystems. From this perspective it appears to be most attractive. It achieves high levels of human well-being with relatively low risks and intrusion on ecosystems and nature. Only TechnoGarden has lower impact on ecosystems. But TechnoGarden has high and unknown risks of collapse due to technology failure, while Adapting Mosaic is low risk. This development path highlights the benefits of evolutionary responses fostered by investments in social, natural, and human capital at local and global levels. There is recognition that natural capital underpins other forms of capital, such that property rights are attached to ecosystem services. In other words, they are internalized in decision processes.

Thus, Adapting Mosaic is the scenario with the highest degree of assumed feedback from nature to the human sphere and that includes explicit consideration of ecosystems. In the other three scenarios, ecosystems are reduced to the benefits provided by ecosystem services. In this sense, Global Orchestration and TechnoGarden come closest to achieving a sustainability transition, but somewhat ironically, Global Orchestration does so without vigorous diffusion of new technologies and TechnoGarden without high rates of economic development. This might indeed constitute a possible internal contradiction between these two storylines.

TechnoGarden also improves human well-being, but with higher risk and uncertainty. Technological approaches alone, without appropriate institutional and social embedding, cannot resolve the challenges of the future. In addition, technology itself may be the source of additional problems due to the potential for breakdowns in highly controlled systems. Also, the assumption in this scenario is that the described changes toward ‘‘greener technologies’’ might take some time to occur. Therefore, technology does not lead to a higher level of economic growth right away.

In the past, technological change has generally been the main driver of economic development in the long run. In TechnoGarden, technological change is used to improve provision of ecosystem services and does not provide the means for rapid rates of development and elimination of poverty, as in the Global Orchestration strategy. The difference is primarily in the focus in Global Orchestration on global institutions to improve equality and eliminate poverty. For example, technology leads to a rapid shift away from the current reliance on fossil energy in this scenario so that its consequences for climate change are lower than in other scenarios; however, there is no attempt to improve access to energy sources for all people. It is possible that the realized rates of development in this scenario would be higher if some of these positive environmental externalities were included as a resource. The cumulative effect of technological change and lower environmental impacts in this future world could indeed lead to the highest level of human well-being. However, the high risk of collapse would remain.

The Order from Strength development path is the least sustainable both because of its disregard for the impacts on ecosystems and because of the lack of development. It comes close to embodying many of the fears associated with a perilous development path or a failure in human development. It is indeed surprising that despite these monumental failures, the development path manages to improve some aspects of human well-being in the currently rich countries. (See Chapter 11.)

The scenarios also do not include a development path characterized by a ‘‘best case’’—a success of sustainable development associated with a high degree of environmental protection at all scales. This would be a scenario that combines some of the positive characteristics of Global Orchestration, TechnoGarden, and Adapting Mosaic into a development path that is both evolutionary and has high social and technological innovative capacities without a disregard for natural or human capital, such as where there is a high dependency by the poor on biodiversity. Such a scenario might serve to illustrate the policies and strategies that would be required over the next decades to reduce human intrusion on nature while improving human well-being for all future generations. The MA nevertheless chose not to develop this ‘‘rosy’’ scenario, as for each country and in each location-specific case the mix of these different elements is likely to differ.

The MA scenarios show increasing pressures on biodiversity and many other adverse impacts on ecosystems up to 2050 and beyond. However, ecosystems play a crucial role in overall biophysical processes. For example, they are an important regulating component of the global carbon cycle. The potential impacts of ecosystem service changes on global and climate change are twofold. They include the interplay of ecosystem services and other service in co-determining water, air, and land use as well as the emissions of greenhouse gases. They also include the regulating function of ecosystems in global and climate change. MA scenarios describe the former impacts explicitly. The latter ones are more difficult to capture in the models. For example, climate models do not include changes in the carbon cycle that might emerge due to anthropogenic causes of ecosystems changes, nor do they include the effects of albedo change arising from land use change.

13.3 Robust Findings of the MA Scenarios

A striking feature of the four MA scenarios is that they all show increased demand for ecosystem services and place increased pressure on ecosystems to supply those services. People in each scenario pursue different methods for ameliorating the increased pressure on ecosystems. In some scenarios, such as TechnoGarden, the greater pressure on ecosystems is somewhat relieved through technological advances to improve efficiency of service delivery. In Global Orchestration, society focuses on equal access to ecosystem services in the hopes that this will eventually lead to greater care of ecosystems. In general, scenarios in which increased demand for ecosystem services is coupled with disregard for regulating and supporting services (Order from Strength and Global Orchestration) suffer from high risk of breakdowns in access to provisioning ecosystem services. Those scenarios in which learning about ecosystem function is a priority (TechnoGarden and Adapting Mosaic) tend to do better in maintaining supporting services.

Together, the scenarios illustrate that it is difficult to replace the provision of ecosystem services with alternatives without fundamentally changing human well-being. That is, replacing one service with another often creates demands on ecosystems in another place, in a future time, or for a different service. For example, we can replace biofuels with fossil fuels, which may improve local forests but which may also lead to increased demand for carbon sequestration globally. One of the most common types of these trade-offs is to favor provisioning services at the expense of supporting services. As noted earlier, however, ignoring supporting services leads to high risk of future breakdown in access to provisioning services. One of the implications of this may be that ecosystems may not be able to support large human populations at high levels of material human well-being—levels that are associated with increasing consumption and production patterns.

Highlighting this trend is an important message for policymakers. Describing irreversible trends, such as the loss of forest area, which occurs in all scenarios, can help to focus attention on developing strategies to ameliorate the consequences of these developments and devise adaptation mechanisms. The MA scenarios provide some hints about how this might be done. In addition, the scenarios alert policymakers to possible unexpected irreversibilities that they might foster through the decisions they take today.

A major driver for the portrayed irreversible trends in the MA scenarios is increasing land use for human purposes, which in return reduces the area available to unmanaged ecosystems. This trend is further exacerbated by climate change and other adverse environmental developments such as loss of water and air quality. For example, changes in land use are expected to be the major driver of biodiversity changes (based on quantitative assessment of species-area relationships in the next century across all four scenarios), followed in importance by changes in climate, nitrogen deposition, biotic exchanges, and atmospheric concentrations of carbon dioxide. (See Chapter 10.)

Storylines and qualitative assessment of ecosystem services and their impacts on human well-being provide more insights into possible future events and developments that models are not currently capable of quantifying. As noted earlier, human well-being has five key, reinforcing components: basic material needs for a good life, health, good social relations, security, and freedom and choice. Ecosystems underpin human well-being through their supporting, provisioning, regulating, and culturally enriching services. (See Chapter 11.) World populations increase in all four MA scenarios along with incomes and material consumption, which help determine human well-being. The tacit assumption is that there are biophysical limits to ecosystems' ability to produce services for human use. In scenarios, this decline cannot be completely compensated for by technological and social changes. This critical result is associated with high scientific confidence. (See Chapter 11.)

In some ways, this important result unearths one of the most interesting findings of the MA scenarios. All four scenarios support larger populations with higher levels of income and consumption, which puts increasing stress on ecosystem services. Ecosystems in the MA scenarios are generally able to support the increasing demand for services, but at the cost of supporting and regulating services and therefore at the cost of increased risk of breakdowns in provisioning services. This seeming contradiction raises a question: Is it possible to imagine sustainable futures with more people on the planet all enjoying higher human well-being compared with today but without further degradation of ecosystems and their services? Such a future would imply that the human "footprint" on the planetary processes would need to decrease through more efficient provision of services or that provisioning ecosystem services would need to be substantially decreased without affecting human well-being. The ultimate limits in the substitutability of ecosystem services is a critical research topic that clearly emerges from the findings of the MA scenarios.

The MA scenarios explore management and policy options that are currently being discussed by decision-makers. In this way, the scenarios provide a long-term perspective for different near-term decisions about ecosystem management and use. This can give useful concrete policy guidance to decision-makers along with the options discussed today. For example, new technologies could be developed that are able to improve the efficiency of ecosystem service provision. Bioengineering and tremendous progress in genetically modified organisms are one possibility for reducing the burden on natural ecosystems to meet human demands, but this is already controversial. The scenarios show that there are possible benefits, as well as enormous risks to use of these technologies. They hold the promise of limiting human demands for space and ecosystem services. At the same time, they may lead to a multitude of unintended adverse consequences.

The possible convergence of some new technologies discussed in Chapter 7 could lead to revolutionary changes and a new wave of economic development not based on current consumption patterns. There is a considerable research effort on the possible benefits, risks, and ethics of nano, genetic, information, and new cognitive science and technologies. Their convergence toward meeting new human needs and providing services could be a powerful economic drive that could in principle reduce the impact on ecosystems. However, they carry great risk of problems and unforeseen consequences on ecosystem services and human well-being. A lower risk possibility is a fundamental change in human behavior that leads to much better ecosystem management and more humble demands on ecosystem services despite more affluent and larger future populations.

13.4 Lessons Learned about Policy, Planning, and Development Frameworks

13.4.1 Global Policies in Context of Other Scale Policies

A complex and interacting set of processes that span environmental, economic, technological, social, cultural, and political dimensions drive the global system. Policies aimed at one aspect, such as poverty alleviation, may exacerbate other problems, such as environmental degradation. Contradictory sectoral policies can negate one another or backfire. Scenario analysis helps identify opportunities for mutual reinforcement between sectoral policies.

Policies need to be consistent across scales as well as across sectors. For instance, national policies should neither inhibit local initiatives nor undermine global policies. Moreover, since each human community and ecosystem is unique, policies should allow for and encourage adaptations to the local context and conditions. Again, the integrated scenario approach can illuminate the requirements for a multilevel policy framework. In the new century, environmental problems will continue to cross borders. Water pollution, air pollution, and depletion of the stratospheric ozone layer are problems that do not respect national borders. Neither does the buildup of greenhouse gases in the atmosphere that contributes to climate change. Nor do the birds, fish, and zooplankton that may be contaminated in one country but become part of the food web in another. Facing these challenges will require cooperative regional, continental, and global solutions.

Dealing with cross-border problems requires much the same kind of institutional apparatus at the local and national levels as described earlier: problems must be detected and diagnosed, interests must be balanced within and across borders, and agreements need to be implemented. There is, however, one big difference: at the global level, commitment is a more difficult problem, and there is no central authority to enforce agreements, although the emergence of a world environment organization could be envisaged under certain scenarios.

Social, political, economic, and ecological processes can be more readily observed at some scales than others, and these may vary widely in terms of duration and extent. Furthermore, social organization has more- or less-discrete levels, such as the household, community, and nation, which correspond broadly to particular scale domains in time and space.

A long time horizon is an obvious requirement for policies that aim to affect development over many decades. But long-term policy is often, by default, the cumulative result of a series of policies with a shorter-term outlook. Therefore, the long-range impacts of short-term policies should be designed and assessed in advance. Alternative policies may achieve similar short-term goals but have very different long-term impacts. Ideally, policies should create a platform for the next round of new and more advanced policies. The scenario approach is particularly appropriate for incorporating long-term considerations into today's policy discussions.

New social actors are becoming increasingly important, complementing traditional modes of decision-making and action. In particular, NGOs encompass a broad variety of interests, including educational organizations, trade unions, religious organizations, aid and development organizations, charities, and the media. The policy process needs to involve and mobilize all relevant institutions, tapping into their diverse capacity and potential for interaction, synergy, and complementarity. This means that participation, negotiation, and the articulation of multiple goals should substitute for antagonism and exclusion. Again, a scenario-building process that can cultivate contrasting visions and perspectives is a critical technique for fostering pluralistic dialogue.

13.4.2 The Usefulness of the MA Scenarios for Stakeholders

This section explores what we learned about the usefulness of scenarios (development, modeling, analysis) for generating policy-relevant information. It also assesses the usefulness of the information in the scenarios for preparing policy analyses for selected stakeholder groups discussed in greater detail in Chapter 14. Most of the selected indicators, however, refer to the quantitative results of the scenario modeling exercise. Understanding many of the assumptions that the qualitative storylines portray in more detail and their consequences for different stakeholder groups can add substantially to the analysis. Chapter 14 also addresses what different user groups are likely to find most useful or missing when they conduct their own policy analyses of the MA scenarios.

13.4.2.1 Background

Scenarios have become a popular tool in environmental assessment and management in the past two decades. They played a limited role in the 1960s, when local and largely short-term problems dominated the environmental agendas. Increasing concerns over multifaceted, continental- to global-scale, and especially long-term problems led to the growing use of scenarios. Although policy-making is only one of many possible uses of scenarios, an increasing number of scenario applications attempt to provide useful information for decision-makers in public policy or private entities. Global scenarios represent a special cluster within this realm.

The work of the MA Scenarios Working Group has built on other global environmental assessments to design a relatively ''user-driven'' process. This is an ambitious objective. The range of targeted stakeholders includes the main international environmental agreements explicitly concerned with specific ecosystems or their services (the U.N. conventions on biodiversity, desertification, and wetlands), national governments (both parties to the international agreements and regulators of domestic policies), the private sector (extending from local resource operators to multinational companies using ecosystem services), and civil society (communities crucially depending on the local ecosystems and their services as well as NGOs protecting specific community interests or broader environmental values). This user-driven objective has been pursued from the beginning of the overall MA process.

Representatives of this wide-ranging and diverse intended audience have been surveyed concerning the information they would most need from the MA. The user questions have been sorted, analyzed, and summarized in Chapter 5.

Yet this goal of stakeholder participation must confront the reality of the scenario development process (scenarists getting carried away by their own storylines and visions of the future) and, most important, the constraints of the tools currently available to obtain the information users require. In this respect, an important question is related to the distance between the variables in the models and scenarios on the one hand and the indicators related to the stakeholders interests, values, and mandates on the other.

The quickest way to obtain information from the scenarios for policy analysis is when the indicators of interest are directly available as input (assumptions about driving forces) or output (results of the model calculation or the qualitative assessment based on the input assumptions) variables in the storylines or in the assessment models. An almost equally simple way to acquire information is when scenario or model variables can serve as precursors that can be converted by generally accepted procedures into policy-relevant indicators. Post-processing is required when the relationship between scenario variables and policy indicators are indirect. This can take the form of statistical processing of model output or running additional models fed by the primary model output to generate the required policy-relevant indicator. Inferred indicators require expert judgments and special procedures to be derived from one or several scenario or model output variables. Finally, distant indicators are those on which some sparse information is available in the model results but obtaining them would entail special post-processing arrangements (such as an expert panel). Given the limited time and resources available to conduct the policy analyses in Chapter 14, most indicators were taken directly from scenario storyline and model results (Chapters 8 and 9) and their interpretation and analysis by fellow experts in Chapters 10, 11, and 12.

13.4.2.2 Usefulness of the MA Scenarios to Specific Stakeholder Groups

The United Nations Convention on Biological Diversity has evolved into a complex web of thematic issues. A detailed comprehensive assessment of the implications for all themes and subprograms is not possible here. However, a good deal of relevant information on biodiversity is available in the scenarios.

Among the major threats to biodiversity, habitat transformation is the most important one, and quantitative results are available on key drivers: population growth and urbanization, fossil fuel extraction, change in agricultural area, forest conversion, and land fragmentation. Agricultural intensification and water withdrawal are available as indicators for the threat of overexploitation and inappropriate management. The information about pollution as a threat to biodiversity is limited to SO_2 and NO_x emissions, critical load excess, and return flows as proxies for water pollution. Climate change as a threat is characterized by changes in temperature and precipitation and by biome shifts. In contrast, there is no quantitative scenario output that would indicate the evolution of invasive species that is an increasing concern among threats to biodiversity.

The Convention on Wetlands (the Ramsar Convention) is concerned with wetlands, which exist in all continents, are diverse, and provide important functions and services. The quantitative model output of the scenarios does not contain direct or precursor indicators of wetlands change. This is because global models are designed to capture broad patterns of global change and because modeling techniques have not advanced much for wetlands processes, which generally take place at much smaller scales. One good way to generate wetland-related indicators would be to use the output of the global models operated in the MA scenarios exercise as input to drive general or location-specific wetland models to explore the potential impacts of different global scenarios. This was not possible in the present assessment. Therefore, conceivable impacts for wetlands are assessed on the basis of coarse indicators like regional water withdrawal, return flows, and water quality. This leads to a rather rough assessment of the emerging risks to wetlands, but the characteristic differences among the scenarios are apparent even at this level.

The mandate of the United Nations Convention to Combat Desertification is to address and alleviate degradation of land in arid, semiarid, and dry subhumid areas. The causes and processes of desertification are multiple and diverse. The desertification process itself is not directly depicted in global models because the process involves many local biophysical and socioeconomic factors that the global models cannot address. One possibility could be to use such models as post-processors of the global model runs. This was not feasible in the present assessment. Instead, an attempt was made to define suitable proxy variables from which indicators of desertification could be inferred. One of the main socioeconomic drivers behind desertification is unsustainable land use in arid areas. Models provide output that can be used to generate indirect indicators by taking the extent of arid areas under agriculture in different regions as a proxy to assess the desertification risk. These indicators do not provide a rich information base, but they are suitable for conducting a broad assessment of desertification risk and response options under the MA scenarios.

The main insights from the MA scenarios for national governments are analyzed at two time horizons in Chapter 14. The medium-term assessment looks at the implications for the prospects of reaching the Millennium Development Goals. The long-term assessment seeks to estimate the prospects for implementing the long-term objectives of sustainable development as confirmed and proclaimed by the Johannesburg Declaration at the World Summit on Sustainable Development in 2002.

The MA scenarios and model results contain a lot of useful information about the evolution of ecosystem services that is related to the achievement of these near- and long-term objectives. In some cases, the information is available on the relevant MDG indicator or its close proxy or precursor version (such as the proportion of land area covered by forests or of population with sustainable access to an improved water source). For many MDG indicators, implications of the scenarios can be assessed from indirect indicators. Good examples are the indicators defined to measure progress on Target 2: ''halve the proportion of people who suffer from hunger.'' The indicator of prevalence of underweight children is well approximated by the model output indicating the percent of malnourished children (a composite indicator, see Chapter 14 for details), while the indicator on the proportion of population below minimum level of dietary energy consumption can be inferred, albeit roughly, from the model output indicating the amount of calories available per capita per day.

A lot of qualitative information can also be used as inferred indicators relating to the MDGs, like income growth in regions for the prospects of achieving Target 1: halving the proportion of people whose income is less than $1 a day. In contrast, the scenarios are rather vague about general development issues like education (school enrollment, literacy rates), overall health status (under-five and infant mortality rates, immunization against measles). Finally, the MA scenarios are totally silent about the financial aspects of development, such as the prospects for official development assistance, for debt and debt relief, especially for heavily indebted developing countries, or for foreign direct investments.

The situation is similar in the case of the indicators that can be used to measure progress on the objectives of the Johannesburg Declaration up to 2050. General economic development indicators (GDP growth, for example, or the gap between rich and poorer regions), many directly or indirectly environment-related social indicators (food security, hunger, access to energy), and many environmental indicators are readily available and provide useful information for policy analysis. However, the more specific characterization of the economic and financial development (access to financial resources, sharing the benefits from opening markets, or access to health care) is omitted due to the primary focus on global ecosystems futures.

One of the most useful aspects of the scenarios for communities and NGOs is the effort to assess the relationship between ecosystem changes and human health and well-being. Given their global nature, however, the scenarios are not able to fully model all the trade-offs and interactions between ecosystem services and human well-being, especially in reaction to specific response options and adaptation. Given the scenarios' inability to fully model all ecosystem services (cultural and supporting, along with provisioning and regulating), as well as the complex interactions between ecosystem services, human well-being, and response options over time, it is difficult to address the thresholds at which further ecosystem degradation and reductions in human well-being might occur. The scenarios do not fully meet the needs of civil society stakeholders to have the MA address the impact of ecosystem change on the vulnerability and resilience of human communities and on their cultural concerns. These issues are more successfully addressed in the sub-global assessments. Communities are interested in learning about site-specific impacts in relation to global changes, but the scenario methodology is not sufficiently advanced yet to make such cross-scale assessments readily possible.

There is a wealth of information in the MA scenarios that is useful and relevant for the private sector, but it is not easy to extract and summarize it. First, virtually all issues that are important in these scenarios are likely to have some degree of private-sector implications, for the private sector that is closely related to or has indirect stakes in ecosystem services is widespread and diverse—from large multinational companies to small local resource operators. Second, the MA scenarios address a large number and diversity of ecosystems and human well-being issues. The intersection of these features implies that it is a major challenge to consolidate the complex ecological data, analytical information, and modeling results in a succinct assessment for the private sector. There are two principal ways this task could be accomplished. The first is to focus on the specific interests of a small and carefully selected set of stakeholders (logging companies interested in timber, pharmaceutical firms pursuing genetic resources, and so on) and to prepare targeted assessments of the implications of different scenarios for them. The second possibility is to consider the interests of the private sector as a whole in ecosystem services and then derive general insights about the risks and opportunities emerging under different assumptions about the future. The second option was taken in Chapter 14, which means that there remains a lot of unveiled information in Chapters 8–12 that might be useful for the private sector and worth exploring.

In summary, the MA scenarios provide rich and useful pictures of broad patterns of possible futures at the global scale and at the level of world regions. However, it is impossible to perform detailed quantitative analyses of local processes and impacts with the set of models adopted in the present endeavor. The qualitative scenarios and storylines address many issues that the models cannot, providing a more rich and detailed investigation. One crucial improvement for the quantitative models in future assessments would be to soft-link sector- and region-specific models by using the global scenario framework and outputs of global models to drive them. A particularly useful feature of the current effort is that scenarios provide information about socioeconomic and technological development patterns, which is necessary for the assessment of the viability and effectiveness of various instruments and response strategies. Such tools may be currently available or might become available in the future for different stakeholder groups to protect their interests or fulfill their mandates in the contexts of widely diverging but plausible futures.

13.4.3 Path-dependencies, Irreversibilities, and Their Implications

Most complex systems display non-linear behavior in which relevant phenomena drastically change after certain threshold values are exceeded or where initially small but cumulative effects become ever more important as the system evolves. They also display hysteresis (a history or path dependence of systems behavior, which in the case of complex systems means that they do not return to their original state even when the influence of the driving forces that changed them ceases), leading to important irreversibilities in their behavior. This is often referred to as path-dependency. Many systems are characterized by such irreversibilities; examples include technological change, global climate change, and biodiversity loss. Often very similar initial conditions can lead to fundamentally different outcomes, and these are usually very sensitive to the actual development path taken. They can be characterized by emergent properties that can evolve in fundamentally different ways along alternative future development paths.

The MA scenarios are themselves examples of such path-dependencies. By the end of the twenty-first century, they have evolved and branched out into fundamentally different futures that depend on a myriad of intervening changes and decisions taken along the way. Some of the path-dependent phenomena could undergo abrupt changes over the time frames considered in the MA scenarios. Climate-related abrupt changes could include loss of the Greenland ice sheet, shutdown of the North Atlantic Thermohaline Circulation, or the release of methane from permafrost or from deep sea clathrates deposits. In technology, abrupt and path-dependent changes could include rapid deployment and improvement of renewable energy technologies leading to low emissions futures, but also major breakthroughs in availability of fossil energy sources rendering them practically inexhaustible (such as methane clathrates as energy source). Similarly, overfishing could irreversibly deplete stocks, while new fish farming methods with low environmental impacts could allow for a recovery of now-endangered fish stocks. Finally, desertification could become irreversible beyond some critical levels of vegetation and soil loss.

Future anthropogenic climate change is characterized both by path-dependencies and numerous irreversibilities. Human activities have caused and will continue to cause climate change. The main direct causes are the global emissions of greenhouse gases primarily due to energy and land use changes. Emissions of particulate matter, aerosols, and many other substances also affect current and future climate change. For the wide range of IPCC emissions scenarios (Nakićenović et al. 2000), Earth's mean surface temperature change is projected to warm 1.4–5.8° Celsius by the end of the twenty-first century, with land areas warming more than the oceans and the high latitudes warming more than the tropics (Cubasch et al. 2001). The associated sea level rise is projected to be 9–88 centimeters.

The range of future mean surface temperature changes for the MA scenarios is narrower, with 1.6–2° Celsius by 2050 because of two important factors, namely that one single integrated assessment model and one climate model were used to estimate future climate changes. Six different IAMs and different climate models were used by the IPCC, adding significantly to the range of uncertainties and widening the range up to 5.8° Celsius. It is indeed possible that the full range of climate change for the MA scenarios would be comparable if the scenario approach were extended to a wider range of models and quantifications. An important indication that this may be the case is that cumulative carbon emissions across scenarios are comparable with the IPCC ranges. In other words, the climate implications are likely to be underestimated through the approach taken by the MA.

The seemingly small changes in temperature and sea level rise across the scenarios mask the more fundamental path-dependencies. For example, the scenario with the highest emissions by 2050, Global Orchestration, leads to almost five times higher emissions than the scenario with the lowest emissions, TechnoGarden. It is clear that reducing Global Orchestration emissions fivefold would dramatically change the nature of the scenario, requiring massive emissions mitigation measures and policies ranging from radical technology change to modified human behavior. In other words, greenhouse gas emissions (and many other scenario characteristics) differ in their emerging properties, associated irreversibilities, and resulting development paths.

Despite this possible underestimation of the future climate changes across MA scenarios (given the current uncertainties), the impacts on ecosystem services and human well-being will be significant and pose a major reason for concern. For example, anthropogenic climate change will have fundamental impacts on biodiversity. It affects individual organisms, populations, species distributions, and ecosystem composition and function both directly (through increases in temperature and change in precipitation, for instance, and in the case of marine and coastal ecosystems also through changes in sea level and storm surges) and indirectly (through changing the intensity and frequency of disturbances such as wildfires, for example). Processes such as habitat loss, modifications, and fragmentation and the introduction and spread of non-native species will affect the impacts of climate change.

The general effect of human-induced climate change is that the habitats of many species will move poleward (toward higher latitudes) or upward (toward higher altitudes) from their current locations (Gitay et al. 2002). It is clear that such significant impacts on biodiversity by anthropogenic climate change would also lead to significant additional loss of ecosystem services beyond those that occur due to other pressures of human development on ecosystems in MA scenarios.

Ecological systems can also be involved in abrupt changes both at small and large scales, usually acting in concert with physical and chemical components of the Earth system and frequently also due to the influence of human systems. One of the best-known examples from the past of such an abrupt change is the transition from a green to an arid Sahara in the mid-Holocene (Claussen et al. 1999; de-Menocal et al. 2000). About 6,000 years ago, the climate in northern Africa was much more humid than today, supporting savanna vegetation throughout the region, with little or no desert. The change that occurred was both abrupt and severe, leading to a complete desertification of much of this area—the formation of the present Sahara Desert. The ultimate trigger for the shift was a small change in the distribution of incoming solar radiation in the region due to a subtle change in Earth's orbit (Steffen et al. 2004). This change by itself was not significant enough to drive the vegetation shift but rather nudged the Earth system across a threshold that triggered a number of biophysical feedbacks that led rapidly to a drying climate and then to an abrupt change in vegetation (Steffen et al. 2004). This episode demonstrates the complexity of the dynamics that lie behind threshold-abrupt change behavior.

The behavior of the terrestrial carbon cycle is an aspect of Earth-system functioning that may experience abrupt change, particularly in the second half of this century, which is over the time frame adopted in the MA scenarios. At present, terrestrial ecosystems absorb about 25–30% of the CO_2 emitted by human activities, thus providing a valuable free ecosystem service that slows the rate of climate change. Simulations of the evolution of terrestrial carbon sinks from 1850 to 2100 (Cramer et al. 2001) show the development of the current strong sink through the second half of the twentieth century. The sink will continue to grow in size through the first half of this century, according to these simulations, but is likely to saturate around 2050, with no further increase. One simulation shows a rapid collapse of the sink through the second half of the century, with the terrestrial biosphere as a whole (Cox et al. 2000) perhaps even becoming a net source of CO_2 to the atmosphere by 2100 because of a much drier climate in Amazonia and a subsequent loss of the remaining forests there (Steffen et al. 2004). This again indicates the possible irreversibilities associated with high carbon emissions paths such as those of Order from Strength and to a lesser extent Global Orchestration and Adapting Mosaic futures.

Marine ecosystems commonly show threshold-abrupt change behavior, sometimes called regime shifts. For example, there appear to have been dramatic and synchronous changes to marine ecosystems in the North Pacific Ocean in the late 1970s. Such changes cannot be ascribed to local ecological interactions only. They involve many different biological and environmental parameters (over 100 in the case of the North Pacific), show coherence over large spatial scales, and are correlated to very large-scale external forcings, often teleconnections in the climate system. The 1977 regime shift in the North Pacific, for example, is correlated to a sharp increase in mean global surface temperature (Steffen et al. 2004).

Human impacts can also trigger abrupt changes in marine ecosystems, particularly through overfishing and eutrophication. Recent reports (Myers and Worm 2003) claim that about 90% of the large predatory fish biomass has been removed from the world's oceans, with removal rates being highest with the onset of post–World War II industrial fisheries. Given the importance of top-down controls on the dynamics of marine ecosystems, there is the possibility that such overfishing could lead to regime shifts in marine ecosystems, with reverberations through to lower trophic levels such as zooplankton. On a smaller scale, overfishing is already known to cause sharp regime shifts in coastal ecosystems (Jackson et al. 2001).

Human-dominated waste loading on the coastal zone has also led to abrupt changes (from an Earth system perspective) in the functioning of marine ecosystems in the form of eutrophication. If the level of nutrient loading is high enough, significant changes can occur to the species composition of the ecosystem, often leading to a simplification of ecosystem structure (domination by one or a few species) (Gray et al. 2002). Severe eutrophication can lead to the formation of hypoxic (oxygen-depleted) zones, in which the dissolved oxygen concentration is below that necessary to sustain animal life (Rabalais 2002), usually resulting in drastic changes to ecosystem structure. The region of the Gulf of Mexico near the mouth of the Mississippi River and the Baltic Sea in northern Europe are regions where hypoxic zones commonly occur (Steffen et al. 2004). In certain cases, hypoxic zones such as those that seasonally occur on the west Indian shelf release nitrogen oxide, a greenhouse gas (Naqvi et al. 2000).

It remains to be seen how overfishing and eutrophication in concert will alter global biogeochemical cycles and the resulting global inventories of carbon, nitrogen, phosphorus, and silica. Despite the seemingly large capacity of marine ecosystems to assimilate the impacts of waste loading and overfishing, the imminent collapse of many coastal ecosystems is a warning that human and systemic global pressures may act synergistically to trigger large-scale regime shifts in global marine ecosystems (Steffen et al. 2004). The loss of such ecosystem services and their possible adverse impacts on human well-being cannot be treated adequately in the current IAM approaches. The MA has made a significant contribution by linking a fisheries model to its IAM. This is an important area and direction for future improvements in our capacity to model complex global systems and their future development paths.

Critical thresholds and irreversible changes are probably hidden in the largely unexplored domain of interactions among climate and environmental change, socioeconomic development, and human and animal health. Scenarios remain the main tool for gaining a better understanding of these critical interactions and numerous feedbacks. Human activities have already become a geophysical and biogeochemical force that rivals natural processes, and this is likely to increase, but to differing degrees, across all four MA scenarios. This implies that major discontinuities in the socioeconomic domain may lead to corresponding disruptions in the biogeochemical/physical and ecosystem domains—that is, that abrupt changes can be expected in the coupled human-environment system. Thus abrupt changes in socioeconomic systems could attenuate or amplify changes occurring in other aspects of the coupled system (Steffen et al. 2004).

Abrupt changes in coupled socioeconomic and natural systems have occurred in the past. The archeological and paleoecological records indicate that major shifts in societal conditions in the past often appear to have been linked with abrupt changes in the biophysical environment (Alverson et al. 2003), including, perhaps, the collapse of the Classic Period and lowland Maya civilization and various ''pulses'' of Mongul expansion from Mongolia, which had significant consequences for Imperial China and eastern Europe (Steffen et al. 2004).

One of the most important potential discontinuities is the spread of a new disease vector, resulting in a pandemic. High population densities in close contact with animal reservoirs of infectious disease facilitate rapid exchange of genetic material, and the resulting infectious agents can spread quickly, with few barriers to transmission through a worldwide contiguous, highly mobile human population. The almost instantaneous outbreak of SARS in different parts of the world is an example of such potential, although rapid and effective action contained its spread. Warmer and wetter conditions as a result of climate change may also facilitate the spread of diseases such as malaria. Malnutrition, poverty, and inadequate public health systems in many developing countries provide large immune-compromised populations with few immunological and institutional defenses against the spread of an aggressive infectious disease. An event similar to the 1918 Spanish Flu pandemic, which is thought to have killed 20–40 million people worldwide, could now result in over 100 million deaths within a single year. Such a catastrophic event, the possibility of which is being seriously considered by the epidemiological community, would probably lead to severe economic disruption and possibly even rapid collapse in a world economy dependent on fast global exchange of goods and services (Steffen et al. 2004).

Another important area of emergent properties and a possible source of abrupt and irreversible changes is the interaction of technological change and the natural environment, including ecosystems. An obvious case is the current advances in bioengineering that can affect and interact with natural ecosystems. The possible interactions include adverse and irreversible impacts on regional ecosystems. Historical examples are many, including the introduction of new species into foreign environments leading to dramatic ecosystem changes and shifts. The other possibility is production of resistant and better-adapted species to overcome some future challenges. MA scenarios explore many but not all possibilities that might emerge during the twenty-first century as the result of technological changes that may either directly affect ecosystem services or indirectly affect both ecosystem services and human well-being.

A century is ample time for pervasive diffusion of fundamentally new technologies and systems. In fact, whole new technoeconomic paradigms have emerged in the past over similar time scales—from the emergence of the coal, steam, steel, and telegraph eras to the ages of oil, gas, internal combustion, gas turbines, petrochemicals, pharmaceuticals, mass production, and so on. Also in the future, new technologies could lead to new combinations of technologies and human activities. Today, the possible convergence of nano-, cogno-, bioengineering, and information technologies is seen as a possible way of enhancing human performance, modifying organisms into components of larger technoeconomic systems, and directly interacting with many micro- and nano-scale systems of both inanimate and biological origin.

All four MA scenarios consider further economic development in the world despite increases in human population. Much of the increased human productivity would stem from ecosystem services, some of which might indeed be enhanced by convergence of advanced technologies into new paradigms during the twenty-first century. At the same time, many of these future technological possibilities may bring with them unanticipated effects—some that might threaten human well-being and ecosystems and some that might enhance them and reduce human interference with natural systems. MA scenario storylines tackle many of these complex issues. However, dramatic effects of such technological developments were not pursued in scenario quantifications, presumably partly because models used in the MA were not designed for the assessment of technological changes and technology diffusion. Technology might indeed prove to be one of the most fundamental drivers of future human development and ecosystem services.

The question of how robust an increasingly interlinked, globalized world economy is must be addressed urgently (Steffen et al. 2004). There will almost surely be significant increases in need in the future for the provisioning of natural resources and ecosystem services. And despite technological advances, meeting these needs will have impacts on the Earth system and especially on many already-threatened ecosystems. There is a high probability that droughts, floods, and severe storms will occur more frequently, and an increasing probability that the more drastic, abrupt changes of the type described earlier could also occur. Coping with such stresses would take an increasing share of economic activity away from the evolution and growth of the economy in general (Steffen et al. 2004). How many such stresses, occurring when and where, would it take for the global economic system to begin a downward, self-reinforcing spiral that would lead to a rapid collapse? Should such a collapse occur, it could lead to a significant and probably long-lasting change in the fundamental human-ecosystem relationship.

13.5 Information Gaps and Research Needs

This section describes the research needed to improve the development of global scenarios in the future. It includes both research needed in the formal sense as well as improvements that could be made in methodology and in the manner in which the scientific community operates.

13.5.1 Global Storyline Development

Determining the nature of the MA global storylines by choosing the key drivers that would vary across scenarios and those drivers that would follow the same trend in all scenarios was a long and sometimes difficult process. This was partly the result of divergent views on the use of scenarios, and partly the result of divergent disciplinary approaches to science. Here, we describe some research and changes in research methods that could improve the development of global storylines in the future.

- Development of regional and local scenarios linked to the global scenarios would help create better global sce-

narios. Regional and local scenarios can use more accurate local information and might represent some system dynamics more accurately. They can also pinpoint specific variables of interest. Expanding methodologies for linking scenarios developed at different geographical scales or nesting them within one another to foster the exchange of information across scales will be an important step to help improve scenario development methods.
- Better communication and interaction with policy-makers would help inform the development of the storylines by indicating the key variables that are of interest to decision-makers. Improved communication with policy-makers would be useful both for understanding policy-makers' most pressing questions and for communicating results to them at the end of the process. Having a greater presence of policy- and decision-makers within the working group may be one way to improve this communication.
- Better communication and interaction across scientific disciplines would help facilitate future global scenario development projects. During the MA scenario development process, it turned out that the differences among disciplines' core beliefs about how the world functions were also often the critical issues that policy-makers wanted to have addressed in the scenarios. (See a more detailed discussion in Chapter 5.) However, it took our working group several meetings to come to a full understanding of the differences of core beliefs among disciplines. Better interdisciplinary communication prior to initiation of this project might have made this process easier.

13.5.2 Modeling Complex Systems

The response of complex systems to environmental change is assessed using models that are based on multiple driving variables, along with their interactions. Models currently can provide part but not all of the information needed for scenarios of ecosystem services. For example, temperature trends at the broad scale can be assessed relatively well through current climate models, whereas rainfall patterns cannot. Nevertheless, rainfall is important for many ecosystem services in many regions, often more important than temperature. The assessment therefore is incomplete and can be improved once more-reliable rainfall simulations are made or the uncertainty range of rainfall simulations are considered explicitly (which was not possible within the MA models).

While the assessment models can provide useful information to scenarios, their coverage of the Earth system is incomplete, and their description of essential ecosystem functioning is better for some processes than others. Climate and carbon cycle impacts are relatively well understood while even the most basic nutrient cycles are less reliable in current models.

With regard to analyzing ecosystem services, the current models have a critical deficiency in that they are not able to simulate the important feedbacks—the changes, often small, in ecosystems, that feed back and affect social systems, sometimes in large ways—that were described in the MA storylines. Therefore, the qualitative assessments by the storylines of some of these feedbacks loops became an important means to describe likely changes under the four MA scenarios.

The models are also incomplete in the sense that we need to better understand the interactions among variables across models. For example, we urgently need better models that link likely changes in such things as land cover to likely changes in essential ecosystem processes, including nutrient cycles, primary production, energy flow, and key community dynamics, as well as the relationship of these changes to ecosystem services. One of the important weaknesses of our current understanding is the lack of data for broad-scale (long-term and large-scale) ecological dynamics. Improved models and approaches are required to better understand ecosystems and their interaction with human systems, but such more-advanced models will still not lead to a complete and full integration and may never lead to full understanding of the complex interactions. The better models based on broad-scale dynamics would enhance our understanding of the ecosystem patterns and ecosystem processes. The benefits and requirements for these improved models and approaches are as follows:
- Better models for the relationship between ecosystem change and provision of ecosystem services would greatly improve quantification of the scenarios. Even in cases where we can develop decent models of the ecosystem, it is extremely difficult to predict the end result for provision of ecosystem services.
- Much better models for the relationship between ecosystem services and human well-being are desirable. In cases where we were able to model changes in ecosystem services (only provisioning and regulating services), we were rarely able to estimate the impact on human well-being. Most of the quantifiable indicators of human well-being related to population and demographics. It proved much more difficult to estimate spiritual well-being, recreation opportunities, or even impacts on human health.
- Models currently estimate only provisioning and regulating services. As pointed out in Chapter 12, this aligns perfectly with our understanding that provisioning and regulating services are often given greater priority than cultural and supporting services in management decisions. Certainly not by accident, the models focus on the ecosystem services that are perceived by society as more important (driving research agendas and funding); they give less attention to cultural and supporting services. There are two consequences of this bias.

First, cultural and supporting services are left out of the quantitative modeling exercise altogether: changes in these services simply are not quantified. This has critical implications. Supporting services are necessary for the production of all other ecosystem services, yet we cannot quantify how they may change in the future. If supporting services are declining, we may face severe and possibly sudden loss of provisioning and regulating services in the future.

Second, the fact that models are able to only explore a small subset of ecosystem services (even within provisioning and supporting services) means that a smaller set of potential trade-offs can be quantified. Thus, even if the models were able to perfectly characterize all the trade-offs among the ecosystem services that they considered, this would plainly underestimate the consequences of any societal choice, as many other trade-offs would remain unquantified. The consequence is that model results, at best, represent a crude lower bound of the expected consequences of any specific scenario.

- Improvements in modeling interactions among drivers or services would improve the quantification of scenarios. For example, it was very difficult to model how changes in agricultural production interacted with changes in water quality.
- Developments are needed to improve comparison of results across different models. Because the models we used calculated different variables or used different region boundaries, many variables were not comparable. Even in cases where two models calculated, say, land cover change, we could not always easily compare the results across models to ensure that our models were giving similar results. Comparison across models was even more difficult in the cases where the models were calculating different variables.
- There is a great deal of research needed on focused scientific topics. This is covered in Chapter 4.

13.5.3 Harmonizing Models and Storylines for Understanding Complex Systems

A major challenge for future scenario exercises will be to improve the level of harmonization between storylines and quantifications of the scenario. This involves three main tasks.

First, adequate time has to be given between the development of storylines, deriving model inputs from the storylines, running the models, interpreting model output, and revising the storylines. Perhaps two or three full iterations of this cycle are required to achieve a high level of consistency between the storylines and model calculations. Iterations are also required for achieving convergence among various subcomponents of the scenarios in addition to facilitating scenario consistency.

Second, the models need to be able to incorporate some of the important factors in the storylines, such as cross-scale feedbacks, thresholds, and small-scale changes. We know that these types of changes, which the models cannot fully address, are important determinants of the future. If the models are not able to address these factors, they will never match the richness or plausibility of the storylines in developing pathways to the future.

Third, it is important to make the conversion of information between the storylines and models more transparent and less arbitrary. Currently, information from the storyline is used to prescribe model inputs in an ad hoc (although consistent) fashion. For example, general statements about technological progress in the storylines were used to specify important input parameters to the modeling exercise, such as the rate of change of crop yield and the rate of improvement of domestic water use efficiency. Likewise, results from the modeling exercise (such as estimates of land use or cover change) are used ad hoc to modify or enhance the qualitative statements of the storylines. Rather than perform this conversion ad hoc, systems analysis techniques should be used to make the conversion more transparent and scientifically rigorous. For example, future exercises should consider the usage of fuzzy sets or agent-based approaches to convert from the linguistic statements of the storylines to the numerical information needed for model inputs, and from numerical model outputs to linguistic statements. Various techniques of qualitative modeling may also be useful for this conversion of information.

13.5.4 Research on Vulnerability

Further research on ecosystems and human well-being is needed. At the moment, scientific models for assessing thresholds of vulnerability in ecosystems are very few and not sufficiently developed (Peterson et al. 2003). Similarly, possible ways these thresholds will affect human well-being could be better understood. Research on thresholds is needed to more fully understand socioecological resilience and human well-being.

While we can sometimes quantify the trajectory of provision of a given ecosystem service, we cannot always determine whether the trajectory will continue the same way or whether it will change radically upon crossing some unknown threshold. Yet these threshold changes are often the most important changes in ecosystem services to understand. Research about thresholds and socioecological resilience would greatly improve our understanding of how to quantify and anticipate thresholds in management. A key issue here though is whether we have enough information to assess the thresholds or the vulnerability of ecosystems and human well-being to extreme events (ecological and socioeconomic surprises). Integrated assessments can be one of the main tools used to understand the resilience (buffer) of ecosystems and human well-being.

13.6 Conclusions

The MA scenarios have broadened global scenario exercises in their scope and methodology. By including and focusing on the many services that ecosystems provide to sustain anthropogenic systems, the MA scenarios explore the manifold linkages that exist between ecological and human systems. Previous scenario exercises have focused on some of the links between specific driving forces of environmental change and their impacts. For example, the IPCC explored connections among energy and land use and climate change. However, previous scenarios have not included ecological dynamics in their storylines or analysis and have not attempted to understand the effects of change on a suite of ecosystem services and human well-being. The MA scenarios expand the reach of analysis by including multiple ecosystem services and by linking environmental changes to their impacts on human well-being.

In addition, the MA scenarios contribute to the methodology of scenario analysis in various ways. They advance the role of qualitative and quantitative information and highlight the advantages of combining the two in the scenario development process. The scenarios also demonstrate the importance of integration across various disciplines to derive internally consistent, detailed pictures of the future. They also stress the significance of including various stakeholder perspectives in the scenario development process, so that the scenarios focus on questions about the future that are relevant for their potential users. Furthermore, the scenarios reveal the imminent path-dependencies and irreversibilities of plausible development pathways, which helps highlight the implications of decisions taken today.

With this analysis, the MA scenarios provide important insights for various stakeholder groups, such as the U.N. conventions, national governments, NGOs, local communities, and the private sector. Each group can derive implications from the set of scenarios in order to develop robust strategies for their policy decisions.

The MA scenario analysis can be improved in future scenario projects for ecosystem services. Modeling complex socioecological systems with their interactions and feedback loops remains a key challenge. Providing information not just on services with the highest immediate priority for many people and organizations (provisioning and regulating services) but also on supporting and cultural ecosystem services will enhance the level of analysis for decision-making. Furthermore, linking global models to models that operate at smaller geographical scales can enhance the consistency and quality of the derived information.

The qualitative analysis of ecological feedback loops, thresholds, risks, and vulnerabilities as part of scenario development can provide important insights that existing global ecological change models have so far not been able to capture. Global modeling and integrated assessment efforts, though, can provide important consistency checks of assumptions on key driving forces and their interactions. Enhancing the methodology for combining quantitative and qualitative analysis in the future will greatly improve our ability to deal with the complexities that lie ahead of us.

References

Alverson, A., R. Bradley, and T. Pedersen, eds., 2003: Paleoclimate, global change, and the future, *IGBP,* Global Change Series, Springer-Verlag, Berlin and New York.

Claussen, M., C. Kubatzki, V. Brovkin, A. Ganopolski, P. Hoelzmann, and H.J. Pachur, 1999: Simulation of an abrupt change in Saharan vegetation at the endo fo the mid-Holocene. *Geophysical Research Letters,* **24,** 2037–2040.

Cox, P.M., R.A. Betts, C.D. Jones, S.A. Spall, and I.J. Totterdell, 2000: Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature,* **408,** 184–187.

Cramer, W., A. Bondeau, F.I. Woodward, I.C.Prentice, R.A. Betts, V. Brovkin, P.M. Cox, V. Fisher, J.A. Foley, A.D. Friend, C. Kucharik, M.R. Lomas, N. Ramankutty, S. Sitch, B. Smith, A. White, C. Young-Molling, 2001: Global response of terrestrial ecosystem structure and function to CO_2 and climate change: Results of six dynamic global vegetation models. *Global Change and Biodiversity,* **7,** 357–373.

Cubasch, U., G.A. Meehl, G.J. Boer, R.J. Stouffer, M. Dix, A. Noda, C.A. Senior, S. Raper, and K.S. Yap, 2001: Projections of Future Climate Change. *Climate Change 2001: The Scientific Basis,* Third Assessment Report, Working Group I of the Intergovernmental Panel on Climate Change (IPCC), 525–582. Cambridge University Press, Cambridge. Available at http://www.ipcc.ch.

deMenocal, P.D., J. Ortiz, T. Guilderson, J. Adkins, M. Sarnthein, L. Baker, M. Yarusinsky, 2000: Abrupt onset and termination of the African humid period: Rapid climate response to gradual insolation forcing. *Quaternary Science Review,* **19,** 347–361.

Gitay, H., A. Suarez, R.T., and D.J. Dokken, 2002: Climate Change and Bodiversity, the Intergovernmental Panel on Climate Change, IPCC Technical Paper V, IPCC, Geneva.

Gray, J.S., R.S. Wu, and Y.Y. Or, 2002: Effects of hypoxia and organic enrichment on the coastal marine environment. *MEPS,* **238,** 249–279.

IPCC (Intergovernmental Panel on Climate Change), 2001: *Climate Change 2001: Synthesis Report,* IPCC R.T. (ed.), Cambridge University Press, Cambridge.

Jackson, J.B.C., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S. Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Peterson, R.S. Steneck, M.J. Tegner, and R.R Warner, 2001: Historical overfishing and the recent collapse of coastal ecosystems, *Science,* **293,** 629–637.

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

Morita, T., and J. Robinson, 2001: Greenhouse Gas Emission Mitigation Scenarios and Implications. *Climate Change 2001—Mitigation.* Report of Working Group III of the Intergovernmental Panel on Climate Change. B. Metz, O. Davidson, R. Swart, and J. Pan. Cambridge University Press, Cambridge, 115–166.

Myers, R.A. and B. Worm, 2003: Rapid worldwide depletion of predatory fish communities. *Nature,* **423,** 280–283.

Nakićenović, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, Tae Yong Jung, T. Kram, E. Lebre La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, Zhou Dadi 2000: *Special Report on Emissions Scenarios* (SRES). Working Group III of the Intergovernmental Panel on Climate Change (IPCC), 595 pp. Cambridge: Cambridge University Press. Available at http://www.grida.no/climate/ipcc/emission/index.htm.

Naqvi, S.W.A., D.A. Jayakumar, P.V. Narvekar, H.Naik, V.V.S.S.Sarma, W.D. Souza, S. Joseph and M.D. George, 2000: Increased marine production of N_2O due to intensifying anoxia on the Indian continental shelf. *Nature,* 2000, Nov 16, **408 (6810),** 346–349.

Peterson, G.D., S.R. Carpenter, and W.A. Brock, 2003: Uncertainty and the management of multistate ecosystems: An apparently rational route to collapse. *Ecology,* **84(6),** 1403–1411.

Rabalais, N., 2002: Nitrogen in aquatic ecosystems. *Ambio,* **31,** 102–112.

Raskin, P., G. Gallopin, A. Hammond, and R. Swart, 1998: *Bending the Curve: Toward Global Sustainability, A Report of the Global Scenario Group.* Stockholm, Stockholm Environment Institute.

Rayner, S. and E. Malone, 1988: The challenge of climate change to the social sciences. In: *Human Choice and Climate Change, Volume 4—What Have We Learned.* S. Rayner and E. Malone. Battelle Press, Columbus, OH.

Robinson, J., and P. Timmerman, 1993: Myths, rules, artifacts, ecosystems: framing the human dimensions of global change. In: *Human Ecology: Crossing Boundaries,* T. D. S. Wright, R. Borden, G. Young and G. Guagnano. The Society for Human Ecology, Colorado, pp. 236–246.

Schwartz, P., 1992: *The Art of the Long View.* London, Century Business.

Steffen, W., M.O. Andreae, B. Bolin, P.J. Crutzen, P. Cox, U. Cubasch, H. Held, N. Nakićenović, R.J. Scholes, L. Talaue-McManus, B.L. Turner, 2004: Abrupt changes: the Achilles heels of the earth system. *Environment,* **46(3),** 8–20.

Swart, R., P. Raskin, J. Robinson, 2004: The problem of the future: sustainability science and scenario analysis. *Global Environmental Change,* **14,** 137–146.

Wack, P., 1985a: Scenarios: uncharted waters ahead. *Harvard Business Review,* **5** (Sept./Oct.), 72–89.

Wack, P., 1985b: Scenarios: shooting the rapids. *Harvard Business Review,* **6** (Nov./Dec.), 139–150.