7 *Analytical Approaches*

Executive Summary

- The overall analytical approach to be used to achieve the goals of the Millennium Ecosystem Assessment (MA) has nine major tasks: identifying and categorizing ecosystems and their services; identifying links between human societies and ecosystem services; identifying the direct and indirect drivers of change; selecting indicators of ecosystem conditions, services, human well-being, and drivers; assessing historical trends and the current state of ecosystems, services, and drivers; evaluating the impact of a change in services on human well-being; developing scenarios of ecosystems, services, and drivers; evaluating response options to deal with ecosystem changes and human well-being; and analyzing and communicating the uncertainty of assessment findings.
- The MA will rely on five major categories of data and indicators: core data sets (shared among all MA Working Groups), data and indicators for assessment reports (closely targeted to individual analyses), indicators for summary and synthesis reports (a smaller set of clear, policy-relevant indicators), new data sets (developed during the MA process for continued use), and metadata (data documenting all of these data sets).
- Although new synoptic data sets (for example, from remote sensing) enable more comprehensive global assessments, they nevertheless have deficiencies that need to be addressed. These include incomplete and inconsistent spatial and temporal data coverage, contradictory definitions of types of data, and the mismatch of ecological, geographic, and political boundaries. Some of these deficiencies will be addressed when the MA acts to assure the quality of data used in the assessment. Various steps could be taken for data quality assurance, such as setting up a data archive, sponsoring the development of MA data sets, or using data already described in the scientific literature.
- Models will play an integrative role in the MA and will complement data collection and analysis. Modeling will be used to analyze interactions among processes, fill data gaps, identify regions for priority data collection, and synthesize existing observations into appropriate indicators.
- The MA will develop four or five scenarios of medium- to long-term changes in ecosystems, services, and drivers. The scenarios will have an explicitly ecological perspective and will explore such themes as ecological surprises and cross-scale ecological feedbacks. They will build on the social and economic information contained in existing global scenarios.

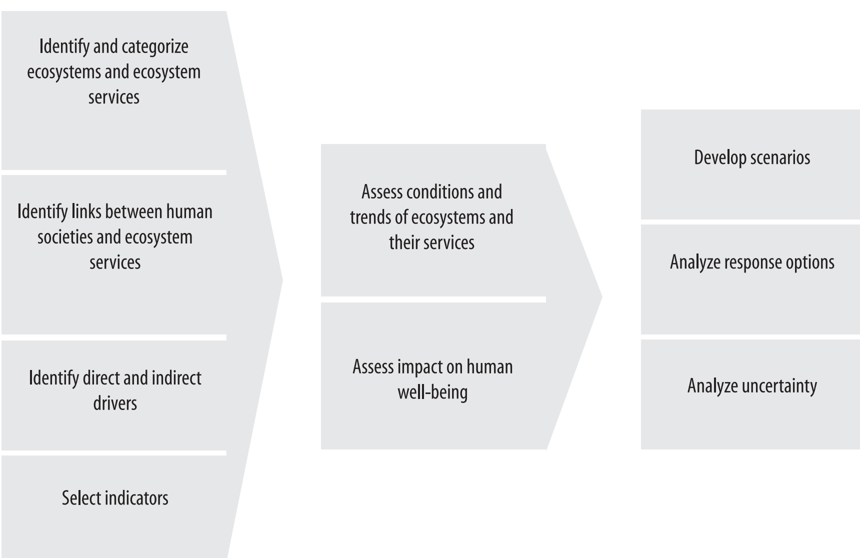
- Scientists must make every effort to estimate the certainty of important findings. They must then distinguish and communicate which findings are robust, which are partially understood, and which are uncertain or even speculative. As a rule, uncertainties from all aspects of an assessment should be reported in a consistent and transparent way.

Introduction

The analytical approach used to achieve the goals of the Millennium Ecosystem Assessment (MA) must be suitable to the many disciplines involved in the MA and address the MA conceptual framework, synthesizing the state of knowledge concerning the impact of ecosystem changes on human well-being. The management, analysis, and interpretation of information are key issues because of their relevance to maintaining high scientific standards in the assessment and because they can facilitate the accessibility and usefulness of MA results. Moreover, the effective management of information is a vital requirement for providing a scientific record of a comprehensive global assessment of the world's ecosystems.

There are nine major tasks in the analytical approach of the MA. (See Figure 7.1.) Note that few arrows are shown in Figure 7.1 to emphasize

FIGURE 7.1 The Analytical Approach of the Millennium Ecosystem Assessment and Its Main Tasks



that many of the activities will be carried out simultaneously rather than in sequence, although at some junctures information will feed in from one task to another.

- *Identify and categorize ecosystems and their attendant services.* To facilitate the assessment of complex ecosystems, the MA will classify them into a limited number of categories as a basis for assessing the services they provide. Ecosystem services are identified and grouped into functional categories: provisioning, regulating, cultural, and supporting. (See Chapter 2.)
- *Identify links between services and human societies.* Here the links are described between human societies and the particular ecosystem services that they use or benefit from. This includes defining the components of human well-being that are affected by the services (such as health, livelihood, culture, and equity), as well as the human activities that in turn affect ecosystems and the supply of services (such as population growth, consumption, and governance). (See Chapter 3.)
- *Identify indirect and direct drivers.* In this task a list of indirect and direct drivers of the state of ecosystems and their services is drafted. Indirect and direct drivers affect not only ecosystems and their services but also each other. For example, demographic changes (an indirect driver) can affect ecosystems though land use change (a direct driver) but also can influence other indirect drivers such as social values and institutions. (See Chapter 4.)
- *Select indicators of ecosystem conditions, services, human well-being, and drivers.* A set of indicators is selected to assess the state of ecosystems, ecosystem services, human well-being, and drivers. As an example, if the ecosystem service is food provision, then a potential indicator for the ecosystem state would be area under cultivation; for the service, quantity of food produced; for human well-being, rates of malnutrition; and for drivers, population growth. Next, these indicators are quantified or otherwise evaluated for use in the other analytical tasks. (See Chapters 2, 3, and 4.)
- *Assess historical trends and the current state of ecosystems and their services and drivers.* The current state of ecosystems and their services is assessed by assembling and analyzing data on the indicators selected. The details of how these data will be analyzed have not been completely worked out, but some considerations are discussed in Chapter 2. Since ecosystems are dynamic, an important issue to be addressed is the meaning of "current conditions." In some cases this will refer to the most

recent data collected, but for most ecosystems it must take into account year-to-year and perhaps inter-decadal variability. (For example, it is not useful to refer to the availability of fresh water for a particular year because of its strong year-to-year variability.)

- *Evaluate impact on human well-being.* This is among the most challenging tasks in the MA, since it involves the translation of information largely from the natural sciences (such as the state of fresh water, soil, and forests) into variables of concern to society (health, livelihoods, wealth, and security, for instance). One challenge is that a given service can affect several components of human well-being. Another challenge lies in sorting out the many possible trade-offs among services. Finally, the distribution of service benefits among societal groups will need careful consideration.
- *Develop scenarios.* The MA is concerned not only with the historical, present, and short-term future trends of ecosystems, but also with future trends over the medium and longer term. This information is needed to anticipate critical changes in ecosystems and to develop response strategies. The aim of this task is to identify a set of plausible futures or "scenarios" for ecosystems, services, and drivers.
- *Evaluate possible responses.* In this task the many possible "response options" are identified for preventing the deterioration of ecosystem services or recovering lost services. This includes evaluating the success of past response options and developing guiding principles for designing needed policies. Consistency is needed between the response strategies identified here and those used in the scenarios. (See Chapter 8.)
- *Analyze and communicate uncertainty.* Since the MA is concerned with a new and rapidly changing body of knowledge, it is clear that many of the findings will be uncertain. Assessing and communicating the level of certainty in a clear and consistent manner is therefore a central task of the MA.

These nine tasks and Figure 7.1 do not pertain to any particular spatial or temporal scale. Nevertheless, assessments carried out on the sub-global scale might require some refinement of the tasks. For example, in a sub-global assessment the selection of ecosystem categories must take into account the unique conditions of a region, such as its existing biogeographic zones. Another example is the selection of indirect and direct drivers, which should reflect the relevant temporal and spatial scales of the assessment, while also taking into account possible external global drivers. As a general rule, the nine MA tasks described should be adjusted to the particular needs of each sub-global assessment.

At the global scale, the MA has distributed these tasks among three Working Groups. The Condition and Trends Working Group is concerned with the first six tasks, the Scenarios Working Group builds on these to focus on the seventh task, and the Responses Working Group builds on all the earlier tasks to focus on the eighth task. All three Working Groups are centrally concerned with the analysis and presentation of uncertainty and with incorporating uncertainty into decision-making.

The MA Working Groups also focus on distinct time intervals. The Condition and Trends Working Group will assess current conditions and historic trends, typically over the last 40 years. This group will also consider issues of sustainability, presenting short-term projections (typically over the next 10 years) of changes in ecosystems, ecosystem services, and associated human well-being. The Scenarios Working Group will consider plausible futures over the next 25, 50, and 100 years. The Responses Working Group will assess the success of past and current responses and will use these assessments to evaluate available future responses.

The conceptual issues surrounding these nine tasks are discussed further in previous chapters, and the specific methodologies involved in accomplishing them will be better described and applied in the Working Group reports. The remainder of this chapter describes several of the major cross-cutting issues in the MA analytical approach:

- data,
- units of analysis and reporting,
- modeling,
- scenarios, and
- scale and uncertainty.

Data

A global assessment of world ecosystems and their services obviously requires an enormous amount of data. These needs have been summed up into five broad categories in the MA sub-group report, *Core Data Sets and Indicators*:

- *Core data sets*. Core data sets are those with wide potential application in the MA. They could cover, for example, land use, land cover, freshwater resources, marine resources, population, and infrastructure. Establishing common core data sets for use by all Working Groups and scientists within the MA will maximize consistency among analyses. In general, the MA will ensure timely access for all participants to such core data sets via an online data archive. Core data sets could be data already available or data developed specifically for an assessment.

- *Data and indicators for assessment reports.* Each chapter of the MA will necessarily make extensive use of published data and indicators. In addition, it is likely that some chapters will develop new indicators to meet their particular needs, recalculate existing indicators based on the agreed-upon core data sets (for example, recalculate a measure of fish production based on an updated marine ecosystem classification), or extend indicators developed for specific regions to the global scale.
- *Indicators for summary and synthesis reports.* Compared with the many indicators used in the full MA reports, only a small number can be included in the Summaries for Decision-makers or the Synthesis Reports. These key indicators (perhaps 10–15) either will be selected from the larger number or will be compound indicators incorporating several others. An enormous weight will fall on these indicators in communicating the core MA findings to decision-makers. They must generally be highly relevant to policy-makers, easily understood, and effectively convey the bottom-line findings concerning the consequences of ecosystem change on human well-being. Given the pivotal role these indicators will play with respect to the perception and impact of the MA beyond the scientific community, they will be explicitly identified and targeted for development.
- *New data sets.* The existence of the MA will probably stimulate the production of new data sets that may be less useful to the MA itself (because of their timing, perhaps, or their resolution) yet would be valuable for other institutions. These data sets could be helpful, for example, in building the capacity of institutions to undertake their own regional, national, or sub-national integrated assessments of ecosystems and their services. For instance, the United States has promised to provide the MA with complete global terrestrial cover from Landsat 7 for the year 2000. Although it is unlikely these data will be fully available in time for the MA, they will ensure that geo-referenced Landsat data will be available at low cost to any country or institution interested in undertaking a more fine-grained analysis of land cover change.
- *Metadata.* For both scientific and technical purposes, it is important to document the data used in the MA (so-called metadata) and to make the documentation widely available. This need arises in part from the

scientific responsibility to make the work of the assessment transparent, traceable, and reproducible. But there are also reasons of data management, given the breadth and diversity of data used in global assessments (for instance, gathering sufficient information to define the origin of the data and assess its reliability). It is becoming more common that software behind, for example, geographic information systems and Web browsers uses standardized metadata descriptions to organize and search for information. Standards for metadata should include the number and format of data description fields, original data grain and extent, and the selection of appropriate searchable keywords.

To facilitate access to both core data sets and metadata, the MA will establish a data archive. The archive will receive computer support over several years and have the appropriate technical characteristics for conveniently storing and transferring large data sets.

Challenges in Using Data

There has been a recent proliferation of data sets of differing geographic extent relevant to the work of the MA. They describe the location, extent, and condition of ecosystems, the provision of ecosystem services, and, less frequently, the relationships among drivers and ecosystem services or among ecosystem services and human well-being. Some of these are based on remote sensing and other relatively recent technologies, while others are from new field programs. These data sets will allow the MA to conduct more rigorous, inclusive, and globally consistent assessments than would have been possible perhaps 10–15 years ago.

Nevertheless, the MA faces several difficult issues in using these data effectively. First, the data are incomplete in coverage and are often collected by many different researchers who sometimes use incompatible methods. Second, data often have inconsistent spatial scales and time periods, use distinctive definitions and characterization approaches, and are rarely adequately documented, particularly in terms of describing the accuracy and reliability of data sets and models. Third, the reality is that widely accepted data sets for many important aspects of the world's ecosystems are simply not available. For example, land cover derived from different global data sources (different remote sensing instruments and ground-truthing techniques) often provides conflicting information, none of them match national land use statistics, and time series data of global land cover have never been produced.

Perhaps the greatest challenge is that the MA aims to be a global and integrated assessment, yet the available and relevant data continue to be of uneven quality in terms of geographic and temporal extent as well as resolution, taxonomy, and economic sector. (For example, crop data are of generally better quality than fisheries or livestock data, which in turn are likely to be better than fuelwood or biodiversity statistics.) Unfortunately, from a geographical perspective, the completeness and reliability of data are often inversely related to the rate of ecosystem change and to levels of human welfare.

Data on subjects as varied as species diversity patterns, deforestation rates, invasive plant distributions, human demographic trends, and economic indicators are often more accessible, of greater reliability, and of higher spatial and temporal resolution in richer countries. For example, reliable estimates of crop areas in nearly all counties of the United States can be downloaded from the Internet free of charge, whereas it is sometimes difficult to obtain any reliable data for a state or province (much coarser spatial units) in poorer countries where statistical bureaus lack adequate support. At a smaller geographic scale, much of the information on species distributions, crop yields, resource degradation, and so on is gathered from the most accessible areas near, for example, roads, research stations, and other human centers. The MA will need to carefully account for these biases at all scales, and may need to focus many analyses on regional and sub-regional case studies where adequate data are available.

Another type of bias arises from the tendency of scientists to collect data about "popular" taxa such as birds, mammals, butterflies, and trees at the expense of a more balanced coverage for all taxa (although the data coverage of even these popular taxa may suffer from geographic biases). Indeed, these popular taxa can be less important from the standpoint of ecosystem services than neglected groups such as bees, microbes, fungi, and aquatic plants. Not only are the spatial distributions of microbes and other such groups often poorly understood, but their ecological role in relation to ecosystem function and services is also not well documented. As a result, the MA may need to focus on case studies involving well-chosen indicator taxa as proxies and illustrative examples.

Other biases also have influenced the type of ecosystem data collected. For example, some types of data tend to be more abundant because they are easier to measure than others (point source wastewater discharges tend to be better documented in most watersheds, for instance, even though non-point discharges can also have a large influence on the state of water quality) or because they have a more direct effect on human welfare (for example, more data tend to be available about a river's impact on society during droughts and floods than under less catastrophic circumstances).

Differences in collection periods also present a challenge to data integration and quality. For instance, global initiatives on biodiversity assessment and soil degradation present different snapshots in time compiled from local data. While such data have their own quality problems, it is actually the change in such factors over time that is central to the concerns of the MA. But analyzing the change in ecosystems over time obviously requires time series data, which are often not available. Consequently, the MA may have to rely on only short-term trends, whose temporal resolution may or may not match those of the processes being studied. (See Chapter 5.)

The MA's integrated approach requires data on a wide variety of ecosystem services, their drivers, and their effects on human welfare. Yet the quality and coverage of these data vary greatly from one service to another. An example is the difference in data availability for provisioning versus supporting services of food production. The provisioning services are well described by abundant and relatively reliable data on crop and livestock production and on per capita food consumption. By comparison, the supporting services that make agricultural production possible, such as pollination and climate regulation, are much more poorly described. Nevertheless, for the sake of completeness, the MA must attempt to describe all aspects of ecosystem services, even those with poor data coverage.

Although current services of an ecosystem can be estimated, the MA must also determine whether these services can be sustained. But it is difficult and sometimes impossible to use current data to estimate the long-term sustainability of an ecosystem. As an example, it is possible to estimate the current production of a fishery, but nearly impossible to deduce from these data whether and for how long this production can be maintained. Hence we need information on the thresholds of sustainable production of natural resources. Sometimes this information can be provided by models that simulate the long-term dynamics of an ecosystem, as described later in this chapter.

In addition, assessing the contribution of ecosystem services to human well-being requires data that are usually not available. In particular, information is lacking on the material resources of individuals, their social relations, the state of governance, the role of freedoms and choices, and the state of equity. Moreover, available data are usually inadequate for analyzing temporal trends or for comparing one part of the world with another.

Another challenge for the MA is the use of traditional knowledge and undocumented experience. Because this information comes from sources outside of peer-reviewed publications, it needs to be critically assessed by other methods before being used. As an example, sometimes the quality of information (say, on the change in abundance over time of a particular plant or animal species) can be cross-checked from more than one source. Another step for controlling its quality would be to publicly archive the source and type of information. Archiving will also ensure that all researchers have access to this information.

Data Quality Assurance

Although quality assurance of data is obviously needed in any global assessment of world ecosystems and their services, there are different ways of achieving this. The method to be used within the MA has to take some special factors into account. First, global assessments typically rely on the voluntary efforts of numerous scientists and experts throughout the world. Second, the coordinators of global assessments normally do not have the capacity to examine carefully all the data sets to be used. In other words, the MA has neither the strong authority nor the capacity to intervene in the details of data analysis of its scientists. This does not mean that it should give up on quality control. On the contrary, the Intergovernmental Panel on Climate Change (IPCC) has shown that de facto quality control of data can be achieved without a formal quality assurance program. The following actions have made this possible:

- Most data used or cited by the IPCC stem from peer-reviewed scientific publications. It is expected that major deficiencies in data sources would be identified and “filtered out” in the course of peer-review.
- Some data sets come from large national or international organizations such as the United Nations Food and Agriculture Organization, the Center for International Earth Science Information Networks of Columbia University, or the United Nations Environment Programme (UNEP) World Conservation Monitoring Centre, that have internal procedures for maintaining quality control.
- Some data sets are assembled according to IPCC guidelines (such as emission inventories and estimates of carbon flux to forests). Data quality control is one of the aims of these guidelines.

To assure the quality of the data, the MA will build on the experience of the IPCC and insist on the use of data published in the scientific literature where possible. It will draw on the data of large organizations with their own data-control procedures and sponsor the development of its own data sets, as described earlier. Another step for quality control will be to set up a data archive containing metadata and some full data sets, as mentioned. This will give assessment coordinators an overview of much of the data being used in the assessment. Archiving would also help assure the quality of information coming from traditional knowledge and undocumented experience, as indicated earlier.

Indicator Selection

Global assessments of ecosystems and their services by definition involve the handling and evaluation of a huge number and variety of data and themes. It is clear that an assessment is only manageable if experts can focus on a limited number of representative indicators of ecosystems and their services. Because of the great weight these indicators hold, they must be carefully chosen. Earlier we described some of the particular types of indicators needed in an MA-type assessment. Here we pose the question, What are the characteristics of a "good indicator"? This depends on who is using the indicator and for what purpose, but three characteristics are common to all purposes: representativeness, reliability, and feasibility (Hardi and Zdan 1997; Prescott-Allen 2001).

For an indicator to be *representative*, it must cover the most important aspects of ecosystems and their services. As an example, consider the different possible indicators for "human health." "Life expectancy at birth" is not a bad indicator because it reflects all the causes of death that a typical person would be exposed to throughout life. "Healthy life expectancy at birth" is an even better indicator, however, because it subtracts the number of years likely to be lost to illness and injury.

For an indicator to be representative it must also be a sign of the degree to which an objective of an ecosystem service is met. For example, the indicator "healthy life expectancy at birth" shows the extent to which "having a long life in good health" has been attained, whereas immunization rates, health expenditures, and numbers of doctors are indirect indicators of this objective. Finally, to be representative, an indicator must illustrate trends in ecosystems and their services over time, as well as differences between places and groups of people.

An indicator is likely to be *reliable* if it is well founded, accurate, and measured in a standardized way using an established or peer-reviewed method and sound and consistent sampling procedures. And an indicator is *feasible* if it depends on data that are readily available or obtainable at reasonable cost.

The quality of potential indicators depends on how well they meet the above criteria. If no indicator can be found that adequately meets all these, then the component should be excluded from an assessment and its exclusion clearly noted.

The choice of components and indicators and their underlying methodologies must also be clearly documented. The more rigorous and systematic the choice of indicators, the more likely an indicator-based assessment will be transparent, consistent, and useful for decision-making. And the more involved decision-makers and stakeholders are in the selection of indicators, the greater will be their acceptance of results of the assessment. But a potential problem needs to be noted here: the time and technical skills required for selecting indicators might make it difficult for decision-makers and stakeholders to participate fully in the selection of indicators. This could work against the goal of maintaining an open process in the MA. (See Chapter 8.) At the same time, experts carrying out the assessment have the responsibility to ensure that the selection of indicators and the assessment as a whole are technically and scientifically sound. Hence in the area of indicators, as in other areas of the MA, a way must be found to maximize both the technical excellence of the assessment and the engagement of participants from government, civil society, and industry.

Units of Analysis and Reporting

Ecosystem Boundaries

Because the MA is concerned fundamentally with ecosystems and their functioning, it is necessary to describe these ecosystems and their spatial extent in as consistent a way possible, reflecting the state of scientific understanding. Indeed, many of the tasks described at the beginning of this chapter require an up-to-date characterization and mapping of the world's ecosystem types. For example, assessing the current state of ecosystems and their services or evaluating the impact of changes in these services on human well-being requires a consistent global overview of ecosystems.

At the most basic level, there are two fundamentally different ecosystem classifications: those based on actual ecosystem extent and those based on "original" or "potential" extent. The first type delineates ecosystem types based on their current distributions, including, for example, various agricultural and urban ecosystems developed by people through conversion of natural systems. The practical approach to assessing the location and extent of contemporary ecosystems at the regional scale has been through land cover interpretation of satellite data. For example, the International Geosphere-Biosphere Programme has identified 17 land cover types (deciduous broadleaf forest, for example, and cropland) using satellite data of 1-kilometer resolution (Belward 1996). These are widely accepted as proxies of aggregate ecosystem types.

Classifications of the second type, based on original or potential ecosystem extent, attempt to depict the ecosystems that would occur without human modification—in other words, due to prevailing biotic and abiotic conditions. For example, the World Wide Fund for Nature has developed a global system of 871 terrestrial ecoregions, nested within 14 biomes and 8 biogeographic realms, based largely on patterns of potential natural vegetation (Olson and Dinerstein 1998). Of course, marine ecosystems provide special problems in defining ecosystem boundaries. Nevertheless, at least two marine classification systems exist, and they provide an estimate of boundaries between biogeochemical provinces and large marine ecosystems in the world's oceans (Longhurst 1991; Sherman and Duda 1999).

Ecosystem classifications of both types are likely to be useful to the MA. Current ecosystem data are essential for determining the services that ecosystems provide today as well as for establishing a baseline against which changes in land cover and services will be assessed using scenarios or in future assessments. At the same time, data on the original extent of ecosystems places patterns of land use change into ecological context. In fact, comparing the two types of classifications, especially where they differ, can yield insights into the relative extent of conversion of original habitat types.

Several issues must be considered. First, because factors defining ecosystems vary continuously in space, the boundaries of any set of ecologically defined units will necessarily represent zones of transition instead of sharp boundaries. As a result, the precise location of these ecosystem boundaries should be downplayed, and the meaning of the changes occurring across those lines emphasized.

Second, the appropriate ecosystem classification often will depend on the ecosystem service being considered. For example, in a mountainous region, analyses of fresh water would tend to link upland areas via stream and groundwater flow to the rest of the river basin below. Terrestrial analyses, in contrast, would link these same upland areas to areas of similar elevation on the other side of the divide, based on similarity of vegetation, fauna, and climate.

Third, ecosystem services operate at wide range of characteristic scales. (See Chapter 5.) Matching the scale of ecological assessment (and thus the units used) to the scale of the service considered will be an important, and often difficult, aspect of the MA's task.

Finally, even if ecosystems can be delineated with confidence, ecosystem processes and services often transcend local ecological units and boundaries or involve interactions among them. For example, services provided by mangrove ecosystems (such as water purification, sediment capture, and habitat for juvenile fish) will be best maintained by proper management of both terrestrial and marine ecosystems. In addition, modern transportation systems have allowed ecosystems to provide services to people living far away, complicating and broadening the "ecological footprint" of human population centers.

Recognizing some of these difficulties in describing the location and extent of broad ecological systems, the MA has adopted definitions for such systems that allow for overlap in their extents. (See Chapter 2.) Thus areas of forest fragmented by patches opened up for agriculture are dealt with, from a systems perspective, in both the forest systems and the cultivated systems chapters of the Condition and Trends Reports, while cross-system summary tables control for possible double-counting of the ecosystem services provided.

Relating Ecological and Human-centered Units

An ecosystem's function and its ability to supply services to a particular human population are often best evaluated across its full extent, not only in the political unit in which that population lives. For example, water quality for a given municipality may depend more on the condition of the upstream portions of the watershed than on the areas within the city limits. At the same time, evaluating the importance of these ecosystem services to human welfare, as well as formulating policy to better manage them, will necessarily be conducted within the context of political units such as counties, cities, or provinces (Balvanera et al. 2001).

As a result, the MA conceptual framework will require frequent translation between ecological units and political or other society-centered units, particularly when linking indirect to direct drivers or ecosystem services to human well-being. For instance, demographic shifts may be an important indirect driver of many ecosystem changes, such as deforestation or soil erosion. Analyzing this relationship, however, will require relating demographic information collected for political units (such as counties) to ecological data necessarily assembled on ecological units (such as forest types). In addition, relating ecosystem services to human well-being, as in the water quality example, requires the reverse translation: from ecological units (watersheds) to political entities (cities).

Because ecological and political boundaries rarely overlap exactly, these translations among units are often difficult. For instance, it is hard to attribute human population densities collected on a national level to the country's ecosystems accurately.

Reporting Units

In order to best inform and assist the various users of MA products, it will be important to report assessment findings in units most relevant to those users. Many findings will be relevant to national and sub-national governments, and thus MA findings need to be reported in a form useful to these governments. In addition, the MA's scope and mandate clearly overlaps with those of existing international organizations and with previous scientific assessments (such as the Convention on Biological Diversity and the Convention to Combat Desertification). Hence, special efforts will be made to report MA findings in terms of the established units and frameworks used by these organizations.

Translating MA findings into various reporting units presents many challenges. In particular, the need to summarize the same findings in different forms has required careful collection and collation of information from the very start.

Modeling Issues

Models play an essential role in global assessments of ecosystems and their services. They can be used to analyze interactions between processes, fill data gaps, identify regions for data collection priority, or synthesize existing observations together into appropriate indicators of ecosystem services. They also provide the foundations for elaborating scenarios. As a result, models will play a synthesizing and integrative role in the MA, complementing the data collection and analysis efforts.

It is relevant to note that all models have built-in uncertainties linked to inaccurate or missing input data, weaknesses in driving forces, uncertain parameter values, simplified model structure, and other intrinsic model properties. One way of dealing with this uncertainty in the MA is to encourage the use of alternative models for computing the same ecosystem services and then compare model results. Having at least two independent sets of calculations can add confidence in the robustness of the model calculations, although it will not eliminate uncertainty.

To summarize the use of models in the MA, we have grouped them into two categories: environmental system models and human system models. The distinction between these two classes is somewhat blurred, however. What we call "environmental system models" often contain descriptions of some aspects of the human system, and "human system models" in turn often include aspects of environmental systems. Within each category, we identify some, although by no means all, classes of models that could be used in a global assessment.

Environmental System Models

A large number of freshwater resource models already exist and are used from local (small catchments), regional (watersheds and river networks), continental (large drainage basins), and global scales (e.g., Vörösmarty et al. 1989; Coe 2000; Donner et al. 2002; Alcamo et al. 2003). Included in this general class are the water balance and water transport models that consider the flow of water through plants, soil, underground, and storage systems. A new class of integrated water resource models expands these to include water use by society. These models can be used to assess how changes in a given component of the system affect the ability of other parts to provide ecosystem services associated with freshwater systems.

New models of marine resources are becoming available that can provide quantitative input to the assessment of ecosystem services provided by the marine environment. A representative of this group is the framework of models developed at the Fisheries Centre of the University of British Columbia (Walters et al. 1997; Pauly et al. 1998). Their approach, incorporated in the widely used Ecopath with Ecosim suite of software, is structured around a mass-balance concept that allows a simplified parameterization of the dynamics of freshwater and marine fisheries. These new models can be used to develop fisheries scenarios constrained by the feeding interactions within an ecosystem, thus leading to more realistic scenarios than the traditional fisheries management approaches, where such constraints are ignored. The modeling framework of the University of British Columbia also depicts fishery dynamics on a spatial grid of the world's oceans, thus providing a spatially explicit estimate of changes in the ecosystem services associated with the world's marine resources.

There are numerous models of terrestrial ecosystem processes that are appropriate for analyses at the local, regional, and global scale (Prentice et al. 1992; Melillo et al. 1993; Alcamo et al. 1994; Foley et al. 1996; Kucharik et al. 2000). Biogeochemistry models describe the flow of energy, water, and nutrients in the biosphere and are used to estimate essential properties such as productivity, carbon storage, and other functional aspects of ecosystems. At a more general level, biogeography models are used to describe patterns of plant distribution with respect to climate and soils and can be used to test the impact of changes in those variables. Land cover models provide insights in land cover change by analyzing the relationship between the various drivers of the process; such models are often spatially explicit and can help in assessing the impact of decisions affecting the use of land. Finally, integrated global ecosystem models provide a dynamic framework for studying changes in ecosystem structure and function under changing pressures. These models have largely focused on natural vegetation systems but are starting to turn to managed ecosystems.

A wide variety of climate models exists, and some of them can be used to quantify relationships between ecosystems and climate (Cox et al. 2000; Foley et al. 2000; Wang and Eltahir 2000). In particular, they help in examining both how ecosystems contribute to climate regulation and, conversely, how changes in climate may affect the capacity of ecosystems to provide goods and services in the future. General circulation models (GCMs) have been the traditional working tool for climate research, but up to now their linkage with ecosystems has been limited mostly to their representation of the influence of surface albedo on energy fluxes. Fully coupled climate-biosphere models are extensions of GCMs; they simulate physical and biogeochemical interactions between ecosystems and the climate system. These models, which can be of varying complexity, are more relevant to the MA.

For the most part, each genre of environmental models can be applied at various scales—local, regional, continental, and global. Their usefulness at various scales depends on their capability to capture input data and processes at a resolution that is consistent with processes at play at those scales. At local scales, models may be used to demonstrate the characteristic dynamics of ecosystems in different geographic areas where observational data are lacking. At regional and continental scales, models can assist in making up for observational data deficiencies and addressing biome-wide issues. At the global scale, models could be used to describe, among other subjects, changes in vegetation cover and biodiversity, linkages between global hydrology and water use, and food and crop production in a changing economic or climatic context. They also provide a standardized method for computing ecosystem indicators everywhere in the world. (See also Chapter 5.)

Human System Models

Social scientists model human behavior at various levels of aggregation, such as at the household level, the sub-national sectoral level, and the national and international level. Although these models strive toward quantification, purely conceptual models also play an important role in social science thinking and policy decision-making.

Household models examine the impact of changes in the external environment on production, consumption, and investment decisions. They have been used in particular to analyze differences between households in their access to resources. By comparison, sectoral models describe the various components of a complete economic sector. Sectoral models are used to address questions about the relationship between external factors and the performance of the sector—for example, anticipating the impact of a falling global wheat price on wheat production in Asia. Recently researchers have begun to apply sectoral models to the question of the impact of a particular economic sector on natural resources, as in the case of the impact of agricultural production on the availability of land and water (and vice versa) (e.g., Rosegrant et al. 2002).

Some human system models, particularly economic models, are available at the national and international level. They describe either a particular sector (for instance, energy or agriculture) at this level or a grouping of sectors. A particular class of national and global models is made up of the computable general equilibrium (CGE) models, which trace through economy-wide linkages of changes that are targeted to particular sectors. CGE models have the potential to be used for assessing the consequences of environmental change, but few examples of such use exist.

It should be stressed that the majority of "human system models" focus on economic efficiency and the economically optimal use of natural resources. Thus the broader issues of human well-being addressed by the MA, including such factors as freedom of choice, security, and health, will require a new generation of models. At a minimum, the present cadre of models needs to be extended to address these critical constituents of human well-being and their links to ecosystem services.

Integrated Models

There is also a small set of global integrated models that combine descriptions of the environmental system with the human system (e.g., Alcamo et al. 1996; Edmonds et al. 1996; Kainuma et al. 2003). These models relate demographic, economic, and technological factors with global changes in climate, natural vegetation, agricultural production, water resources, and other aspects of the Earth system. Some take into account feedbacks from the environmental system to the human system. Such models can be used in the MA to fill in data gaps in describing the current state of ecosystem services and for generating scenarios of future ecosystem services.

Scenario Analysis

The MA is concerned not only with assessing the current state and historical trends of ecosystems but also with developing medium- and long-term scenarios. This is because decision-making involves not only immediate options but also their consequences for the future (Carpenter 2002). Known or potentially long-lasting effects (decades or longer) must be explicitly taken into account in the decision-making process. Of particular relevance are situations where management decisions lead to irreversible changes in ecosystem conditions and processes. In these cases the policy decision must be informed by the probability of reaching such an irreversible threshold in the set time frame.

Ecology has many methods for anticipating the future of ecosystems (Clark et al. 2000). These include prediction, forecasting, and projecting, each with its own methods for estimating ecological outcomes, probabilities, and uncertainties. Ecological forecasts themselves are insufficient for the needs of the MA, however. (See Box 7.1.) Although the MA will use forecasts and other types of model projections where possible, additional methods are needed to provide a more comprehensive coverage of future ecological change in a format useful for decision-making. Scenarios are one of those alternatives.

Scenarios for Ecological Services

The MA will use scenarios to summarize and communicate the diverse trajectories that the world's ecosystems may take in future decades. Scenarios are plausible alternative futures, each an example of what might happen under particular assumptions. They reveal the dynamic processes and causal chains leading to different outcomes of the future (Rotmans et al. 2000). Scenarios can be used as a systematic method for thinking creatively about complex, uncertain futures. In this way, they help us to understand the upcoming choices that need to be made and highlight developments in the present (Rotmans et al. 2000). In our case, we are particularly concerned with scenarios that deal with changes in ecosystem services and their impact on human well-being.

The MA Scenarios Working Group will develop scenarios that connect possible changes in drivers (which may be unpredictable or uncontrollable) with human demands for ecosystem services. The scenarios will link these demands, in turn, to the futures of the services themselves and the aspects of human welfare that depend on them. The scenario building exercise will break new ground in several areas:

BOX 7.1 Ecological Forecasting

While ecological forecasting has had notable success in a limited number of well-studied cases (Clark et al. 2000; Carpenter 2002), scientists' ability to forecast ecological change and its probability distributions has important limitations. Often the amount of information available for projecting ecosystem behavior is insufficient. Some particularly large changes in ecosystems occur only infrequently and are therefore difficult to study, characterize, and predict (Turner and Dale 1998). Other changes are simply random. The dynamics of socioecological systems are especially challenging, and most of the systems of interest to the Millennium Ecosystem Assessment are socioecological ones. Last, many of the current and anticipated changes in ecosystems, and in human use of ecosystems, are new, and there is therefore no historical experience on which to base forecasts.

For these reasons, the probability distributions of ecological predictions or forecasts frequently cannot be characterized (Ludwig et al. 2001; Carpenter 2002). Ecological forecasts may also have many dimensions or contingencies, which means that a large number of potential outcomes must be considered. The multiplicity, contingency, and complexity of these many potential outcomes may be a barrier to understanding that limits the usefulness of the forecasts for decision-makers or the general public.

- development of scenarios for global futures linked explicitly to ecosystem services and the human consequences of ecosystem change,
- consideration of trade-offs among individual ecosystem services within the "bundle" of benefits that any particular ecosystem potentially provides to society,
- assessment of modeling capabilities for linking socioeconomic drivers and ecosystem services, and
- consideration of ambiguous futures as well as quantifiable uncertainties.

Review of Scenario Types and Approaches

Scenario analysis was first used for strategic planning during the early cold war period. However, scenarios about long-term sustainability of natural resource use did not emerge until the 1970s. These studies included the well-known report by Meadows et al. (1972) in which the authors discussed limits to human population growth. Scenarios were also being used by some businesses at this time, including Royal Dutch/Shell (Wack 1985), that have since become leaders in the field of scenario use for business and other uses.

Since 1995, there has been widespread use of scenarios to assess the status of the global environment. The MA intends to build on these examples, such as the reports of the Global Scenarios Group, UNEP's *Global Environmental Outlook*, the *Special Report on Emissions Scenarios* released by the IPCC, the scenarios of the World Business Council on Sustainable Development, the *World Water Vision Scenarios* of the World Water Commission, and the scenarios computed with the IMAGE model, to explore long-range dynamics of global environmental change. (See Table 7.1.)

In general, scenarios contain a description of step-wise changes, driving forces, base year, time horizon and time steps, and a storyline (Alcamo 2001). They are often classified by the method used to develop them, the goals and objectives, or the output. One classification of scenarios discriminates between "exploratory" and "anticipatory" scenarios. Exploratory scenarios are descriptive: they begin in the present and explore trends into the future. Anticipatory scenarios start with a vision of the future that could be optimistic, pessimistic, or neutral and work backwards in time to imagine how society might reach that future. The MA approach to development scenarios is likely to be a mixture of exploratory and anticipatory approaches.

Scenarios can be built around qualitative information, quantitative information, or a combination of both. Qualitative scenarios include qualitative information and use a narrative text to convey the main scenario messages. This can be helpful when presenting information to a nonscientific audience. Quantitative scenarios usually rely on models based on quan-

TABLE 7.1 Overview of Some Global Scenario Projects

Name	Description	Citation
Global Scenario Group (GSG)	Examines global scenarios based on three classes: conventional worlds, barbarization, and great transitions	Gallopin 1997, Raskin et al. 1998, Raskin et al. 2002
Global Environmental Outlook 3 (GEO-3)	Similar to GSG, with emphasis on regional texture	UNEP 2002
World Business Council on Sustainable Development (WBCSD)	Scenarios aimed at helping corporate members reflect on the business risks and opportunities of the sustainable development challenge (FROG!, GEOpolity, and Jazz)	WBCSD 1997
World Water Vision (WWV)	Three global water scenarios focusing on water supply and demand, including water requirements for ecosystems	Cosgrove and Rijsberman 2000, Gallopin and Rijsberman 2000
IPCC Special Report on Emission Scenarios (SRES)	Greenhouse gas emissions scenarios to the year 2100; axes of change are sustainable to unsustainable, and globally integrated to globally fragmented	SRES 2000

titative information to calculate future developments and changes; they are presented in the form of graphs and tables (Alcamo 2001). Both scenario types can be combined to develop internally consistent storylines based on quantification with models, which are then disseminated in a narrative form. This approach will be used to develop the MA scenarios. That is, we will develop a general qualitative storyline supported by quantification. Scenario development will be an iterative process, involving development of zero-order storylines, quantification of driving forces and indicators, and revision of the storylines together with various scenario user groups.

According to Alcamo (2001), good scenarios fulfill the objectives of the exercise; are sufficiently documented; are plausible; are internally consistent; challenge the beliefs and broaden the understanding of readers (experts, policy-makers, and laypeople); and convey complex interactions in the socioecological system. We will attempt to meet these goals through a participatory process that involves dialogue among scenario experts, scientists, decision-makers, user communities, and others.

The MA Approach to Scenario Analysis

At the most general level, the MA scenarios should connect possible changes in drivers with human demands for ecosystem services and, in turn, to the futures of the ecosystem services themselves and the aspects of human welfare that depend on them. This is a complex task.

Some of the drivers that might be considered ambiguous and uncontrollable include governance, economic globalization, climate, or emergence of disease. For example, the MA scenarios could consider the implications of increasing interconnectedness of economies at the global scale. How will such global economic changes affect the capacity of ecosystems to produce food and fiber, provide fresh water, and sustain biodiversity? What are the impacts of these ecological changes for the alleviation of poverty? And what are the implications for ecosystem services of changes in human welfare? Such feedbacks are at the heart of MA scenarios.

The Scenarios Working Group developed the following objectives to guide its scenario-building work:

- to illustrate that global changes are connected to ecosystem services at every scale, from global to local, and that these changes have implications for human well-being;
- to highlight major trade-offs among ecosystem services;

- to illustrate the effectiveness of different policies in making ecosystem services available and maintaining these services, including evaluating the effectiveness of policies at different scales; and
- to fulfill the objectives of scenario users.

The objective of the scenario-building exercise can also be summed up by the question, What are the possible co-evolutions of humanity and Earth's ecosystems? Several other more specific questions follow logically from this first one:

- How will ecosystem services support human well-being in the future?
- What are the major threats to the world's ecosystems?
- What are the trade-offs (in space, between current and future use, between ecosystem services, and so on)?
- What can be done to harmonize human welfare and production of ecosystem services?
- What are the appropriate incentive structures to ensure that ecosystems are used wisely?
- What are the signatures of different drivers of ecosystem goods and services and human well-being?
- What are the threats and opportunities for provision of ecosystem services?
- What are the appropriate scales for addressing ecosystem services, drivers, and interventions?

The current proposal under consideration by the Scenarios Working Group is to develop four or five scenarios. The group first evaluated five "zero-order" (very preliminary) scenarios found in previous global scenario exercises. (See Table 7.2.) Although the previous scenarios are detailed and carefully constructed, their focus is largely on social and economic issues. Environmental changes enter into many of them, both directly (for example, in the IPCC scenarios on global climate change) and indirectly (as drivers of societal change, for instance), but the many complex feedbacks that characterize real ecosystems are not explored or tested in detail in any existing global scenario.

The MA will approach the construction of global scenarios from an explicitly ecological perspective. That is, we will draw on previous scenarios but will focus on ecological surprises and cross-scale ecological feedbacks. MA scenarios should address branch points in global dynamics that are related to changes in ecosystem services. For example, how would the

TABLE 7.2 Zero-order Millennium Ecosystem Assessment Storylines Derived from Previous Global Scenario Exercises

Name*	Key Words	Similar To
EGS-1	Market-driven globalization, trade liberalization, institutional modernization	IPCC: A1 GEO-3: markets first GSG: market forces
EGS-2	As above, except strong policy focus on sustainability	IPCC: B1 GEO-3: market first / policy first GSG: market forces + policy reform
EGS-3	Value shift toward sustainability in industrial world; policy focus on poverty, sustainability	IPCC: B1 GSG: great transition GEO-3: sustainability first
EGS-4	Fragmented development; conservation of local identities; regionalization of economies	IPCC: A2, B2 GSG: multiworlds
EGS-5	Elites in fortresses (national or local); poverty and repression outside	WWV: business as usual GSG: fortress world GEO-3: security first

* EGS = ecosystem global scenario

global system change if ecosystems are more fragile than expected, or more robust than expected?

Scenarios will be developed for the global system. Quantitative outputs of the scenarios will be aggregated from regional data. As with previous global scenarios, a regional breakdown of quantitative outputs will be provided in some cases. Quantification will be accomplished using a combination of the models developed for other global scenarios projects, as described in this section. (See Table 7.3.)

Indicators will be chosen so that they reflect user needs, integrate information across ecosystem types, connect clearly to human well-being, are compelling, have scientific legitimacy, and are scalable. They should also be useful in estimating the vulnerability of society to changes in ecosystem services, including society's ability to cope and adapt to these changes.

Models to Support Scenario Analysis

As noted, part of the MA strategy for scenario analysis calls for the use of models to "quantify" the scenarios—that is, to generate quantitative aspects of the scenarios. For this task a wide range of models will be needed, as large a variety as described earlier for filling in data gaps.

Models will be used to "translate" the language of the scenarios into quantitative illustrations of changes in ecosystem services. The family of

TABLE 7.3 Matching of Millennium Ecosystem Assessment Scenarios with Earlier Scenario Exercises

Earlier Exercises	Models	EGS-1	EGS-2	EGS-3	EGS-4	EGS-5
GSG	PoleStar	Market forces	Policy reform	Great transitions	Eco-communalism	Fortress world
SRES	AIM, IMAGE, MESSAGE,MARIA, MINICAM, ASF	A1	A1-policy, B1	B1-policy	B2/A2-policy	A2
GEO-3	PoleStar, IMAGE, AIM, WaterGap Globio	Markets first	Policy first	Sustainability first	—	Security first
WWV	PoleStar, WaterGap IFPRI	TEC	TEC	VAL	—	BaU
WBCSD	—	FROG!	GEOpolity	Jazz	—	—
OECD	Jobs, PoleStar	Reference	Policy variants			

scenarios will each have associated changes in indirect and direct drivers—these can be used to drive process-based models of ecosystem services to help determine the ecological outcomes of the scenarios. For example, changes in climate, land use patterns, and water demand may be fed into watershed models to assess changes in freshwater availability, water quality, and aquatic habitats. Likewise, changes in forest cover and climate could be used to drive models of habitat loss in order to assess changes in biological diversity.

Because the MA is a multiscale assessment, and because the scenarios will be evaluated at multiple scales, modeling will be performed at local, regional, and global scales. At the global scale, gross changes in ecosystem services may be responding to changes in climate, atmospheric chemistry, and patterns of land use. Such modeling exercises could help pinpoint changes in freshwater availability, crop production, carbon sequestration, and habitat. At regional scales, modeling exercises could help illustrate more detailed outcomes of the scenarios: changes in water flows, agricultural systems, disease pathways, and water quality may be addressed at these scales. Finally, at local scales, questions related to community access to natural resources, as well as the relationships between environmental conditions and human health, may be best addressed.

Ultimately, models provide the means of translating the storylines of scenarios into quantitative assessments of changing ecosystem services. The degree of quantification that is performed will likely be somewhat limited in scope, as models are not available for every ecosystem process at every scale.

Overarching Issues

Matters of Scale

The issue of scale arises in nearly all aspects of an MA-type of assessment. By the "scale issue" we mean the question of whether data analyses and data comparisons correctly take into account the different aggregation levels by which ecosystems can be described. Here we only mention some of the main points of this issue, as Chapter 5 covers these questions more completely.

The scale issue is critical to the analytical approach of the MA because ecosystems operate and are measured and observed at different scales. At each scale researchers characterize the extent, pressures, conditions, and trends of ecosystem types. For any size patch other than the global scale, there will be a set of factors external to the ecosystem that influence how it functions and, in turn, there will be flows of mass and energy between the patch and the larger scales. On one hand, the larger the scale, the more inclusive the description of mass and energy flows. On the other hand, the larger the scale, the rougher the description of the ecosystem. Hence part of the scale issue is determining the correct spatial and temporal coverage and resolution to assess ecosystems and their services and drivers. Other examples of scale issues that must be addressed by the MA include the following:

- There needs to be as close a match as possible between the scale used to map ecosystems and the scale required to characterize ecosystem services.
- Ecosystem services themselves are described at different scales. For example, some services (such as providing fresh water) tend to operate more locally than others (such as climate regulation). The differences in scales must be taken into account in comparing the value of different ecosystem services.
- Many scale issues arise when models are used to provide information for an assessment. For example, coarse-scaled output from global climate models may be difficult to apply to local decisions or to use as input to finer-scaled local vegetation models.
- The analysis of response options also raises complex issues of scale. Often the management of natural resources such as forests or fisheries involves many different political and economic actors (local and na-

tional governments, for instance, and local and multinational companies) operating at many different spatial and organizational scales.

Review and Validation Procedures

The MA assessment reports will undergo two rounds of peer-review involving experts and governments. An independent Review Board has also been established to oversee this review process and to ensure that the review comments received are handled appropriately by the assessment authors. Much of the information contained in the assessment reports will be based on published scientific literature, which in turn has been through a formal process of peer review. However, the MA also seeks to incorporate information from traditional knowledge, practitioners' knowledge, and undocumented experience. This is particularly important in the case of the MA sub-global assessments—particularly the community-scale ones—since much of the information available for these may not be in the form of published scientific articles. Each of the MA sub-global assessments will develop a process to validate unpublished information, including many, if not all, of the following features:

- self-critical review notes or reflective diaries—the researcher should record information on his or her own perceptions of where information being recorded may be incomplete, biased, or in error;
- triangulation—multiple sources of information should be obtained, particularly for critical pieces of information;
- review by communities—where the information involves local or traditional knowledge, members of the community should be given an opportunity to review the findings prior to finalization of the assessment; and
- review by stakeholders at higher and lower scales—individuals who may not have detailed local knowledge of the area being assessed, but with knowledge of the region in which the assessment is located, should be given an opportunity to review the findings prior to finalization of the assessment.

In addition, when unpublished information is included in the global MA assessment reports, detailed information concerning the source of the information (such as names of people interviewed, dates and types of notes recorded, the presence or absence of a researcher's self-critical review notes, and other sources of information validating the information) will be made available to the co-chairs of the Working Group.

Analysis of Uncertainty

This section draws heavily on the document developed for handling uncertainty in IPPC assessments (Moss and Schneider 2000).

An assessment of the relative credibility of the range of ecosystem conditions, processes, and outcomes should be a major goal of assessment reports. It is important to adopt a consistent approach for assessing, characterizing, and reporting uncertainties. This will help improve communication between the research community and decision-makers regarding what is known and unknown (and to what degree) about the relevant issues covered in the assessment.

The scientific community must bear in mind that users of assessment reports are likely to estimate for themselves the extent of uncertainties if authors do not provide uncertainty estimates. Hence it is desirable for experts to give their best estimates of these uncertainties (e.g., Morgan and Henrion 1990).

An "uncertain estimate" can mean different things to different experts, ranging from an estimate just short of complete certainty to an informed guess or speculation. Sometimes uncertainty results from a lack of information; on other occasions it is caused by disagreement about what is known or even knowable. Some categories of uncertainty are amenable to quantification, while other kinds cannot be sensibly expressed in terms of probabilities. (See Schneider et al. 1998 for a survey of the literature on characterizations of uncertainty.)

Uncertainty is not unique to the domains of biophysical and socioeconomic research. Uncertainties also arise from such factors as linguistic imprecision, statistical variation, measurement error, variability, approximation, subjective judgment, and disagreement. These problems can be compounded, however, by additional characteristics of environmental change research, such as potentially long time lags between driving forces and response at larger scales. Moreover, because environmental change and other complex, sociotechnical policy issues are not just scientific topics but also matters of public debate, it is important to recognize that even good data and thoughtful analysis may be insufficient to dispel some aspects of uncertainty associated with the different standards of evidence and degrees of risk aversion or acceptance that individuals may hold (Morgan 1998; Casman et al. 1999).

In many cases, a "Bayesian" or "subjective" characterization of probability will be appropriate (Gelman et al. 1995; Bernardo and Smith 2000). The Bayesian paradigm is a formal and rigorous method for calculating probabilities, and is often used in the "rational" analysis of decisions

(Lindley 1985; Pratt et al. 1995). Bayesian statistics can be used to calculate probability distributions in the absence of information by using prior distributions that represent best estimates by the scientists making the calculations. This is a different type of subjectivity, which must be addressed in a straightforward and transparent way in the MA calculations.

Although "science" itself strives for objective empirical information to test theory and models, "science for policy" must be recognized as a different enterprise, involving being responsive to policy-makers' needs for expert judgment at a particular time, given the information currently available, even if those judgments involve a considerable degree of subjectivity. Such subjectivity should be both consistently expressed (linked to quantitative distributions when possible), and explicitly stated so that well-established and highly subjective judgments are less likely to get confounded in policy debates. The key point is that authors should explicitly state what sort of approach they are using in a particular case. Transparency is the key in all cases.

Vague or broad statements of "medium confidence" that are difficult to support or refute should be avoided. For example, scientists could have at least medium confidence that "desalinization could alter biodiversity." Such a statement is not particularly informative unless the degree of desalinization and the direction and severity of the biodiversity change are specified. The point is to avoid conclusions that are essentially indifferent statements based on speculative knowledge.

The procedure for carrying out an uncertainty analysis depends very much on the data and information available about a particular subject. Where the amount of information is relatively rich, the following procedure can be followed:

- For each major finding, identify the most important factors and uncertainties that are likely to affect the conclusions.
- Document ranges and distributions from the literature, including sources of information on the key causes of uncertainty and the types of evidence available to support a finding.
- Make an initial determination of the appropriate level of precision—determine whether quantitative estimates are possible, or only qualitative statements.
- Specify the distribution of values that a parameter, variable, or outcome may take in either quantitative or qualitative form. Identify end points of the range and provide an assessment of the central tendency and general shape of the distribution, if appropriate.

- Rate and describe the state of scientific information on which the conclusions or estimates in the preceding step are based.
- Prepare a "traceable account" of how the estimates were constructed, describing reasons for adopting a particular probability distribution.

Note that some of these steps (particularly those having to do with estimating the probability distributions of parameters and variables) sometimes must be omitted because of lack of information or time to carry out a full analysis.

Not only is the method for assessing uncertainty important, so is the communication of uncertainty. Among the effective ways to communicate uncertainty is to present it in clear graphical form. Various approaches for graphical presentation of uncertainties are available, involving tradeoffs between simplicity and sophistication, particularly in the choice of the number of dimensions to use in presenting the information. Using various approaches, the degree to which experts agree on the uncertainty estimates can also be depicted.

Conclusion

The aim of this chapter has been to provide a road-map for how the MA will be carried out. We have pointed out that such a complex and comprehensive assessment will raise many difficult issues about data handling, data analysis, uses of modeling, scenario analysis, and so on. Although some of these issues will only be resolved in the course of implementing the MA, this chapter suggests many useful actions for resolving these issues. Taken together, these actions make up a coherent analytical approach for achieving the goals of the Millennium Ecosystem Assessment.

8 *Strategic Interventions, Response Options, and Decision-making*

Executive Summary

- Decision-making processes and institutions operate across spatial scales and organizational levels—from the village to the planet. Decision processes are value-based and combine political and technical elements to varying degrees. Desirable properties of decision-making processes include equity, attention to vulnerability, transparency, accountability, and participation.
- Strategies and interventions that will help meet societies' goals for the conservation and sustainable use of ecosystems include incorporating the value of ecosystems in decisions, channeling diffuse ecosystem benefits to decision-makers with focused local interests, creating markets and property rights, educating and dispersing knowledge, and investing to improve ecosystems and the services they provide.
- The choice among options will be greatly influenced by the temporal and physical scale of the problem or opportunity, the uncertainties, the cultural context, and questions of equity.
- Mechanisms for accomplishing these interventions include conventions, laws, regulations, and enforcement; contracts, partnerships, and collaboration; and private and public action.
- Institutions at different levels have different response options available to them, and special care is required to ensure policy coherence. Decision-making processes combine problem identification and analysis, policy option identification, policy choice, policy implementation, and monitoring and evaluation in an iterative fashion.
- A range of tools is available to choose among response options—from cultural prescriptive rules to cost-benefit and cost-effectiveness analysis. In the selection of an analytical tool and in the evaluation of response options, the social, economic, environmental, and historical context should be taken into account.
- Policies at each level and scale need to be adaptive and flexible in order to learn from past experience, to hedge against risk, and to consider uncertainty. However, trade-offs between the responsiveness and the stability of the policy environment need to be considered.