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Ecosystems and Human Well-being: Current State and Trends, Volume 1

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Ecosystems and Human Well-being: Current State and Trends, Volume 1

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Findings of the Condition and Trends Working Group
of the Millennium Ecosystem Assessment

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Ecosystems and Human Well-being: A Framework for Assessment
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Millennium Ecosystem Assessment: Objectives, Focus, and Approach

The Millennium Ecosystem Assessment was carried out between 2001 and 2005 to assess the consequences of ecosystem change for human well-being and to establish the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems and their contributions to human well-being. The MA responds to government requests for information received through four international conventions—the Convention on Biological Diversity, the United Nations Convention to Combat Desertification, the Ramsar Convention on Wetlands, and the Convention on Migratory Species—and is designed to also meet needs of other stakeholders, including the business community, the health sector, nongovernmental organizations, and indigenous peoples. The sub-global assessments also aimed to meet the needs of users in the regions where they were undertaken.

The assessment focuses on the linkages between ecosystems and human well-being and, in particular, on "ecosystem services." An ecosystem is a dynamic complex of plant, animal, and microorganism communities and the nonliving environment interacting as a functional unit. The MA deals with the full range of ecosystems—from those relatively undisturbed, such as natural forests, to landscapes with mixed patterns of human use and to ecosystems intensively managed and modified by humans, such as agricultural land and urban areas. Ecosystem services are the benefits people obtain from ecosystems. These include *provisioning services* such as food, water, timber, and fiber; *regulating services* that affect climate, floods, disease, wastes, and water quality; *cultural services* that provide recreational, aesthetic, and spiritual benefits; and *supporting services* such as soil formation, photosynthesis, and nutrient cycling. The human species, while buffered against environmental changes by culture and technology, is fundamentally dependent on the flow of ecosystem services.

The MA examines how changes in ecosystem services influence human well-being. Human well-being is assumed to have multiple constituents, including the *basic material for a good life*, such as secure and adequate livelihoods, enough food at all times, shelter, clothing, and access to goods; *health,* including feeling well and having a healthy physical environment, such as clean air and access to clean water; *good social relations,* including social cohesion, mutual respect, and the ability to help others and provide for children; *security,* including secure access to natural and other resources, personal safety, and security from natural and human-made disasters; and *freedom of choice and action,* including the opportunity to achieve what an individual values doing and being. Freedom of choice and action is influenced by other constituents of well-being (as well as by other factors, notably education) and is also a precondition for achieving other components of well-being, particularly with respect to equity and fairness.

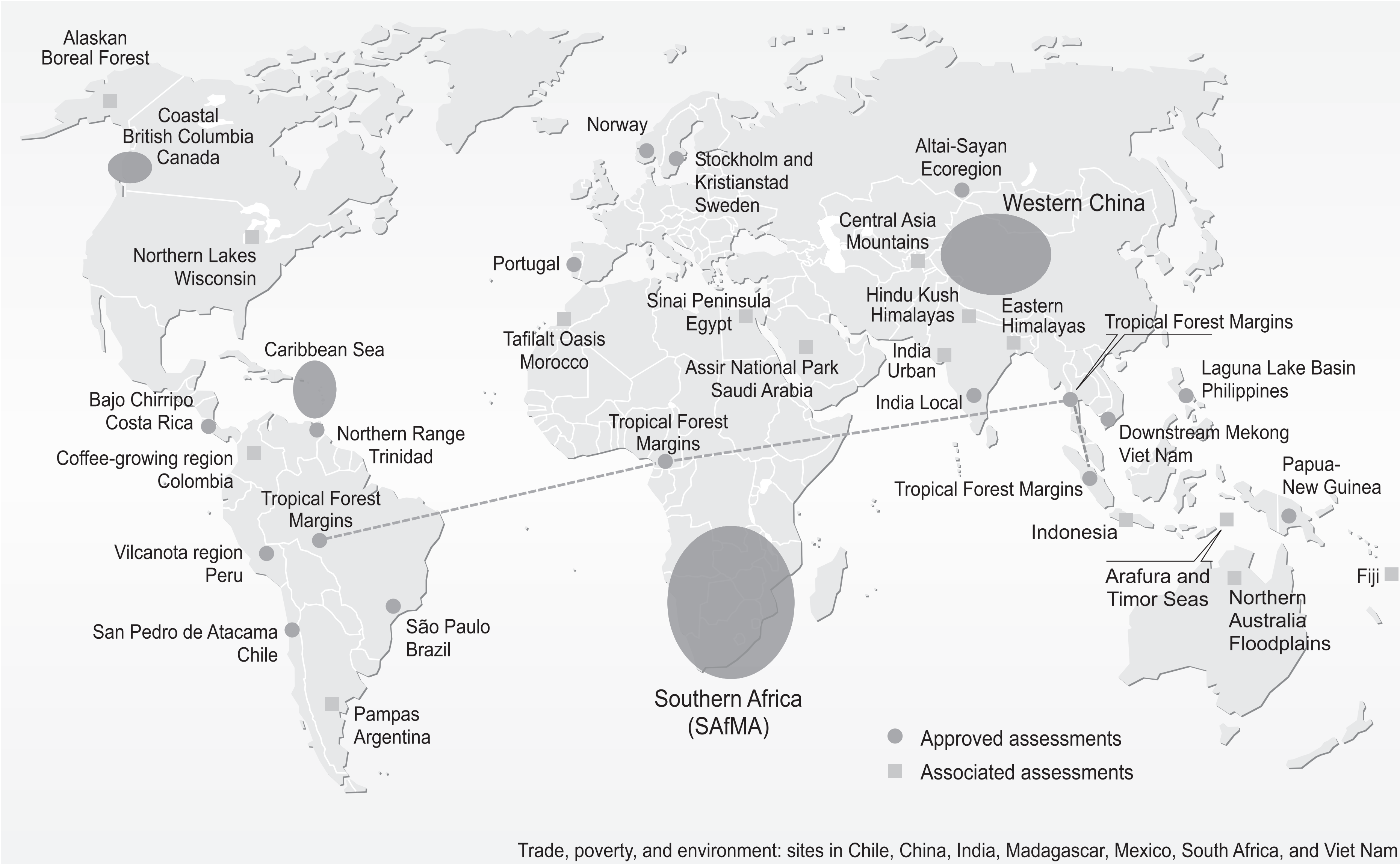
The conceptual framework for the MA posits that people are integral parts of ecosystems and that a dynamic interaction exists between them and other parts of ecosystems, with the changing human condition driving, both directly and indirectly, changes in ecosystems and thereby causing changes in human well-being. At the same time, social, economic, and cultural factors unrelated to ecosystems alter the human condition, and many natural forces influence ecosystems. Although the MA emphasizes the linkages between ecosystems and human well-being, it recognizes that the actions people take that influence ecosystems result not just from concern about human well-being but also from considerations of the intrinsic value of species and ecosystems. Intrinsic value is the value of something in and for itself, irrespective of its utility for someone else.

The Millennium Ecosystem Assessment synthesizes information from the scientific literature and relevant peer-reviewed datasets and models. It incorporates knowledge held by the private sector, practitioners, local communities, and indigenous peoples. The MA did not aim to generate new primary knowledge but instead sought to add value to existing information by collating, evaluating, summarizing, interpreting, and communicating it in a useful form. Assessments like this one apply the judgment of experts to existing knowledge to provide scientifically credible answers to policy-relevant questions. The focus on policy-relevant questions and the explicit use of expert judgment distinguish this type of assessment from a scientific review.

Five overarching questions, along with more detailed lists of user needs developed through discussions with stakeholders or provided by governments through international conventions, guided the issues that were assessed:

- What are the current condition and trends of ecosystems, ecosystem services, and human well-being?
- What are plausible future changes in ecosystems and their ecosystem services and the consequent changes in human well-being?
- What can be done to enhance well-being and conserve ecosystems? What are the strengths and weaknesses of response options that can be considered to realize or avoid specific futures?
- What are the key uncertainties that hinder effective decision-making concerning ecosystems?
- What tools and methodologies developed and used in the MA can strengthen capacity to assess ecosystems, the services they provide, their impacts on human well-being, and the strengths and weaknesses of response options?

The MA was conducted as a multiscale assessment, with interlinked assessments undertaken at local, watershed, national, regional, and global scales. A global ecosystem assessment cannot easily meet all the needs of decision-makers at national and sub-national scales because the management of any



Eighteen assessments were approved as components of the MA. Any institution or country was able to undertake an assessment as part of the MA if it agreed to use the MA conceptual framework, to centrally involve the intended users as stakeholders and partners, and to meet a set of procedural requirements related to peer review, metadata, transparency, and intellectual property rights. The MA assessments were largely self-funded, although planning grants and some core grants were provided to support some assessments. The MA also drew on information from 16 other sub-global assessments affiliated with the MA that met a subset of these criteria or were at earlier stages in development.

SUB-GLOBAL ASSESSMENT	ECOSYSTEM TYPES										ECOSYSTEM SERVICES								
	COASTAL	CULTIVATED	DRYLAND	FOREST	INLAND WATER	ISLAND	MARINE	MOUNTAIN	POLAR	URBAN	FOOD	WATER	FUEL and ENERGY	BIODIVERSITY-RELATED	CARBON SEQUESTRATION	FIBER and TIMBER	RUNOFF REGULATION	CULTURAL, SPIRITUAL, AMENITY	OTHERS
Altai-Sayan Ecoregion			●	●	●			●			●		●	●		●		●	
San Pedro de Atacama, Chile			●		●						●	●		●			●	●	●
Caribbean Sea	●					●	●				●	●		●				●	
Coastal British Columbia, Canada	●			●	●			●			●			●		●	●	●	
Bajo Chirripo, Costa Rica		●		●	●						●	●		●		●		●	●
Tropical Forest Margins		●		●							●	●		●	●	●	●		●
India Local Villages		●		●	●						●	●	●	●		●	●	●	●
Glomma Basin, Norway		●		●	●			●			●		●			●		●	●
Papua New Guinea	●	●				●	●				●	●	●	●		●	●	●	●
Vilcanota, Peru		●	●					●			●	●		●			●	●	●
Laguna Lake Basin, Philippines		●		●	●						●	●		●	●			●	●
Portugal	●	●	●	●	●	●	●	●		●	●	●		●	●	●	●	●	●
São Paulo Green Belt, Brazil	●	●		●	●					●	●	●		●	●	●	●	●	●
Southern Africa	●	●	●	●	●					●	●	●	●	●		●		●	●
Stockholm and Kristianstad, Sweden		●			●					●	●	●		●	●	●	●	●	●
Northern Range, Trinidad	●			●	●			●			●	●		●		●	●	●	●
Downstream Mekong Wetlands, Viet Nam	●	●			●						●	●	●	●	●	●	●	●	●
Western China		●	●	●	●			●			●	●		●	●		●		●
Alaskan Boreal Forest				●	●						●					●		●	●
Arafura and Timor Seas	●					●	●				●			●	●				●
Argentine Pampas		●									●	●						●	●
Central Asia Mountains								●			●	●		●					●
Colombia coffee-growing regions		●						●			●	●		●				●	
Eastern Himalayas				●				●			●	●	●	●				●	
Sinai Peninsula, Egypt			●					●						●			●	●	●
Fiji	●					●					●	●	●						●
Hindu Kush-Himalayas					●			●				●		●			●	●	●
Indonesia	●					●	●				●			●					●
India Urban Resource										●	●	●	●	●	●			●	●
Tafilalt Oasis, Morocco		●	●								●	●						●	●
Northern Australia Floodplains					●						●	●		●			●	●	●
Assir National Park, Saudi Arabia		●		●				●			●						●	●	●
Northern Highlands Lake District, Wisconsin				●	●							●				●	●	●	●

particular ecosystem must be tailored to the particular characteristics of that ecosystem and to the demands placed on it. However, an assessment focused only on a particular ecosystem or particular nation is insufficient because some processes are global and because local goods, services, matter, and energy are often transferred across regions. Each of the component assessments was guided by the MA conceptual framework and benefited from the presence of assessments undertaken at larger and smaller scales. The sub-global assessments were not intended to serve as representative samples of all ecosystems; rather, they were to meet the needs of decision-makers at the scales at which they were undertaken. The sub-global assessments involved in the MA process are shown in the Figure and the ecosystems and ecosystem services examined in these assessments are shown in the Table.

The work of the MA was conducted through four working groups, each of which prepared a report of its findings. At the global scale, the Condition and Trends Working Group assessed the state of knowledge on ecosystems, drivers of ecosystem change, ecosystem services, and associated human well-being around the year 2000. The assessment aimed to be comprehensive with regard to ecosystem services, but its coverage is not exhaustive. The Scenarios Working Group considered the possible evolution of ecosystem services during the twenty-first century by developing four global scenarios exploring plausible future changes in drivers, ecosystems, ecosystem services, and human well-being. The Responses Working Group examined the strengths and weaknesses of various response options that have been used to manage ecosystem services and identified promising opportunities for improving human well-being while conserving ecosystems. The report of the Sub-global Assessments Working Group contains lessons learned from the MA sub-global assessments. The first product of the MA—*Ecosystems and Human Well-being: A Framework for Assessment,* published in 2003—outlined the focus, conceptual basis, and methods used in the MA. The executive summary of this publication appears as Chapter 1 of this volume.

Approximately 1,360 experts from 95 countries were involved as authors of the assessment reports, as participants in the sub-global assessments, or as members of the Board of Review Editors. The latter group, which involved 80 experts, oversaw the scientific review of the MA reports by governments and experts and ensured that all review comments were appropriately addressed by the authors. All MA findings underwent two rounds of expert and governmental review. Review comments were received from approximately 850 individuals (of which roughly 250 were submitted by authors of other chapters in the MA), although in a number of cases (particularly in the case of governments and MA-affiliated scientific organizations), people submitted collated comments that had been prepared by a number of reviewers in their governments or institutions.

The MA was guided by a Board that included representatives of five international conventions, five U.N. agencies, international scientific organizations, governments, and leaders from the private sector, nongovernmental organizations, and indigenous groups. A 15-member Assessment Panel of leading social and natural scientists oversaw the technical work of the assessment, supported by a secretariat with offices in Europe, North America, South America, Asia, and Africa and coordinated by the United Nations Environment Programme.

The MA is intended to be used:

- to identify priorities for action;
- as a benchmark for future assessments;
- as a framework and source of tools for assessment, planning, and management;
- to gain foresight concerning the consequences of decisions affecting ecosystems;
- to identify response options to achieve human development and sustainability goals;
- to help build individual and institutional capacity to undertake integrated ecosystem assessments and act on the findings; and
- to guide future research.

Because of the broad scope of the MA and the complexity of the interactions between social and natural systems, it proved to be difficult to provide definitive information for some of the issues addressed in the MA. Relatively few ecosystem services have been the focus of research and monitoring and, as a consequence, research findings and data are often inadequate for a detailed global assessment. Moreover, the data and information that are available are generally related to either the characteristics of the ecological system or the characteristics of the social system, not to the all-important interactions between these systems. Finally, the scientific and assessment tools and models available to undertake a cross-scale integrated assessment and to project future changes in ecosystem services are only now being developed. Despite these challenges, the MA was able to provide considerable information relevant to most of the focal questions. And by identifying gaps in data and information that prevent policy-relevant questions from being answered, the assessment can help to guide research and monitoring that may allow those questions to be answered in future assessments.

Contents

Foreword

The Millennium Ecosystem Assessment was called for by United Nations Secretary-General Kofi Annan in 2000 in his report to the UN General Assembly, *We the Peoples: The Role of the United Nations in the 21st Century.* Governments subsequently supported the establishment of the assessment through decisions taken by three international conventions, and the MA was initiated in 2001. The MA was conducted under the auspices of the United Nations, with the secretariat coordinated by the United Nations Environment Programme, and it was governed by a multistakeholder board that included representatives of international institutions, governments, business, NGOs, and indigenous peoples. The objective of the MA was to assess the consequences of ecosystem change for human well-being and to establish the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems and their contributions to human well-being.

This volume has been produced by the MA Condition and Trends Working Group and assesses the state of knowledge on ecosystems and their services, the drivers of ecosystem change, and the consequences of ecosystem change for human well-being. The material in this report has undergone two extensive rounds of peer review by experts and governments, overseen by an independent Board of Review Editors.

This is one of four volumes (*Current State and Trends, Scenarios, Policy Responses,* and *Multiscale Assessments*) that present the technical findings of the Assessment. Six synthesis reports have also been published: one for a general audience and others focused on issues of biodiversity, wetlands and water, desertification, health, and business and ecosystems. These synthesis reports were prepared for decision-makers in these different sectors, and they synthesize and integrate findings from across all of the Working Groups for ease of use by those audiences.

This report and the other three technical volumes provide a unique foundation of knowledge concerning human dependence on ecosystems as we enter the twenty-first century. Never before has such a holistic assessment been conducted that addresses multiple environmental changes, multiple drivers, and multiple linkages to human well-being. Collectively, these reports reveal both the extraordinary success that humanity has achieved in shaping ecosystems to meet the needs of growing populations and economies and the growing costs associated with many of these changes. They show us that these costs could grow substantially in the future, but also that there are actions within reach that could dramatically enhance both human well-being and the conservation of ecosystems.

A more exhaustive set of acknowledgments appears later in this volume but we want to express our gratitude to the members of the MA Board, Board Alternates, Exploratory Steering Committee, Assessment Panel, Coordinating Lead Authors, Lead Authors, Contributing Authors, Board of Review Editors, and Expert Reviewers for their extraordinary contributions to this process. (The list of reviewers is available at www.MAweb.org.) We also would like to thank the MA Secretariat and in particular the staff of the Condition and Trends Working Group Technical Support Unit for their dedication in coordinating the production of this volume, as well as the World Conservation Monitoring Centre, which housed this TSU.

We would particularly like to thank the Co-chairs of the Condition and Trends Working Group, Dr. Rashid Hassan and Dr. Robert Scholes, and the TSU Coordinator, Neville Ash, for their skillful leadership of this Working Group and their contributions to the overall assessment.

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Preface

The *Current State and Trends* assessment presents the findings of the Condition and Trends Working Group of the Millennium Ecosystem Assessment. This volume documents the current condition and recent trends of the world's ecosystems, the services they provide, and associated human well-being around the year 2000. Its primary goal is to provide decision-makers, ecosystem managers, and other potential users with objective information and analyses of historical trends and dynamics of the interaction between ecosystem change and human well-being. This assessment establishes a baseline for the current condition of ecosystems at the turn of the millennium. It also assesses how changes in ecosystems have affected the underlying capacity of ecosystems to continue to provide these services in the near future, providing a link to the Scenarios Working Group's report. Finally, it considers recent trends in ecosystem conditions that have been the result of historical responses to ecosystem service problems, providing a link to the Responses Working Group's report.

Although centered on the year 2000, the temporal scope of this assessment includes the ''relevant past'' to the ''foreseeable future.'' In practice, this means analyzing trends during the latter decades of the twentieth century and extrapolating them forward for a decade or two into the twenty-first century. At the point where the projections become too uncertain to be sustained, the Scenarios Working Group takes over the exploration of alternate futures.

The Condition and Trends assessment aims to synthesize and add to information already available from other sources, whether in the primary scientific literature or already in assessment form. In many instances this information is not reproduced in this volume but is built upon to report additional findings here. So this volume does not, for example, provide an assessment of the science of climate change per se, as that is reported in the findings of the Intergovernmental Panel on Climate Change, but the findings of the IPCC are used here as a basis to present information on the consequences of climate change for ecosystem services.

A summary of the process leading to this document is provided in Figure A.

The document has three main parts plus a synthesis chapter and supporting material. (See Figure B.) After the introductory material in Part I, the findings from the technical assessments are presented in two orthogonal ways: Part II deals with individual categories of ecosystem services, viewed across all the ecosystem types from which they are derived, while Part III analyses the various systems from which bundles of services are derived. Such organization allows the chapters to be read as standalone documents and assists readers with thematic interests. In Part IV, the synthesis chapter pulls out the key threads of findings from the earlier parts to construct an integrated narrative of the key issues relating ecosystem change (through changes in ecosystem services) to impacts on human well-being.

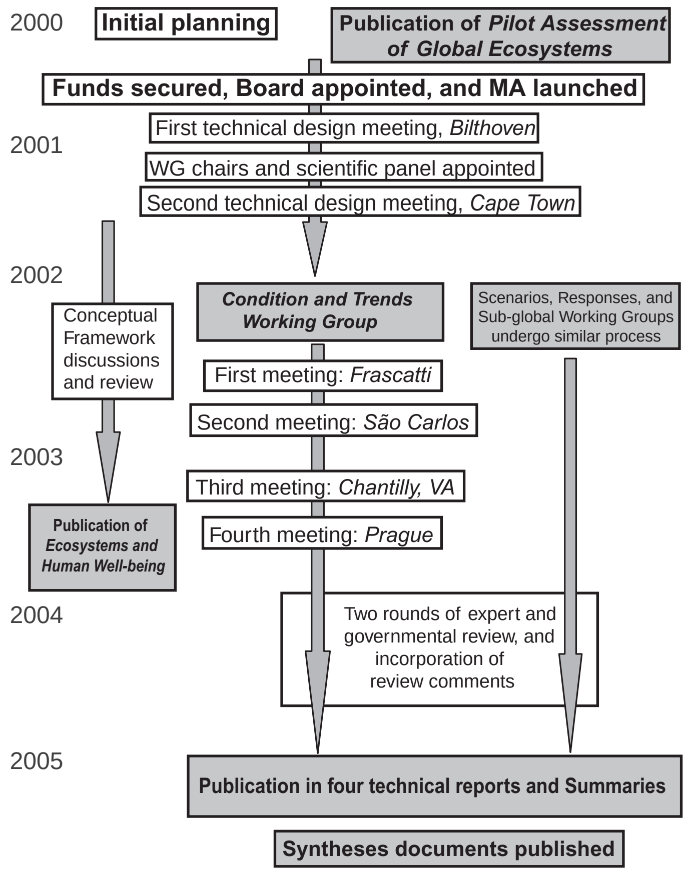

Figure A. Schedule of the Condition and Trends Working Group Assessment

Appendices provide an extensive glossary of terms, abbreviations, and acronyms; information on authors; and color graphics.

Part I: General Concepts and Analytical Approaches

The first part of this report introduces the overarching conceptual, methodological, and crosscutting themes of the MA integrated approach, and for this reason it precedes the technical assessment parts. Following the executive summary of the MA conceptual framework volume (*Ecosystems and Human Well-being: A Framework for Assessment*), which is **Chapter 1,** the analytical approaches to a global assessment of ecosystems and ecosystem services are outlined in **Chapter 2. Chapter 3** provides a summary assessment of the most important changes in key indirect and direct drivers of ecosystem change over the last part of the

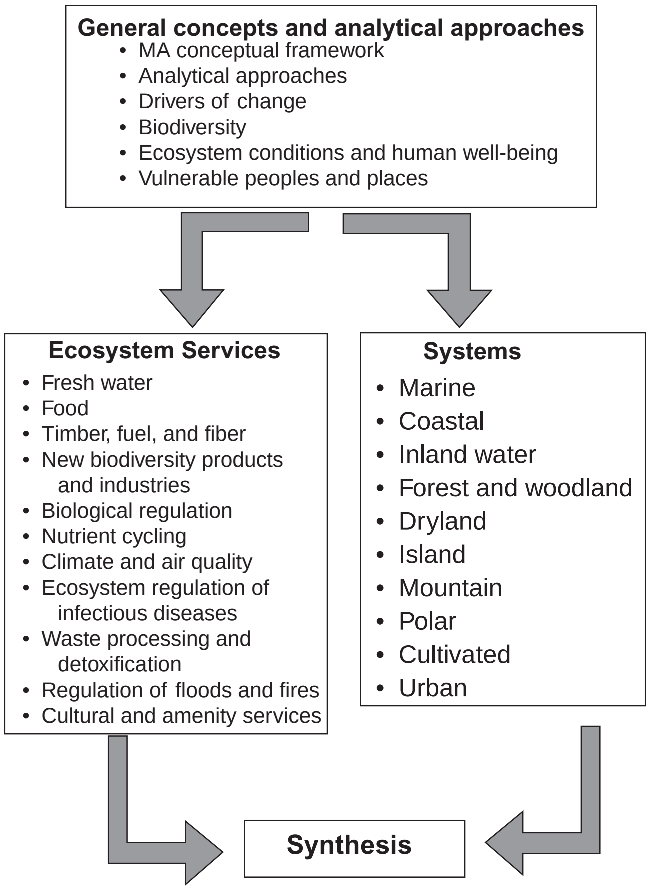

Figure B. Structure of the Condition and Trends Working Group Assessment Report

twentieth century, and considers some of the key interactions between these drivers (the full assessment of drivers, of which this chapter is a summary, can be found in the *Scenarios* volume, Chapter 7). The remaining chapters in Part I—on biodiversity (**Chapter 4**), human well-being (**Chapter 5**), and vulnerability (**Chapter 6**)—introduce issues at a global scale but also contain a synthesis of material drawn from chapters in Parts II and III.

Each of these introductory overarching chapters aims to deal with the general issues related to its topic, leaving the specifics embedded in later chapters. This is intended to enhance readability and to help reduce redundancy across the volume. For example, **Chapter 2** seeks to give an overview of the types of analytical approaches and methods used in the assessment, but not provide a recipe for conducting specific assessments, and **Chapter 3** aims to provide the background to the various drivers that would otherwise need to be discussed in multiple subsequent chapters.

Biodiversity provides composition, structure, and function to ecosystems. The amount and diversity of life is an underlying necessity for the provision of all ecosystem services, and for this reason **Chapter 4** is included in the introductory section rather than as a chapter in the part on ecosystem services. It outlines the key global trends in biodiversity, our state of knowledge on biodiversity in terms of abundance and distribution, and the role of biodiversity in the functioning of ecosystems. Later chapters consider more fully the role of biodiversity in the provision of ecosystem services.

The consequences of ecosystem change for human well-being are the core subject of the MA. **Chapter 5** presents our state of knowledge on the links between ecosystems and human well-being and outlines the broad patterns in well-being around the world.

Neither the distribution of ecosystem services nor the change in these services is evenly distributed across places and societies. Certain ecosystems, locations, and people are more at risk from changes in the supply of services than others. **Chapter 6,** on vulnerable peoples and places, identifies these locations and groups and examines why they are particularly vulnerable to changes in ecosystems and ecosystem services.

Part II: An Assessment of Ecosystem Services

The Condition and Trends assessment sets out to be comprehensive in its treatment of ecosystem services but not exhaustive. The list of "benefits that people derive from ecosystems" grows continuously with further investigation. The 11 groups of services covered by this assessment deal with issues that are of vital importance almost everywhere in the world and represent, in the opinion of the Working Group, the main services that are most important for human well-being and are most affected by changes in ecosystem conditions. The MA only considers ecosystem services that have a nexus with life on Earth (biodiversity). For example, while gemstones and tidal energy can both provide benefits to people, and both are found within ecosystems, they are not addressed in this report since their generation does not depend on the presence of living organisms. The ecosystem services assessed and the chapter titles in this part are:

Provisioning services:
- Fresh Water
- Food
- Timber, Fiber, and Fuel
- New Products and Industries from Biodiversity

Regulating and supporting services:
- Biological Regulation of Ecosystem Services
- Nutrient Cycling
- Climate and Air Quality
- Human Health: Ecosystem Regulation of Infectious Diseases
- Waste Processing and Detoxification
- Regulation of Natural Hazards: Floods and Fires

Cultural services:
- Cultural and Amenity Services

Each of the chapters in this section in fact deals with a cluster of several related ecosystem services. For instance, the chapter on food covers the provision of numerous cereal crops, vegetables and fruits, beverages, livestock, fish, and other edible products; the chapter on nutrient cycling addresses the benefits derived from a range of nutrient cycles, but with a focus on nitrogen; and the chapter on cultural and amenity services covers a range of such services, including recreation, aesthetic, and spiritual services. The length of the treatment afforded to each service reflects several factors: our assessment of its relative importance to human well-being; the scope and complexity of the topic; the degree to which it has been treated in other assessments (thus reducing the need for a comprehensive treatment here); and the amount of information that is available to be assessed.

Part II considers services from each of the four MA categories: provisioning, regulating, cultural, and supporting services. Each service chapter has been developed to cover the same types of information. First the service is defined. Then, for each service, the spatial distribution of supply and demand is quantified, along with recent trends. The direct and indirect drivers of change in the service are analyzed. And finally the consequences of the changes in the service for human well-being are examined and quantified to the degree possible.

Examples are given of the responses by decision-makers at various levels (from the individual to the international) to issues relating to change in service supply. Both successful and unsuccessful interventions are described, as supportive material for the *Policy Responses* volume.

Part III: An Assessment of Systems from which Ecosystem Services Are Derived

The Condition and Trends Working Group uses the term ''systems'' in describing these chapters rather than the term ''ecosystems.'' This is for several reasons. First, the ''systems'' used are essentially reporting units, defined for pragmatic reasons. They represent easily recognizable broad categories of landscape or seascape, with their included human systems, and typically represent units or themes of management or intervention interest. Ecosystems, on the other hand, are theoretically defined by the interactions of their components.

The 10 selected systems assessed here cover much larger areas than most ecosystems in the strict sense and include areas of system type that are far apart (even isolated) and that thus interact only weakly. In fact, there may be stronger local interactions with embedded fragments of ecosystems of a different type rather than within the nominal type of the system. The ''cultivated system,'' for instance, considers a landscape where crop farming is a primary activity but that probably includes, as an integral part of that system, patches of rangeland, forest, water, and human settlements.

Second, while it is recognized that humans are always part of ecosystems, the definitions of the systems used in this report take special note of the main patterns of human use. The systems are defined around the main bundles of services they typically supply and the nature of the impacts that human use has on those services.

Information within the systems chapters is frequently presented by subsystems where appropriate. For example, the forest chapter deals separately with tropical, temperate, and boreal forests because they deliver different services; likewise, the coastal chapter deals explicitly with various coastal subsystems, such as mangroves, corals, and seagrasses.

The 10 system categories and the chapter titles in this part are:

- Marine Fisheries Systems
- Coastal Systems
- Inland Water Systems
- Forest and Woodland Systems
- Dryland Systems
- Island Systems
- Mountain Systems
- Polar Systems
- Cultivated Systems
- Urban Systems

Definitions for these system categories can be found in Box 1.3 in Chapter 1. These system categories are not mutually exclusive, and some overlap spatially. For instance, mountain systems contain areas of forest systems, dryland systems, inland water systems, cultivated systems, and urban systems, while coastal systems include components of all of the above, including mountain systems. Due to this overlap, simple summations of services across systems for global totals should be avoided (an exercise that the MA has avoided in general): some may be double-counted, while others may be underrepresented. Notwithstanding these caveats, the systems have been defined to cover most of the Earth's surface and not to overlap unnecessarily. In many instances the boundaries between systems are diffuse, but not arbitrary. For instance, the coastal system blends seamlessly into the marine system on the one hand and the land systems on the other. The 50-meter depth distinction between coastal and marine separates the systems strongly influenced by actions on the land from those overwhelmingly influenced by fishing. There is significant variation in the area of coverage of each system.

The system definitions are also not exhaustive, and no attempt has been made to cover every part of the global surface. Although ~99% of global surface area has been covered in this assessment, there are just over 5 million square kilometers of terrestrial land surface not included spatially within any of the MA system boundaries. These areas are generally found within grassland, savanna, and forest biomes, and they contain a mix of land cover classes—generally grasslands, degraded forests, and marginal agricultural lands—that are not picked up within the mapping definitions for the system boundaries. However, while these excluded areas may not appear in the various statistics produced along system boundaries, the issues occurring in these areas relating to ecosystem services are well covered in the various services chapters, which do not exclude areas of provision outside MA system boundaries.

The main motivation for dealing with ''systems'' as well as ''services'' is that the former perspective allows us to examine interactions between the services delivered from a single location. These interactions can take the form of trade-offs (that is, where promoting one service reduces the supply of another service), win-win situations (where a single management package enhances the supply of several services), or synergies, where the simultaneous use of services raises or depresses both more than if they were independently used.

The chapters in Part III all present information in a broadly similar manner: system description, including a map and descriptive statistics for the system and its subsystems; quantification of the services it delivers and their contribution to well-being; recent trends in the condition of the system and its capacity to provide services; processes leading to changes in the system; the choices and resultant trade-offs between systems and between services within the system; and the contributions of the system to human well-being.

Part IV: Synthesis

Chapter 28 does not intend to be a summary. That task is left to the summaries or Main Messages of each chapter and to the Summary at the start of this volume. Instead, the synthesis chapter constructs an integrated narrative, tracing the principal causes of ecosystem change, the consequences for ecosystems and ecosystem services, and the resultant main impacts on human well-being. The chapter considers the key intellectual issues arising from the Condition and Trends assessment and presents an assessment of our underlying knowledge on the consequences of ecosystem change for people.

Supporting material for many of the chapters, and further details of the Millennium Ecosystem Assessment, including of the various sub-global assessments, plus a full list of reviewers, can be found at the MA Web site at www.MAweb.org.

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Reader's Guide

The four technical reports present the findings of each of the MA Working Groups: Condition and Trends, Scenarios, Responses, and Sub-global Assessments. A separate volume, *Our Human Planet*, presents the summaries of all four reports in order to offer a concise account of the technical reports for decision-makers. In addition, six synthesis reports were prepared for ease of use by specific audiences: Synthesis (general audience), CBD (biodiversity), UNCCD (desertification), Ramsar Convention (wetlands), business and industry, and the health sector. Each MA sub-global assessment will also produce additional reports to meet the needs of its own audiences.

All printed materials of the assessment, along with core data and a list of reviewers, are available at www.MAweb.org. In this volume, Appendix A contains color maps and figures. Appendix B lists all the authors who contributed to this volume. Appendix C lists the acronyms and abbreviations used in this report and Appendix D is a glossary of terminology used in the technical reports. Throughout this report, dollar signs indicate U.S. dollars and ton means tonne (metric ton). Bracketed references within the Summary are to chapters within this volume.

In this report, the following words have been used where appropriate to indicate judgmental estimates of certainty, based on the collective judgment of the authors, using the observational evidence, modeling results, and theory that they have examined: very certain (98% or greater probability), high certainty (85–98% probability), medium certainty (65%–58% probability), low certainty (52–65% probability), and very uncertain (50–52% probability). In other instances, a qualitative scale to gauge the level of scientific understanding is used: well established, established but incomplete, competing explanations, and speculative. Each time these terms are used they appear in italics.

Ecosystems and Human Well-being: Current State and Trends, Volume 1

Summary: Ecosystems and Their Services around the Year 2000

Core Writing Team: Robert Scholes, Rashid Hassan, Neville J. Ash
Extended Writing Team: Condition and Trends Working Group

CONTENTS

Human Well-being and Life on Earth

- **Human well-being depends, among other things, on the continued supply of services obtained from ecosystems.**
- **Human actions during the last 50 years have altered ecosystems to an extent and degree unprecedented in human history. The consequences for human well-being have been mixed. Health and wealth have, on average, improved, but the benefits are unevenly distributed and further improvement may be limited by an insufficient supply of key ecosystem services.**
- **Biological diversity is a necessary condition for the delivery of all ecosystem services. In most cases, greater biodiversity is associated with a larger or more dependable supply of ecosystem services. Diversity of genes and populations is currently declining in most places in the world, along with the area of near-natural ecosystems.**

Inescapable Link between Ecosystem Condition and Human Well-being

All people depend on the services supplied by ecosystems, either directly or indirectly. Services are delivered both by ''near-natural'' ecosystems, such as rangelands, oceans, and forests, and by highly managed ecosystems such as cultivated or urban landscapes.

Human well-being, by several measures and on average across and within many societies, has improved substantially over the past two centuries and continues to do so. The human population in general is becoming better nourished. People live longer, and incomes have risen. Political institutions have become more participatory. In part these gains in well-being have been made possible by exploiting certain ecosystem services (the provisioning services, such as timber, grazing, and crop production), sometimes to the detriment of the ecosystem and its underlying capacity to continue to provide these and other services. Some gains have been made possible by the unsustainable use of other resources. For example, the increases in food production have been partly enabled by drawing on the finite supply of fossil fuels, an ecosystem service laid down millions of years ago.

The gains in human well-being are not distributed evenly among individuals or social groups, nor among the countries they live in or the ecosystems of the world. The gap between the advantaged and the disadvantaged is increasing. For example, a child born in sub-Saharan Africa is 20 times more likely to die before age five than a child born in an industrial country, and this ratio is higher than it was a decade ago. People living in urban areas, near coasts, and in systems with high ecosystem productivity in general have above-average well-being. **People living in drylands and mountainous areas, both characterized by lower ecosystem productivity, tend to have below-average, and more variable, well-being.**

Populations are growing faster in ecosystems characterized by low well-being and low ecosystem productivity than in high well-being, high productivity areas. Figure C1, which uses GDP as a proxy for human well-being, illustrates this situation. Trends are similar for other measures of human well-being, such as infant mortality rate. [5, 6, 16, 22]

Many human and ecological systems are under multiple severe and mutually reinforcing stresses. The causes include the direct and indirect impacts of extraction of services themselves, as well as the unintended side effects of other human activities. Certain linked ecological-human systems, by virtue of their structure or location, are more sensitive to stress than others. Examples include freshwater, coastal, mountain, island, and dryland systems.

Some groups of people are disproportionately likely to experience loss of well-being associated with declining levels of ecosystem services. The billion people poorest people in the world mostly live in rural areas where they are directly dependent on croplands, rangelands, rivers, seas, and forests for their livelihoods. For them especially, mismanagement of ecosystems threatens survival. Among better-off and urban populations, ecosystem changes affect well-being in less direct ways, but they remain important. They are partly buffered by technology and the ability to substitute some resources with others, but they also remain ultimately dependent on ecosystems for the basic necessities of life. Impacts are experienced differentially as a function of adaptive capacity, which can be manifested at the individual, household, community, national, or regional level. The groups ultimately responsible for the loss or decline of ecosystem services are often not the ones that bear the immediate impacts of their decline.

A large and growing number of people are at high risk of adverse ecosystem changes. The world is experiencing a worsening trend of human suffering and economic losses from natural disasters. Over the past four decades, for example, the number of weather-related disasters affecting at least a million people has increased fourfold, while economic losses have increased tenfold. The greatest loss of life has been concentrated in developing countries. Ecosystem transformation has played a significant, but not exclusive, role in increasing the vulnerability of people to such disasters. Examples are the increased susceptibility of coastal populations to tropical storms when mangrove forests are cleared and the increase in downstream flooding that followed land use changes in the upper Yangtze River. [16]

Special Role of Biodiversity in Supplying Ecosystem Services

In some cases, biodiversity can be treated as an ecosystem service in its own right, such as when it is the basis of nature-based tourism or the regulation of diseases. In other respects, it is a necessary condition underpinning the long-term provision of other services, such as food and clean fresh water. **Variation among genes, populations, and species and the variety of structure, function, and composition of ecosystems are necessary to maintain an acceptable and resilient level of ecosystem services in the long term.** [1]

For ecosystem functions such as productivity and nutrient cycling, the level, constancy of the service over time, and resilience to shocks all decline over the long term if biodiversity declines (*established but incomplete*). In general, there is no sudden biodiversity threshold below which ecosystem services fail. Quantifying the relationship between biodiversity and levels of ecosystem function has only been achieved in a few experimental situations and remains an area of active research. The amount and type of biodiversity required varies from service to service. **Regulatory services generally need higher levels of biodiversity than provisioning services do.** [11]

Changes in species composition can alter ecosystem processes even if the number of species present remains unchanged or increases. Thus, conserving the composition of communities rather than simply maximizing species numbers is more likely to maintain higher levels of ecosystem services. Reduction of the number of species, especially if the species lost are locally rare, may have a hardly detectable effect on ecosystem services in the short term. However, there is evidence from terres-

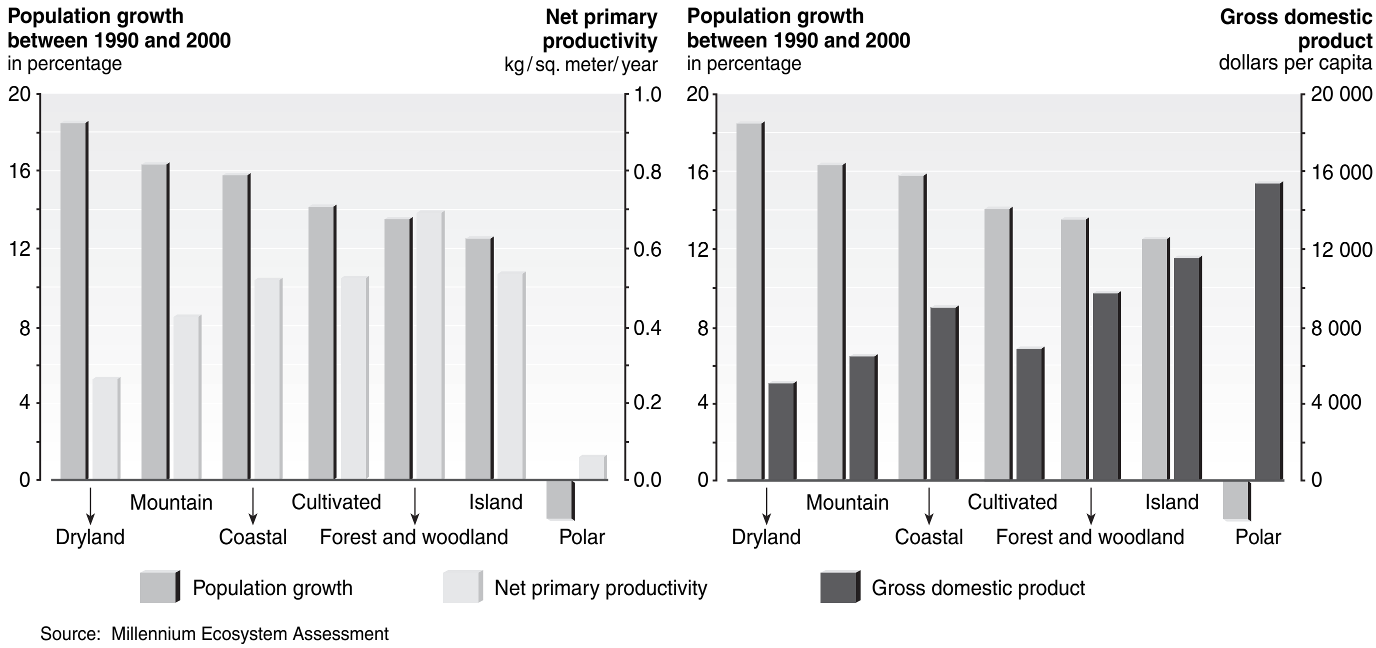

Figure C1. Population Growth Rates in 1990–2000, Per Capita GDP, and Ecosystem Productivity in 2000 in MA Ecological Systems

trial and aquatic systems that a rich regional species pool is needed to maintain ecosystem stability in the face of a changing environment in the long term. [11]

The integrity of the interactions between species is critical for the long-term preservation of human food production on land and in the sea. For example, pollination is an essential link in the production of food and fiber. Plant-eating insects and pathogens control the populations of many potentially harmful organisms. The services provided by coral reefs, such as habitat and nurseries for fish, sediment stabilization, nutrient cycling, and carbon fixing in nutrient-poor environments, can only be maintained if the interaction between corals and their obligate symbiotic algae is preserved. [11]

The preservation of genetic variation among crop species and their wild relatives and spatial heterogeneity in agricultural landscapes are considered necessary for the long-term viability of agriculture. Genetic variability is the raw material on which plant breeding for increased production and greater resilience depends. In general practice, agriculture undermines biodiversity and the regulating and supporting ecosystem services it provides in two ways: through transforming ecosystems by converting them to cultivated lands (extensification) and through the unintended negative impacts of increased levels of agricultural inputs, such as fertilizers, biocides, irrigation, and mechanical tillage (intensification). Agroforestry systems, crop rotations, intercropping, and conservation tillage are some of the agricultural techniques that maintain yields and protect crops and animals from pests without heavy investment in chemical inputs. [11]

A large proportion of the world's terrestrial species are concentrated in a small fraction of the land area, mostly in the tropics, and especially in forests and on mountains. Marine species are similarly concentrated, with the limited area of coral reefs, for example, having exceptionally high biodiversity. Most terrestrial species have small geographical ranges, and the ranges are often clustered, leading to diagnosable ''hotspots'' of both richness and endemism. These are frequently, but not exclusively, concentrated in isolated or topographically variable regions such as islands, peninsulas, and mountains. The African and American tropics have the highest recorded species numbers in both absolute terms and per unit of area. Endemism is also highest there and, as a consequence of its isolation, in Australasia. Locations of species richness hotspots broadly correspond with centers of evolutionary diversity. Available evidence suggests that across the major taxa, tropical humid forests are especially important for both overall diversity and their unique evolutionary history. [4]

Among plants and vertebrates, the great majority of species are declining in distribution, abundance, or both, while a small number are expanding. Studies of African mammals, birds in cultivated landscapes, and commercially important fish all show the majority of species to be declining in range or number. Exceptions can be attributed to management interventions such as protection in reserves and elimination of threats such as overexploitation, or they are species that thrive in human-dominated landscapes. In some regions there may be an increase in local biodiversity as a result of species introductions, the long-term consequences of which are hard to foresee. [4]

The observed rates of species extinction in modern times are 100 to 1,000 times higher than the average rates for comparable groups estimated from the fossil record (*medium certainty*). (See Figure C2.) The losses have occurred in all taxa, regions, and ecosystems but are particularly high in some—for instance, among primates, in the tropics, and in freshwater habitats. Of the approximately 1,000 recorded historical extinctions, most have been on islands. Currently and in the future, the most threatened species are found on the mainland, particularly in locations of habitat change and degradation. **The current rate of biodiversity loss, in aggregate and at a global scale, gives no indication of slowing, although there have been local successes in some groups of species. The momentum of the underlying drivers of biodiversity loss, and the consequences of this loss, will extend many millennia into the future.** [4]

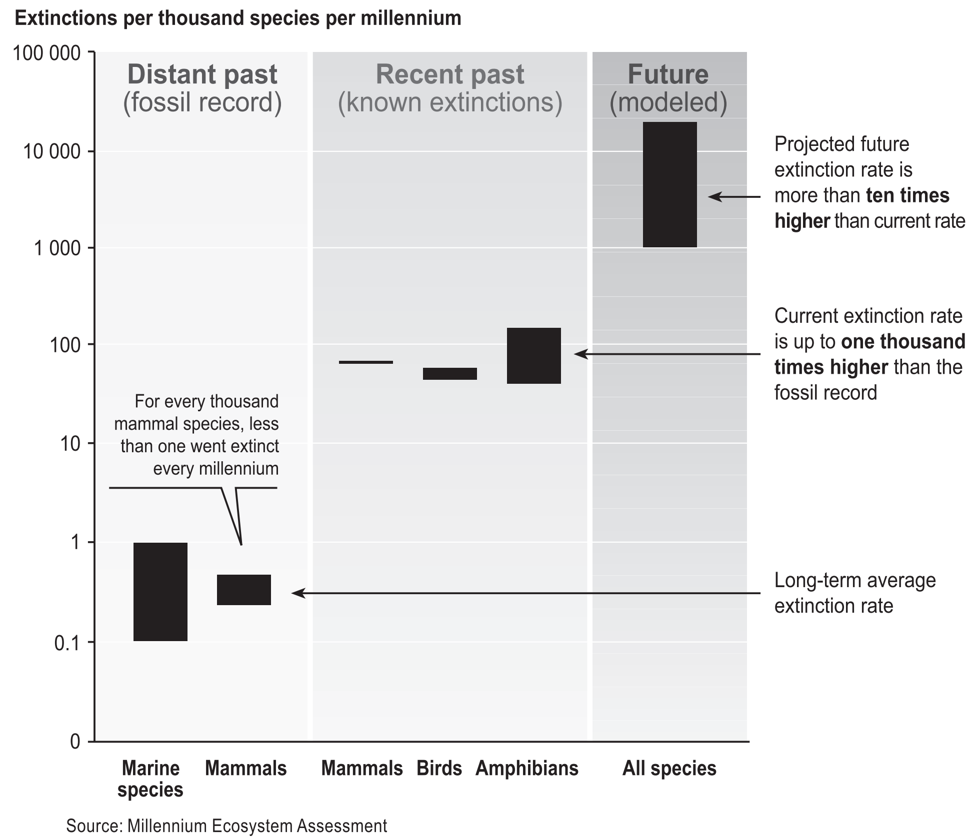

Figure C2. Species Extinction Rates Determined from the Fossil Record, from Observation, and from Estimation of Projected Rates

Less than a tenth of known plant and vertebrate species have been assessed in terms of their vulnerability to extinction (''conservation status''). Birds have the lowest proportion (12%) threatened with global extinction (defined as a high certainty of loss from throughout its range) in the near-to-medium term (*high certainty*). Among mammal species, 23% are threatened with extinction (*high certainty*). Of the amphibia for which sufficient information is available to make an assessment, 32% are threatened (*medium certainty*). For cycads (an ancient group of plants), 52% of the species are threatened, as are 25% of conifer species (*high certainty*). [4]

The taxonomic groups with the highest proportion of threatened species tend to be those that rely on freshwater habitats. Extinction rates, based on the frequency of threatened species, are broadly similar across terrestrial biomes (broad ecosystem types). Most terrestrial extinctions during the coming century are predicted to occur in tropical forests, because of their high species richness. [4]

Factors Causing Changes in Ecosystems

Increasing Demand for Ecosystem Services

Increasing consumption per person, multiplied by a growing human population, are the root causes of the increasing demand for ecosystem services. The global human population continues to rise, but at a progressively slower rate. The population increased from 3 billion to 6 billion between 1960 and 2000 and is likely to peak at 8.2–9.7 billion around the middle of the twenty-first century. Migration to cities and population growth within cities continue to be major demographic trends. The world's urban population increased from about 200 million to 2.9 billion over the past century, and the number of cities with populations in excess of 1 million increased from 17 to 388. (See Figure C3.) [3]

Overall demand for food, fiber, and water continue to rise. Improvements in human well-being, enabled by economic growth, almost invariably lead to an increase in the per capita demand for provisioning ecosystem services such as food, fiber, and water and in the consumption of energy and minerals and the production of waste. **In general, the increase in demand for provisioning services is satisfied at the expense of supporting, regulating, and cultural ecosystem services.** Efficiency gains permitted by new technology reduce per capita consumption levels below what they would have been without technological and behavioral adaptation, but they have tended not to keep pace with growth in demand for provisioning services. [3]

Increasing Pollution and Waste

Ecosystem problems associated with contaminants and wastes are in general growing. Some wastes are produced in nearly direct proportion to population size (such as sewage). Others, such as domestic trash and home-use chemicals, reflect the affluence of society. Where there is significant economic development, waste loadings tend to increase faster than population growth. In some cases the per capita waste production subsequently decreases, but seldom to the pre-growth level. The generation of industrial wastes does not necessarily increase with population or development state, and it may often be reduced by adopting alternate manufacturing processes. The neglect of waste management leads to impairment of human health and well-being, economic losses, aesthetic value losses, and damages to biodiversity and ecosystem function. [3, 15]

The oversupply of nutrients (eutrophication) is an increasingly widespread cause of undesirable ecosystem

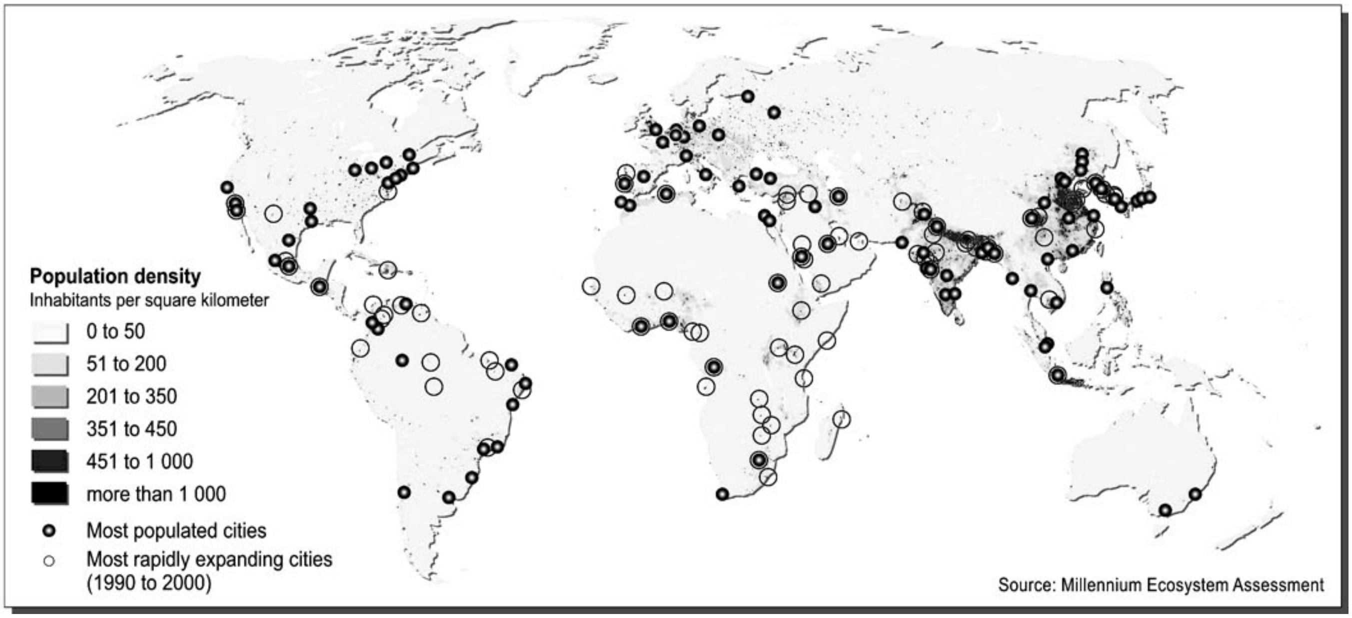

Figure C3. Human Population Density in 1995 and the Most Populated and Rapidly Changing Cities in 1990-2000

change, particularly in rivers, lakes, and coastal systems. Nutrient additions on the land, including synthetic fertilizers, animal manures, the enhancement of N-fixation by planted legumes, and the deposition of airborne pollutants, have resulted in approximately a doubling of the natural inputs for reactive nitrogen in terrestrial ecosystems and an almost fivefold increase in phosphorus accumulation. The reduction of biodiversity at the species and landscape levels has permitted nutrients to leak from the soil into rivers, the oceans, and the atmosphere. Emissions to the atmosphere are a significant driver of regional air pollution and the buildup of the greenhouse gas nitrous oxide (and, to a small extent, methane). [3, 12, 19, 20]

Global Trade

The increasing volume of goods and services that are traded internationally, the distance that they are moved, the mobility of people, and the connectivity of local and global economies have all increased the spatial separation between cause and effect in ecosystem change. **Without appropriate regulation, global trade can be a key driver of overharvesting of resources such as high-value timber and marine resources.** Trade pressures and opportunities underlie patterns of land use change in many parts of the world. The movement of people and goods is an important vector in the spread of diseases and non-native invasive organisms. [3]

Changing Climate

The effects of climate change on ecosystems are becoming apparent, especially in polar regions, where on average temperatures are now warmer than at any time in the last 400 years and the Antarctic peninsular is one of the most rapidly warming regions on the planet; in mountains, where there has been widespread glacier retreat and loss of snowpack; and in coastal systems, where coral reefs in particular have been affected by sea temperature warming and increased carbon dioxide concentrations. Although many of the potential effects of climate change on ecosystem service provision to date have not been clearly distinguishable from short-term variations, **climate change over the next century is projected to affect, directly and indirectly, all aspects of ecosystem service provision.** [3, 13, 19, 24, 25]

Overexploitation of Natural Resources

If a renewable natural resource is used at a faster rate than it is replenished, the result is a decline in the stock and eventually a decrease in the quantity of the resource that is available for human use. Overfishing, overgrazing, and overlogging are widespread examples of overexploitation. In the process of fishing, logging, mining, cultivation, and many other human activities, unintended collateral damage is done to ecosystems, affecting the supply of both the target resource and other services as well. When the net supply of ecosystem services is so damaged that it fails to recover spontaneously within a reasonable period after the level of the action causing the damage is reduced, the ecosystem is degraded. **Significant areas of forest, cultivated land, dryland rangelands, and coastal and marine systems are now degraded, and the degraded area continues to expand.** [4]

Changing Land Use and Land Cover

Current rates of land cover change are greatest for tropical moist forests and for temperate, tropical, and flooded grasslands, with $>$14% of each of these lost between 1950 and 1990. Temperate broadleaf forests, Mediterranean forests, and grasslands had already lost more than 70% of their original extent by 1950. The rates of loss in these forest types have now slowed, and in some cases the forest area has expanded. Deforestation and forest degradation are currently focused in the tropics. Data on changes in boreal forests are especially limited. [4, 21]

Habitat loss is the fastest-growing threat to species and populations on land and will continue to be the dominant factor for the next few decades. Fishing is the dominant factor reducing populations and fragmenting the habitats of marine species and is predicted to lead to local extinctions, especially among large, long-lived, slow-growing species and endemic species. [4]

Habitat fragmentation (the reduction of natural cover into smaller and more disconnected patches) compounds the effects of habitat loss. The disruptive effects of fragmentation extend hundreds of meters inwards from the edges of the patches, making small patches highly vulnerable to loss of species and functions. [11]

Invasion by Alien Species

In a wide range of terrestrial, marine, and freshwater ecosystems, accidental or voluntary introduction of non-native species by humans has altered local biological community interactions, triggering dramatic and often unexpected changes in ecosystem processes and causing large monetary and cultural losses. [3, 4, 23]

Trends in Ecosystem Services

- **The supply of certain ecosystem services has increased at the expense of others. Significant gains in the provision of food and fiber have been achieved through habitat conversion, increased abstraction and degradation of inland waters, and reduced biodiversity.**
- **Fish cannot continue to be harvested from wild populations at the present rate. Deep-ocean and coastal fish stocks have changed substantially in most parts of the world and the harvests have begun to decline and will continue to do so.**
- **The supply of fresh water to people is already inadequate to meet human and ecosystem needs in large areas of the world, and the gap between supply and demand will continue to widen if current patterns of water use will continue.**
- **Declining trends in the capacity of ecosystems to render pollutants harmless, keep nutrient levels in balance, give protection from natural disasters, and control the outbreaks of pests, diseases, and invasive organisms are apparent in many places.**

The main trends in key ecosystem services over the last 50 years are summarized in Table C1. Individual ecosystem services are discussed below in further detail.

Provisioning Services

Food

Major inequalities exist in access to food despite the more than doubling of global production over the past 40 years. An estimated 852 million people were undernourished in 2000–02, up 37 million from 1997–99. [8] There are important differences in the regional trends: the number of undernourished people in China is declining, while the number in Africa continues to increase. Of the global undernourished, 1% live in industrial countries, 4% live in countries in transition, and the remaining 95% are found in developing countries.

Figure C4 demonstrates that the economic value of food production is also not evenly distributed around the world, both because of the uneven distribution of natural factors such as climate and nutrient supply and because the prices obtained for food products vary according to demand and wealth. The impacts of activities associated with food production on other ecosystem services are unevenly distributed as well.

New cultivars of wheat, maize, and rice, coupled with increased inputs of fertilizers, irrigation, and an expansion of the cultivated area, were the main factors underlying the 250% increase in total cereal production since 1960. **The rate of increase of cereal production has slowed over the last decade,** for reasons that are uncertain but that include a long-term decline in the real price of cereals, a saturation in the per capita cereal consumption in many countries, a temporary decline in the use of cereals as livestock feed in the 1970s and 1980s, the declining quality of land in agricultural production, and diminishing returns to efforts aimed at improving yields of maize, wheat, and rice.

Adequate nutrition requires a diverse diet, containing sufficient micronutrients and protein as well as calories. The world's poorest people continue to rely on starchy staples, which leads to protein, vitamin, and mineral deficiencies. **Demand for high-value, protein-rich products such as livestock and fish has increased** with rising incomes in East and Southeast Asia (7% annual growth in livestock production over past 30 years). **The accelerating demand for animal protein is increasingly met by intensive (''industrial'' or ''landless'') production systems,** especially for chicken and pigs. While these systems have contributed to large increases in production, they create serious waste problems and put increased pressure on cultivated systems and fisheries to provide feed inputs (and are thus not truly ''landless'').

The dietary changes that accompany increasing income can improve health; however, overconsumption, leading to obesity and heart disease, is also a growing health problem (65% of Americans and more than 17 million children in developing countries are overweight). Calorie intake is only 20% higher per capita in industrial countries than in developing countries on average, but protein intake is 50% higher and fat intake is almost twice as high.

Harvest pressure has exceeded maximum sustainable levels of exploitation in one quarter of all wild fisheries and is likely to exceed this limit in most other wild fisheries in the near future. In every ocean in the world, one or more important targeted stocks have been classified as collapsed, overfished, or fished to their maximum sustainable levels, and at least one quarter of important commercial fish stocks are overharvested (*high certainty*). Although fish consumption has doubled in developing countries in the last three decades, the per capita annual consumption has declined by 200 grams since 1985, to 9.2 kilograms per person (excluding China). Fish products are heavily traded, and approximately 50% of fish exports are from developing countries. Exports from developing countries and the Southern Hemisphere presently offset much of the demand shortfall in European, North American, and East Asian markets.

The growth in demand for fish protein is being met in part by aquaculture, which now accounts for 22% of total fish production and 40% of fish consumed as food. **Marine aquaculture has not to date relieved pressure on wild fisheries, because the food provided to captive fish is partly based on wild-harvested fish products.**

Government policies are significant drivers of food production and consumption patterns, both locally and globally. Investments in rural roads, irrigation, credit systems, and agricultural research and extension serve to stimulate food production. Improved access to input and export markets boosts productivity. Opportunities to gain access to international markets are conditioned by international trade and food safety regulations and by a variety of tariff and non-tariff barriers. Selective production and export subsidies stimulate overproduction of many food crops. This translates into relatively cheap food exports that benefit international consumers at the expense of domestic taxpayers and that undermine the welfare of food producers in poorer countries.

Wild terrestrial foods are locally important in many developing countries, often bridging the hunger gap created by stresses such as droughts and floods and social unrest. Wild foods are important sources of diversity in some diets, in

Table C1. Trends in the Human Use of Ecosystem Services and Enhancement or Degradation of the Service around the Year 2000

Service	Sub-category	Human Use[a]	Enhanced or Degraded[b]	Notes	MA Chapter
Provisioning Services					
Food	Crops	↑	↑	Food provision has grown faster than overall population growth. Primary source of growth from increase in production per unit area but also significant expansion in cropland. Still persistent areas of low productivity and more rapid area expansion, e.g., sub-Saharan Africa and parts of Latin America.	C8.2
	Livestock	↑	↑	Significant increase in area devoted to livestock in some regions, but major source of growth has been more intensive, confined production of chicken, pigs, and cattle.	C8.2
	Capture Fisheries	↓	↓	Marine fish harvest increased until the late 1980s and has been declining since then. Currently, one quarter of marine fish stocks are overexploited or significantly depleted. Freshwater capture fisheries have also declined. Human use of capture fisheries has declined because of the reduced supply, not because of reduced demand.	C18 C8.2.2 C19
	Aquaculture	↑	↑	Aquaculture has become a globally significant source of food in the last 50 years and, in 2000, contributed 27% of total fish production. Use of fish feed for carnivorous aquaculture species places an additional burden on capture fisheries.	C8 Table 8.4
	Wild plant and animal food products	NA	↓	Provision of these food sources is generally declining as natural habitats worldwide are under increasing pressure and as wild populations are exploited for food, particularly by the poor, at unsustainable levels.	C8.3.1
Fiber	Timber	↑	+/−	Global timber production has increased by 60% in the last four decades. Plantations provide an increasing volume of harvested roundwood, amounting to 35% of the global harvest in 2000. Roughly 40% of forest area has been lost during the industrial era, and forests continue to be lost in many regions (thus the service is degraded in those regions), although forest is now recovering in some temperate countries and thus this service has been enhanced (from this lower baseline) in these regions in recent decades.	C9.ES C21.1
	Cotton, hemp, silk	+/−	+/−	Cotton and silk production have doubled and tripled respectively in the last four decades. Production of other agricultural fibers has declined.	C9.ES
	Wood fuel	+/−	↓	Global consumption of fuelwood appears to have peaked in the 1990s and is now believed to be slowly declining buts remains the dominant source of domestic fuel in some regions.	C9.ES
Genetic resources		↑	↓	Traditional crop breeding has relied on a relatively narrow range of germplasm for the major crop species, although molecular genetics and biotechnology provide new tools to quantify and expand genetic diversity in these crops. Use of genetic resources also is growing in connection with new industries base on biotechnology. Genetic resources have been lost through the loss of traditional cultivars of crop species (due in part to the adoption of modern farming practices and varieties) and through species extinctions.	C26.2.1

(continues)

Table C1. continued

Service	Sub-category	Human Use[a]	Enhanced or Degraded[b]	Notes	MA Chapter
Biochemicals, natural medicines, and pharmaceuticals		⬆	⬇	Demand for biochemicals and new pharmaceuticals is growing, but new synthetic technologies compete with natural products to meet the demand. For many other natural products (cosmetics, personal care, bioremediation, biomonitoring, ecological restoration), use is growing. Species extinction and overharvesting of medicinal plants is diminishing the availability of these resources.	C10
Fresh water		⬆	⬇	Human modification to ecosystems (e.g., reservoir creation) has stabilized a substantial fraction of continental river flow, making more fresh water available to people but in dry regions reducing river flows through open water evaporation and support to irrigation that also loses substantial quantities of water. Watershed management and vegetation changes have also had an impact on seasonal river flows. From 5% to possible 25% of global freshwater use exceeds long-term accessible supplied and require supplied either through engineered water transfers of overdraft of groundwater supplies. Between 15% and 35% of irrigation withdrawals exceed supply rates. Fresh water flowing in rivers also provides a service in the form of energy that is exploited through hydropower. The construction of dams has not changed the amount of energy, but it has made the energy more available to people. The installed hydroelectric capacity doubled between 1960 and 2000. Pollution and biodiversity loss are defining features of modern inland water systems in many populated parts of the world.	C7
Regulating Services					
Air quality regulation		⬆	⬇	The ability of the atmosphere to cleanse itself of pollutants has declined slightly since preindustrial times but likely not by more than 10%. Then net contribution of ecosystems to this change is not known. Ecosystems are also a sink for tropospheric ozone, ammonia, NO_x, SO_2, particulates, and CH_4, but changes in these sinks were not assessed.	C13.ES
Climate regulation	Global	⬆	⬆	Terrestrial ecosystems were on average a net source of CO_2 during the nineteenth and early twentieth century and became a net sink sometime around the middle of the last century. The biophysical effect of historical land cover changes (1750 to present) is net cooling on a global scale due to increased albedo, partially offsetting the warming effect of associated carbon emissions from land cover change over much of that period.	C13.ES
	Regional and local	⬆	⬇	Changes in land cover have affected regional and local climates both positively and negatively, but there is a preponderance of negative impacts. For example, tropical deforestation and desertification have tended to reduce local rainfall.	C13.3 C11.3
Water regulation		⬆	+/–	The effect of ecosystem change on the timing and magnitude of runoff, flooding, and aquifer recharge depends on the ecosystem involved and on the specific modifications made to the ecosystem.	C7.4.4

Erosion regulation		↑	↓	Land use and crop/soil management practices have exacerbated soil degradation and erosion, although appropriate soil conservation practices that reduce erosion, such as minimum tillage, are increasingly being adopted by farmers in North America and Latin America.	C26
Water purification and waste treatment		↑	↓	Globally, water quality is declining, although in most industrial countries pathogen and organic pollution of surface waters has decreased over the last 20 years. Nitrate concentration has grown rapidly in the last 30 years. The capacity of ecosystems to purify such wastes in limited, as evidenced by widespread reports of inland waterway pollution. Loss of wetlands has further decreased the ability of ecosystems to filter and decompose wastes.	C7.2.5 C19
Disease regulation		↑	+/–	Ecosystem modifications associated with development have often increased the local incidence of infectious diseases, although major changes in habitats can both increase or decrease the risk of particular infectious diseases.	C14
Pest regulation		↑	↓	In many agricultural areas, pest control provided by natural enemies has been replaced by the use of pesticides. Such pesticide use has itself degraded the capacity of agroecosystems to provide pest control. In other systems, pest control provided by natural enemies is being used and enhanced through integrated pest management. Crops containing pest-resistant genes can also reduce the need for application of toxic synthetic pesticides.	C11.3
Pollination		↑	↓[c]	There is *established but incomplete* evidence of a global decline in the abundance of pollinators. Pollinator declines have been reported in at least one region or country on every continent except for Antarctica, which has no pollinators. Declines in abundance of pollinators have rarely resulted in complete failure to produce seed or fruit, but more frequently resulted in fewer seeds or in fruit of reduced viability or quantity. Losses in populations of specialized pollinators have directly affected the reproductive ability of some rare plants.	C11 Box 11.2
Natural hazard regulation		↑	↓	People are increasingly occupying regions and localities that are exposed to extreme events, thereby exacerbating human vulnerability to natural hazards. This trend, along with the decline in the capacity of ecosystems to buffer from extreme events, has led to continuing high loss of life globally and rapidly rising economic losses from natural disasters.	C16 C19
Cultural Services					
Cultural diversity		**NA**	**NA**		
Spiritual and religious values		↑	↑	There has been a decline in the numbers of sacred groves and other such protected areas. The loss of particular ecosystem attributes (sacred species or sacred forests), combined with social and economic changes, can sometimes weaken the spiritual benefits people obtain from ecosystems. On the other hand, under some circumstances (e.g., where ecosystem attributes are causing significant threats to people), the loss of some attributes may enhance spiritual appreciation for what remains.	C17.2.3

(continues)

Table C1. continued

Service	Sub-category	Human Use[a]	Enhanced or Degraded[b]	Notes	MA Chapter
Knowledge systems		**NA**	**NA**		
Educational values		**NA**	**NA**		
Inspiration		**NA**	**NA**		
Aesthetic values		⬆	⬇	The demand for aesthetically pleasing natural landscapes has increased in accordance with increased urbanization. There has been a decline in quantity and quality of areas to meet this demand. A reduction in the availability of and access to natural areas for urban residents may have important detrimental effects on public health and economies.	C17.2.5
Social relations		**NA**	**NA**		
Sense of place		**NA**	**NA**		
Cultural heritage values		**NA**	**NA**		
Recreation and ecotourism		⬆	+/–	The demand for recreational use of landscapes is increasing, and areas are increasingly being managed to cater for this use, to reflect changing cultural values and perceptions. However, many naturally occurring features of the landscape (e.g., coral reefs) have been degraded as resources for recreation.	C17.2.6 C19
Supporting Services					
Soil formation		†	†		
Photosynthesis		†	†		
Primary production		†	†	Several global MA systems, including drylands, forest, and cultivated systems, show a trend of NPP increase for the period 1981 to 2000. However, high seasonal and inter-annual variations associated with climate variability occur within this trend on the global scale	C22.2.1
Nutrient cycling		†	†	There have been large-scale changes in nutrient cycles in recent decades, mainly due to additional inputs from fertilizers, livestock waste, human wastes, and biomass burning. Inland water and coastal systems have been increasingly affected by eutrophication due to transfer of nutrients from terrestrial to aquatic systems as biological buffers that limit these transfers have been significantly impaired.	C12
Water cycling		†	†	Humans have made major changes to water cycles through structural changes to rivers, extraction of water from rivers, and, more recently, climate change.	C7

[a] For provisioning services, human use increases if the human consumption of the service increases (e.g., greater food consumption); for regulating and cultural services, human use increases if the number of people affected by the service increases. The time frame is in general the past 50 years, although if the trend has changed within that time frame, the indicator shows the most recent trend.

[b] For provisioning services, we define enhancement to mean increased production of the service through changes in area over which the service is provided (e.g., spread of agriculture) or increased production per unit area. We judge the production to be degraded if the current use exceeds sustainable levels. For regulating and supporting services, enhancement refers to a change in the service that leads to greater benefits for people (e.g., the service of disease regulation could be improved by eradication of a vector known to transmit a disease to people). Degradation of a regulating and supporting service means a reduction in the benefits obtained from the service, either through a change in the service (e.g., mangrove loss reducing the storm protection benefits of an ecosystem) or through human pressures on the service exceeding its limits (e.g., excessive pollution exceeding the capability of ecosystems to maintain water quality). For cultural services, degradation refers to a change in the ecosystem features that decreases the cultural (recreational, aesthetic, spiritual, etc.) benefits provided by the ecosystem. The time frame is in general the past 50 years, although if the trend has changed within that time frame the indicator shows the most recent trend.

[c] *Low to medium certainty.* All other trends are *medium to high certainty.*

Legend

↑ = Increasing (for human use column) or enhanced (for enhanced or degraded column)

↓ = Decreasing (for human use column) or degraded (for enhanced or degraded column)

+/− = Mixed (trend increases and decreases over past 50 years or some components/regions increase while others decrease)

NA = Not assessed within the MA. In some cases, the service was not addressed at all in the MA (such as ornamental resources), while in other cases the service was included but the information and data available did not allow an assessment of the pattern of human use of the service or the status of the service.

† = The categories of "human use" and "enhanced or degraded" do not apply for supporting services since, by definition, these services are not directly used by people. (Their costs or benefits would be double-counted if the indirect effects were included). Changes in supporting services influence the supply of provisioning, cultural, or regulating services that are then used by people and may be enhanced or degraded.

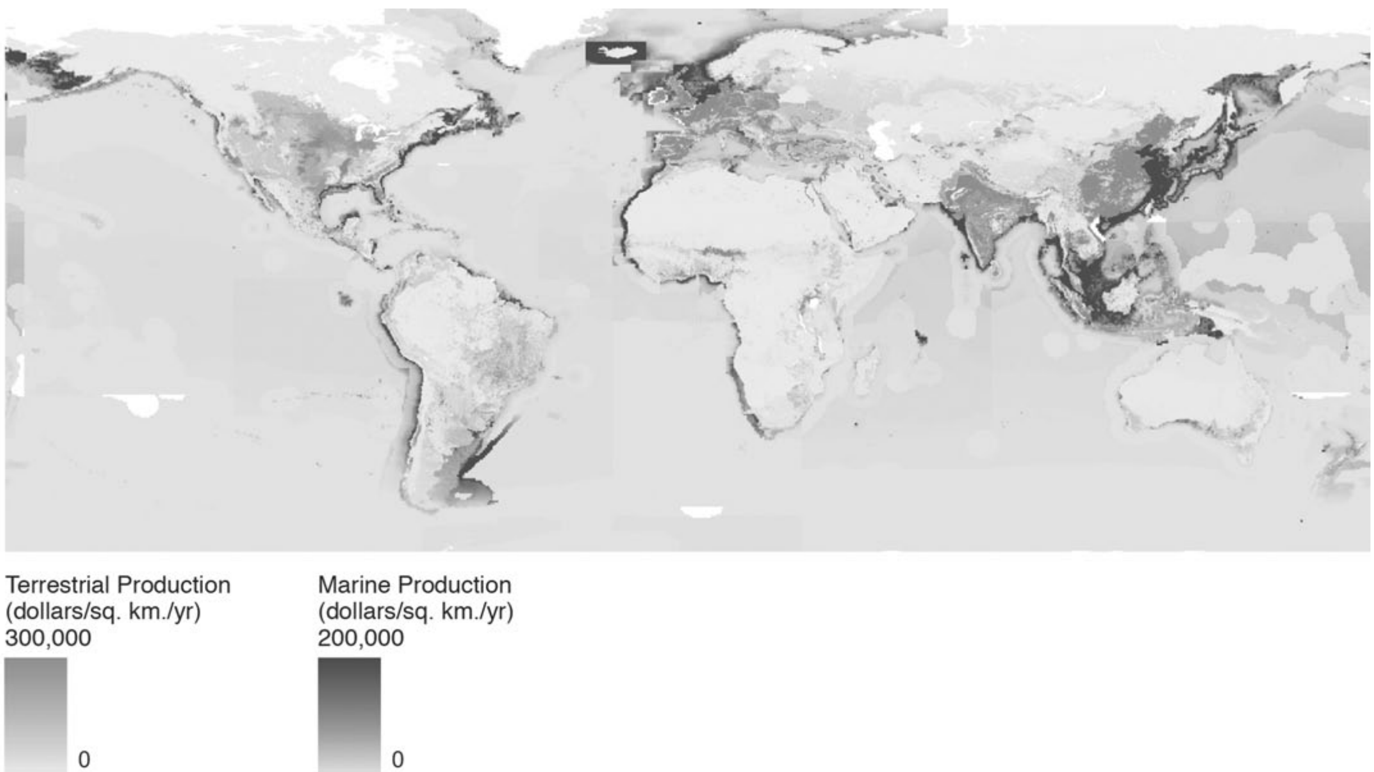

Figure C4. Spatial Distribution of Value of Food Production for Crops, Livestock, and Fisheries, 2000. This Figure was constructed by multiplying the harvest derived from all regions of the world by the average product price obtained in that region. (Data for Iceland were only available aggregated to the rectangular area shown.) A color version of this map appears in Appendix A (see Figure 8.2).

that they are highly nutritious and are often not labor-intensive to collect or prepare. Although they have significant economic value, in most cases wild foods are excluded from economic analysis of natural resource systems as well as official statistics, so the full extent of their importance is poorly quantified.

Wood for Timber and Pulp

The absolute harvest of timber is projected, with *medium certainty*, to increase in the future, albeit at a slower rate than over the past four decades. [9] The high growth in timber harvests since 1960 (60% and 300% for sawlogs and pulpwood respectively) has slowed in recent years. Total forest biomass in temperate and boreal regions increased over this period but decreased in mid-latitude and tropical forests. Demand for hardwoods is a factor in tropical deforestation, but is typically not the main driver. Conversion to agricultural land, a trend often underlain by policy decisions, is overall the major cause. **A third of timber is harvested from plantations rather than naturally regenerating forests, and this fraction is projected to grow.** Plantations currently constitute 5% of the global forest area. In general, plantations provide a less diverse set of ecosystem services than natural forests do.

Most trade in forest products is within-country, with only about 25% of global timber production entering international trade. However, international trade in forest products has increased three times faster in value than in harvested volume. The global value of timber harvested in 2000 was around $400 billion, about one quarter of which entered in world trade, representing some 3% of total merchandise traded. Much of this trade is among industrial countries: the United States, Germany, Japan, the United Kingdom, and Italy were the destination of more than half of the imports in 2000, while Canada, the United States, Sweden, Finland, and Germany account for more than half of the exports.

The global forestry sector annually provides subsistence and wage employment of 60 million work years, with 80% in the developing world. There is a trend in increasing employment in sub-tropical and tropical regions and declining employment in temperate and boreal regions.

Biomass Energy

Wood and charcoal remain the primary source of energy for heating and cooking for 2.6 billion people. [9] Global consumption appears to have peaked in the 1990s and is now believed to be slowly declining as a result of switching to alternate fuels and, to a lesser degree, more-efficient biomass energy technologies. Accurate data on fuelwood production and consumption are difficult to collect, since much is produced and consumed locally by households. The global aggregate value of fuelwood production per capita has declined in recent years, easing concerns about a widespread wood energy crisis, although local and regional shortages persist.

Serious human health damages are caused by indoor pollution associated with the use of traditional biomass fuels in homes of billions of the rural and urban poor that lack adequate smoke venting. In 2000, 1.6 million deaths and the equivalent of 39 million person-years of ill health (disability-adjusted life years) were attributed to the burning of traditional biomass fuels, with women and children most affected. Health hazards increase where wood shortages lead to poor families using dung or agricultural residues for heating and cooking. Where adequate fuels are not available, the consumption of cooked foods declines, with adverse effects on nutrition and health. Local fuelwood shortages contribute to deforestation and result in lengthy and arduous travel to collect wood in rural villages, largely by women.

While examples of full commercial exploitation of modern biomass-based energy technologies are still fairly modest, their production and use is likely to expand over the next decades.

Agricultural Fibers

Global cotton production has doubled and silk production has tripled since 1961, with major shifts in the production regions. [9] The total land area devoted to cotton production has stayed virtually constant; area expansion in India and the United States was offset by large declines in Pakistan and the former Soviet Union. These shifts have impacts on land available for food crops and on water resources, since much of the cotton crop is irrigated. Silk production shifted from Japan to China. Production of wool, flax, hemp, jute, and sisal has declined.

Fresh Water

Water scarcity has become globally significant over the last four decades and is an accelerating condition for roughly 1–2 billion people worldwide, leading to problems with food production, human health, and economic development. Rates of increase in a key water scarcity measure (water use relative to accessible supply) from 1960 to the present averaged nearly 20% per decade globally, with values of 15% to more than 30% per decade for individual continents. Although a slowing in the global rate of increase in use is projected between 2000 and 2010, to 10% per decade, the relative use ratio for some regions is likely to remain high, with the Middle East and North Africa at 14% per decade, Latin America at 16%, and sub-Saharan Africa at 20%. [7]

Contemporary water withdrawal is approximately 10% of global continental runoff, although this amounts to between 40% and 50% of the continental runoff to which the majority of the global population has access during the year.

Population growth and economic development have driven per capita levels of water availability down from 11,300 to about 5,600 cubic meters per person per year between 1960 and 2000. Global per capita water availability is projected (based on a 10% per decade rate of growth of water use, which is slower than the past decades) to drop below 5,000 cubic meters per person per year by 2010 (*high certainty*).

Terrestrial ecosystems are the major global source of accessible, renewable fresh water. Forest and mountain ecosystems are associated with the largest amounts of fresh water—57% and 28% of the total runoff, respectively. These systems each provide renewable water supplies to at least 4 billion people, or two thirds of the global population. Cultivated and urban systems generate only 16% and 0.2%, respectively, of global runoff, but due to their close proximity to humans they serve from 4.5–5 billion people. Such proximity is associated with nutrient and industrial water pollution.

More than 800 million people currently live in locations so dry that there is no appreciable recharge of groundwater or year-round contribution by the landscape to runoff in rivers. They are able to survive there by drawing on "fossil" groundwater, by having access to piped water, or by living along rivers that have their source of water elsewhere. From 5% to possibly 25% of global freshwater use exceeds long-term accessible supplies and is now met either through engineered water transfers or overdraft of groundwater supplies (*medium certainty*). In North Africa and the Middle East, nonsustainable use (use in excess of the long-term accessible renewable supply) represents 43% of all water use, and the current rate of use is 40% above that of the sustainable supply (*medium certainty*).

Growing competition for water is sharpening policy attention on the need to allocate and use water more efficiently. **Irrigation accounts for 70% of global water withdrawals (over 90% in developing countries),** but chronic inefficiencies in irrigated systems result in less than half of that water being used by crops.

The burden of disease from inadequate water, sanitation, and hygiene totals 1.7 million deaths and the loss of up to 54 million healthy life years per year. Some 1.1 billion people lack access to improved water supply and more than 2.6 billion lack access to improved sanitation. It is *well established* that investments in clean drinking water and sanitation show a close correspondence with improvement in human health and economic productivity. Half of the urban population in Africa, Asia, and Latin America and the Caribbean suffer from one or more diseases associated with inadequate water and sanitation.

The management of fresh water through dams, levees, canals, and other infrastructure has had predominantly negative impacts on the biodiversity of inland waters and coastal ecosystems, including fragmentation and destruction of habitat, loss of species, and reduction of sediments destined for the coastal zone. The 45,000 existing large dams (more than 15 meters high) generate both positive and negative effects on human well-being. Positive effects include flow stabilization for irrigation, flood control, and hydroelectricity. Negative effects include health issues associated with stagnant water and the loss of services derived from land that has become inundated. A significant economic consequence of soil erosion is the reduction of the useful life of dams lower in the drainage basin due to siltation.

Genetic Resources

The exploration of biodiversity for new products and industries has yielded major benefits for humanity and has the potential for even larger future benefits. [10] The diversity of living things, at the level of the gene, is the fundamental resource for such "bioprospecting." While species-rich environments such as the tropics are in the long term expected to supply the majority of pharmaceutical products derived from ecosystems, bioprospecting to date has yielded valuable products from a wide variety of environments, including temperate forests and grasslands, arid and semiarid lands, freshwater ecosystems, mountain and polar regions, and cold and warm oceans.

The continued improvements of agricultural yields through plant breeding and the adaptation of crops to new and changing environments, such as increased temperatures, droughts, and emerging pests and diseases, requires the conservation of genetic diversity in the wild relatives of domestic species and in productive agricultural landscapes themselves.

Regulating Services

The Regulation of Infectious Diseases

Ecosystem changes have played a significant role in the emergence or resurgence of several infectious diseases of humans. [14] The most important drivers are logging, dam building, road building, expansion of agriculture (especially irrigated agriculture), urban sprawl, and pollution of coastal zones. There is evidence that ecosystems that maintain a higher diversity of species reduce the risks of infectious diseases in humans living within them; the pattern of Lyme disease in North America is one example. **Natural systems with preserved structure and characteristics are not receptive to the introduction of invasive human and animal pathogens brought by human migration and settlement.** This is indicated for cholera, kala-azar, and schistosomiasis (*medium certainty*).

Increased human contact with ecosystems containing foci of infections raises the risk of human infections. Examples occur where urban systems are in close contact with forest systems (associated with malaria and yellow fever) and where cultivated lands are opened in forest systems (hemorrhagic fevers or hantavirus). Major changes in habitats can both increase or decrease the risk of a particular infectious disease, depending on the type of land use, the characteristics of the cycle of disease, and the characteristics of the human populations. Although disease emergence and re-emergence due to ecosystem alteration can occur anywhere, people in the tropics are more likely to be affected in the future due to their greater exposure to reservoirs of potential disease and their greater vulnerability due to poverty and poorer health infrastructure.

Regulation of Climate, Atmospheric Composition, and Air Quality

Ecosystems are both strongly affected by and exert a strong influence on climate and air quality. [13] **Ecosystem management has significantly modified current greenhouse gas concentrations.** Changes in land use and land cover, especially deforestation and agricultural practices such as paddy rice cultivation and fertilizer use, but also rangeland degradation and dryland agriculture, made a contribution of 15–25% to the radiative forcing of global climate change from 1750 to present.

Ecosystems are currently a net sink for CO_2 and tropospheric ozone, while they remain a net source of methane and nitrous oxide. About 20% of CO_2 emissions in the 1990s originated from changes in land use and land management, primarily deforestation.

Terrestrial ecosystems were on average a net source of CO_2 during the nineteenth and early twentieth centuries; they became a net sink sometime around the middle of the last century (*high certainty*) and were a sink for about a third of total emissions in the 1990s (energy plus land use). The sink may be explained partially by afforestation, reforestation, and forest management in North America, Europe, China, and other regions and partially by the fertilizing effects of nitrogen deposition and increasing atmospheric CO_2. The net impact of ocean biology changes on global CO_2 fluxes is unknown.

The potential of terrestrial ecosystem management to alter future greenhouse gas concentrations is significant through, for instance, afforestation, reduced deforestation, and conservation agriculture. However, the potential reductions in greenhouse gases remain much smaller than the projected fossil fuel emissions over the next century (*high certainty*). The management of ecosystems for climate mitigation can yield other benefits as well, such as biodiversity conservation.

Ecosystems also modify climate through alteration of the physical properties of Earth's surface. For instance, deforestation in snowy regions leads to regional cooling of land surface during the snow season due to increase in surface albedo and to warming during summer due to reduction in transpiration (water recycled by plants to atmosphere). Positive feedbacks involving sea surface temperature and sea ice propagate this cooling to the global scale. The net physically mediated effect of conversion of high-latitude forests to more open landscapes is to cool the atmosphere (*medium certainty*). Observations and models indicate, with *medium certainty*, that **large-scale tropical and sub-tropical deforestation and desertification decrease the precipitation in the affected regions.** The mechanism involves reduction in within-region moisture recycling and an increase in surface albedo. [14]

Tropospheric ozone is both a greenhouse gas and an important pollutant. It is both produced and destroyed by chemical reactions in the atmosphere, and about a third of the additional tropospheric ozone produced as a result of human activities is destroyed by surface absorption in ecosystems. The capacity of the atmosphere to convert pollutants harmful to humans and other life forms into less harmful chemicals is largely controlled by the availability of hydroxyl radicals. The global concentration of these is believed to have declined by about 10% over the past centuries.

Detoxification of Wastes

Depending on the properties of the contaminant and its location in the environment, wastes can be rendered harmless by natural processes at relatively fast or extremely slow rates. The more slowly a contaminant is detoxified, the greater the possibility that harmful levels of the contaminant will occur. Some wastes, such as nutrients and organic matter, are normal components of natural ecosystem processes, but the anthropogenic loading rates are often so much higher than the natural throughput that they significantly modify the ecosystem and impair its ability to provide a range of services, such as recreation and appropriate-quality fresh water and air. **The costs of reversing damages to waste-degraded ecosystems are typically large, and the time scale for remediation is long. In some cases, rehabilitation is effectively impossible.** [15]

Protection from Floods

The impact of extreme weather events is increasing in many regions around the world. [7, 16, 19] For example, flood damage recorded in Europe in 2002 was higher than in any previous year. Increasing human vulnerability, rather than increasing physical magnitude or frequency of the events themselves, is overall the primary factor underlying the rising impact. People are increasingly occupying regions and locations that are exposed to flooding—settling on coasts and floodplains, for instance—thus exacerbating their vulnerability to extreme events. **Ecosystem changes have in some cases increased the severity of floods,** however, for example as a result of deforestation in upland areas and the loss of mangroves. Local case studies have shown that appropriate management of ecosystems contributes to reduction of vulnerability to extreme events.

Cultural Services

Human societies have developed in close interaction with the natural environment, which has shaped their cultural identity, their value systems, and indeed their economic well-being. Human cultures, knowledge systems, religions, heritage values, social interactions, and the linked amenity services (such as aesthetic enjoyment, recreation, artistic and spiritual fulfillment, and intellectual development) have always been influenced and shaped by the nature of the ecosystem and ecosystem conditions in which culture is based. **Rapid loss of culturally valued ecosystems and landscapes has led to social disruptions and societal marginalization in many parts of the world.** [17]

The world is losing languages and cultures. At present, the greatest losses are occurring in situations where languages are not officially recognized or populations are marginalized by rapid industrialization, globalization, low literacy, or considerable ecosystem degradation. Especially threatened are the languages of 350 million indigenous peoples, representing over 5,000 linguistic groups in 70 countries, which contain most of humankind's traditional knowledge. Much of the traditional knowledge that existed in Europe (such as knowledge on medicinal plants) has also gradually eroded due to rapid industrialization in the last century. [17]

The complex relationships that exist between ecological and cultural systems can best be understood through both "formal knowledge" and "traditional knowledge." Traditional knowledge is a key element of sustainable development, particularly in relation to plant medicine and agriculture, and the understanding of tangible benefits derived from traditional ecological knowledge such as medicinal plants and local species of food is relatively well developed. However, understanding of the linkages between ecological processes and social processes and their intangible benefits (such as spiritual and religious values), as well as the influence on sustainable natural resource management at the landscape level, remains relatively weak. [17]

Many cultural and amenity services are not only of direct and indirect importance to human well-being, they also represent a considerable economic resource. (For example, nature- and culture-based tourism employs approximately 60 million people and generates approximately 3% of global GDP.) Due to changing cultural values and perceptions, there is an increasing tendency to manage landscapes for high amenity values (such as recreational use) at the expense of traditional landscapes with high cultural and spiritual values. [17]

Supporting Services

There are numerous examples of both overabundance and insufficiency of nutrient supply. Crop yields and nutritional value in parts of Africa, Latin America, and Asia are strongly limited by poor soils, which have become even more depleted by farming with low levels of nutrient replenishment. On the other hand, overfertilization is a major contributor to environmental pollution through excess nutrients in many areas of commercial farming in both industrial and developing countries.

The capacity of terrestrial ecosystems to absorb and retain the nutrients supplied to them either as fertilizers or from the deposition of airborne nitrogen and sulfur has been undermined by the radical simplification of ecosystems into large-scale, low-diversity agricultural landscapes. Excess nutrients leak into the groundwater, rivers, and lakes and are transported to the coast. Treated and untreated sewage released from urban areas adds to the load. The consequence of the excessive and imbalanced nutrient load in aquatic ecosystems is an explosion of growth of certain plants (particularly algae) and a loss of many other forms of life, a syndrome known as eutrophication. The decomposing residues of the plants (often compounded by organic pollutants) deplete the water of oxygen, creating anaerobic "dead zones" devoid of life forms that depend on oxygen. Such dead zones have been discovered in many lakes and estuaries and off the mouths of several large rivers, and they are expanding.

How Are Key Ecological Systems Doing?

The systems where multiple problems are occurring at the same time, seriously affecting the well-being of hundreds of millions of people, are:

- **wetlands, including rivers, lakes, and salt and saltwater marshes, where water abstraction, habitat loss and fragmentation, and pollution by nutrients, sediments, salts, and toxins have significantly impaired ecosystem function and biodiversity in most major drainage basins;**
- **the arid parts of the world, where a large, growing, and poor population often coincides with water scarcity, cultivation on marginal lands, overgrazing, and overharvesting of trees;**
- **particular coastal systems, notably coral reefs, estuaries, mangroves, and urbanized coasts, where habitat loss and fragmentation, overharvesting, pollution, and climate change are the key issues; and**
- **tropical forests, where unsustainable harvesting and clearing for agriculture threatens biodiversity and the global climate.**

The majority of ecosystems have been greatly modified by humans. Within 9 of the 14 broad terrestrial ecosystem types (biomes), one fifth to one half of the area has been transformed to croplands, mostly over the past two centuries. Tropical dry forests are the most affected by cultivation, with almost half of the biome's native habitats replaced with cultivated lands. Temperate grasslands, temperate broadleaf forests, and Mediterranean forests have each experienced more than 35% conversion. Only the biomes unsuited to crop plants (deserts, boreal forests, and tundra) are relatively intact. (See Table C2.) [4]

Freshwater Systems: Wetlands, Rivers, and Lakes

It is *established but incomplete* that **inland water ecosystems are in worse condition overall than any other broad ecosystem type,** and it is *speculated* that about half of all freshwater wetlands have been lost since 1900 (excluding lakes, rivers, and reservoirs). The degradation and loss of inland water habitats and species is driven by water abstraction, infrastructure development (dams, dikes, levees, diversions, and so on), land conversion in the catchment, overharvesting and exploitation, introduction of exotic species, eutrophication and pollution, and global climate change. [20]

Clearing or drainage for agricultural development is the principal cause of wetland loss worldwide. It is estimated that by 1985, 56–65% of available wetland had been drained for intensive agriculture in Europe and North America, 27% in Asia, 6% in South America, and 2% in Africa. **The construction of dams and other structures along rivers has resulted in fragmentation of almost 40% of the large river systems in the world.** This

Table C2. Comparative Table of Systems as Reported by the Millennium Ecosystem Assessment. Note that these are linked human and ecological systems and often are spatially overlapping. They can therefore be compared but they should not be added up. Figure C1 presents data on human well-being by system type graphically.

System and Subsystem	Area[a] (million sq. km.)	Share of Terrestrial Surface of Earth (percent)	Population: Density (people per square km.) Urban	Rural	Population: Growth rate (percent 1990–2000)	GDP per Capita (dollars)	Infant Mortality Rate[b] (deaths pers 1,000 live births)	Mean NPP (kg. carbon per sq. meter per year)	Share of Systems Covered by PAs[c] (percent)	Share of Area Transformed[d] (percent)
Marine	349.3	68.6[e]	–	–	–	–	–	0.15	0.3	-
Coastal	**17.2**	**4.1**	**1,105**	**70**	**15.9**	**8,960**	**41.5**	**–**	**7**	**–**
Terrestrial	6.0	4.1	1,105	70	15.9	8,960	41.5	0.52	4	11
Marine	11.2	2.2[e]	–	–	–	–	–	0.14	9	–
Inland water[f]	10.3	7.0	817	26	17	7,300	57.6	0.36	12	11
Forest/woodlands	**41.9**	**28.4**	**472**	**18**	**13.5**	**9,580**	**57.7**	**0.68**	**10**	**42**
Tropical/sub-tropical	23.3	15.8	565	14	17	6,854	58.3	0.95	11	34
Temperate	6.2	4.2	320	7	4.4	17,109	12.5	0.45	16	67
Boreal	12.4	8.4	114	0.1	−3.7	13,142	16.5	0.29	4	25
Dryland	**59.9**	**40.6**	**750**	**20**	**18.5**	**4,930**	**66.6**	**0.26**	**7**	**18**
Hyperarid	9.6	6.5	1,061	1	26.2	5,930	41.3	0.01	11	1
Arid	15.3	10.4	568	3	28.1	4,680	74.2	0.12	6	5
Semiarid	22.3	15.3	643	10	20.6	5,580	72.4	0.34	6	25
Dry subhumid	12.7	8.6	711	25	13.6	4,270	60.7	0.49	7	35
Island	**7.1**	**4.8**	**1,020**	**37**	**12.3**	**11,570**	**30.4**	**0.54**	**17**	**17**
Island states	4.7	3.2	918	14	12.5	11,148	30.6	0.45	18	21
Mountain	**35.8**	**24.3**	**63**	**3**	**16.3**	**6,470**	**57.9**	**0.42**	**14**	**12**
300–1,000m	13.0	8.8	58	3	127	7,815	48.2	0.47	11	13
1,000–2,500m	11.3	7.7	69	3	20.0	5,080	67.0	0.45	14	13
2,500–4,500m	9.6	6.5	90	2	24.2	4,144	65.0	0.28	18	6
> 4,500m	1.8	1.2	104	0	25.3	3,663	39.4	0.06	22	0.3
Polar	**23.0**	**15.6**	**161**[g]	**0.06**[g]	**−6.5**	**15,401**	**12.8**	**0.06**	**42**[g]	**0.3**[g]
Cultivated	**35.3**	**23.9**	**786**	**70**	**14.1**	**6,810**	**54.3**	**0.52**	**6**	**47**
Pasture	0.1	0.1	419	10	28.8	15,790	32.8	0.64	4	11
Cropland	8.3	5.7	1,014	118	15.6	4,430	55.3	0.49	4	62
Mixed (crop and other)	26.9	18.2	575	22	11.8	11,060	46.5	0.6	6	43
Urban	**3.6**	**2.4**	**681**	**–**	**12.7**	**12,057**	**36.5**	**0.47**	**0**	**100**
GLOBAL	**510**	**–**	**681**	**13**	**16.7**	**7,309**	**57.4**	**–**	**4**	**38**

[a] Area estimates based on GLC2000 dataset for the year 2000 except for cultivated systems where area is based on GLCCD v2 dataset for the years 1992–93 (C26 Box 1).

[b] Deaths of children less than one year old per 1,000 live births.

[c] Includes only natural protected areas in IUCN categories I to VI.

[d] For all systems except forest/woodland, area transformed is calculated from land depicted as cultivated or urban areas by GLC2000 land cover dataset. The area transformed for forest/woodland systems is calculated as the percentage change in area between potential vegetation (forest biomes of the WWF ecoregions) and current forest/woodland areas in GLC2000. Note: 22% of the forest/woodland system falls outside forest biomes and is therefore not included in this analysis.

[e] Percent of total surface of Earth.

[f] Population density, growth rate, GDP per capita, and growth rate for the inland water system have been calculated with an area buffer of 10 kilometers.

[g] Excluding Antarctica.

is particularly the case in river systems with parts of their basins in arid and semiarid areas. [20]

The water requirements of aquatic ecosystems are in competition with human water demands. Changes in flow regime, transport of sediments and chemical pollutants, modification of habitat, and disruption of the migration routes of aquatic biota are some of the major consequences of this competition. Through consumptive use and interbasin transfers, **several of the world's largest rivers no longer run all the way to the sea for all or part of the year** (such as the Nile, the Yellow, and the Colorado). [7]

The declining condition of inland waters is putting the services derived from these ecosystems at risk. The increase in pollution to waterways, combined with the degradation of wetlands, has reduced the capacity of inland waters to filter and assimilate waste. Water quality degradation is most severe in areas where water is scarce—arid, semiarid, and dry subhumid regions. Toxic substances and chemicals novel to the ecosystem are reaching waterways in increasing amounts with highly uncertain long-term effects on ecosystems and humans. [20]

Estimates are that between 1.5 billion and 3 billion people depend on groundwater supplies for drinking. Groundwater is the source of water for 40% of industrial use and 20% of irrigation globally. In arid countries this dependency is even greater; for example, Saudi Arabia supplies nearly 100% of its irrigation requirement through groundwater. Overuse and contamination of groundwater aquifers are known to be widespread and growing problems in many parts of the world, although many pollution and contamination problems that affect groundwater supplies have been more difficult to detect and have only recently been discovered. [7]

Inland waters have high aesthetic, artistic, educational, cultural, and spiritual values in virtually all cultures and are a focus of growing demand for recreation and tourism. [20]

Dryland Systems: Deserts, Semiarid, and Dry Subhumid Rangelands

Drylands cover 41% of Earth's land surface and are inhabited by more than 2 billion people, about one third of the human population. **Semiarid drylands are the most vulnerable to loss of ecosystem services** (*medium certainty*), because they have a relatively high population in relation to the productive capacity of the system. [22].

Desertification is the process of degradation in drylands, where degradation is defined as a persistent net loss of capacity to yield provisioning, regulating, and supporting ecosystem services. **Worldwide, about 10–20% of drylands are judged to be degraded** (*medium certainty*). The main causes of dryland degradation are grazing with domestic livestock and cutting of trees at rates exceeding the regrowth capacity of the ecosystem, inappropriate cultivation practices that lead to erosion and salinization of the soil, and climate change, which is affecting rates of evapotranspiration and precipitation.

Where the limits to sustainable cultivation and pastoralism have been reached, the promotion of alternative livelihoods such as production of crafts, tourism-related activities, and even aquaculture (such as aquatic organisms of high market value, cultured in often abundant drylands' low-quality water, within evaporation-proof containers) can take some pressure off dryland ecosystems and their services. [22]

Wetlands in drylands, such as oases, rivers, and marshes, are disproportionately important in terms of the biodiversity that they support and the ecosystem services they provide. [20, 22]

It is *well established* that desertification has adverse impacts in non-dryland areas, often many thousands of kilometers away. For example, dust storms resulting from reduced vegetative cover lead to air quality problems, both locally and far away. Drought and loss of land productivity are dominant factors that cause people to migrate from drylands to better-serviced areas. [22]

Forests, Including Woodlands and Tree Plantations

The global area of naturally regenerating forest has declined throughout human history and has halved over the past three centuries. **Forests have effectively disappeared in 25 countries, and more 90% of the former forest cover has been lost in a further 29 countries.** [21]

Following severe deforestation in past centuries, forest cover and biomass in North America, Europe, and North Asia are currently increasing due to the expansion of forest plantations and regeneration of natural forests. From 1990 to 2000, the global area of temperate forest increased by almost 3 million hectares per year, of which approximately 1.2 million hectares were was planted forest. The main location of deforestation is now in the tropics, where it has occurred at an average rate exceeding 12 million hectares per year over the past two decades. (See Figure C5.) **Taken as a whole, the world's forests are not managed in a sustainable way, and there is a total net decrease in global forest area, estimated at 9.4 million hectares per year.** In absolute terms, the rate and extent of woodland loss exceeds that of forests.

The decline in forest condition is caused, among other factors, by the low political power of human communities in forest areas in many countries; deforestation due to competitive land use and poor management; slow change of traditional, wood-oriented forest management paradigms; the lack of forest management on landscape-ecosystem basis; acceleration of natural and human-induced disturbance regimes during the last decade (possibly linked to climate change); and illegal harvest in many developing countries and countries with economies in transition, often linked to corruption. [21]

In addition to the 3.3 billion cubic meters of wood delivered by forests annually, numerous non-wood forest products are important in the lives of hundreds of millions people. Several studies show that the combined economic value of "nonmarket" (social and ecological) services often exceeds the economic value of direct use of the timber, but the nonmarket values are usually not considered in the determination of forest use. Wooded landscapes are home to about 1.2 billion people, and **350 million of the world's people, mostly the poor, depend substantially for their subsistence and survival on local forests.** Forests and woodlands constitute the natural environment and almost sole source of livelihood for 60 million indigenous people and are important in the cultural, spiritual, and recreational life of communities worldwide. [21]

Terrestrial ecosystems, and wooded lands in particular, are taking up about a fifth of the global anthropogenic emissions of carbon dioxide, and they will continue to play a significant role in limiting global climate change over the first decades of this century. Tree biomass constitutes about of 80% of terrestrial biomass, and **forests and woodlands contain about half of the world's terrestrial organic carbon stocks.** Forests and woodlands provide habitat for half or more of the world's known terrestrial plant and animal species, particularly in the tropics. [21]

Marine and Coastal Systems

All the oceans of the world, no matter how remote, are now affected by human activities. Ecosystem degradation associated with fishing activities is the most widespread and dominant impact, with pollution as an additional factor on coastal shelves, and habitat loss a factor in populated coastal areas. [18, 19]

Global fish landings peaked in the late 1980s and are now declining (*medium certainty*). There is little likelihood of this declining trend reversing under current practices. Fishing pressure is so strong in some marine systems that the biomass of targeted species, especially larger fishes as well as those caught incidentally, has been reduced by 10 times or more relative to levels prior to the onset of industrial fishing. **In addition to declining landings, the average trophic level of global landings is declining** (in other words, the high-value top-predator fish are being replaced in catches by smaller, less preferred species), and the mean size of caught fish is diminishing in many species, including yellowfin and bigeye tuna. [18]

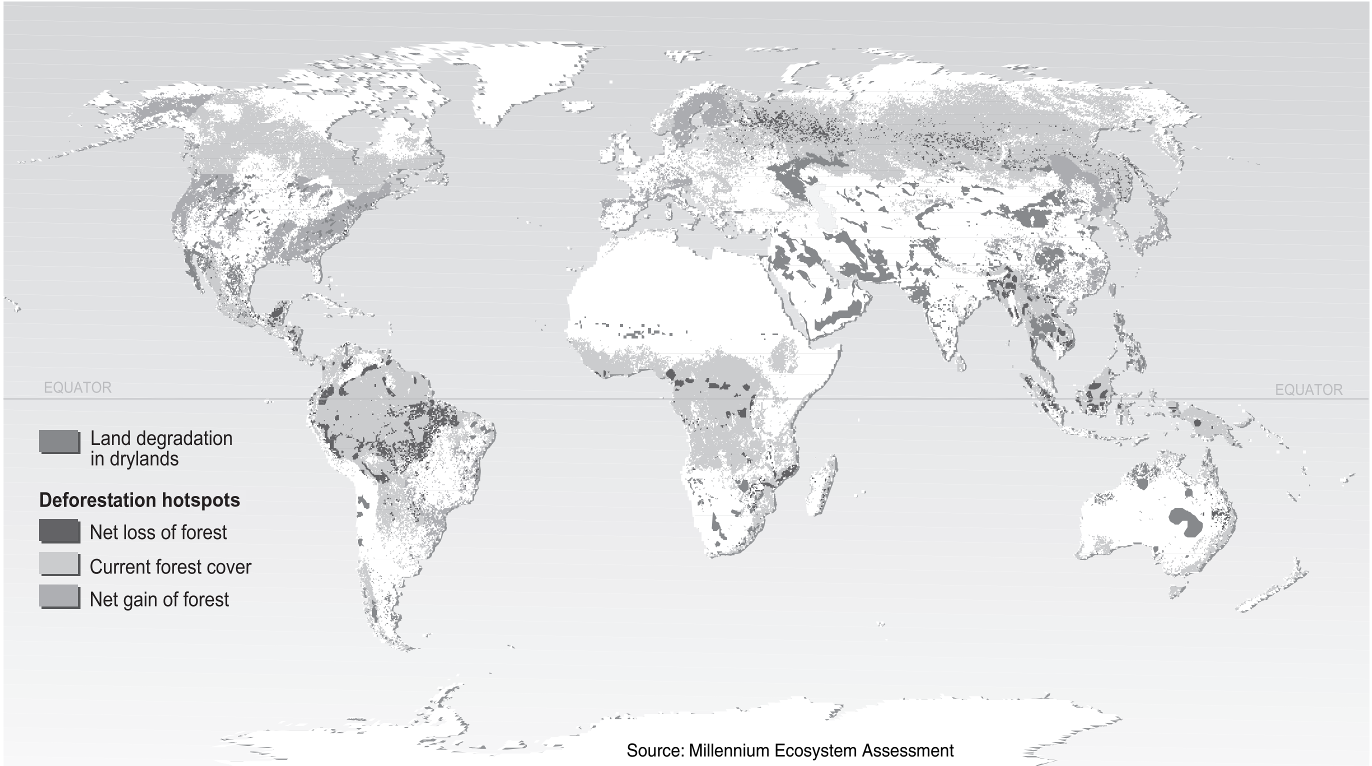

Figure C5. Locations Reported by Various Studies as Undergoing High Rates of Land Cover Change in the Past Few Decades. In the case of forest cover change, the studies refer to the period 1980–2000 and are based on national statistics, remote sensing, and to a limited degree expert opinion. In the case of land cover change resulting from degradation in drylands (desertification), the period is unspecified but inferred to be within the last half-century, and the major study was entirely based on expert opinion, with associated high levels of uncertainty. Change in cultivated area is not shown. Note that areas showing little current change are often locations that have already undergone major change.

Industrial fleets are fishing further offshore and deeper to meet the global demand for fish. Until a few decades ago, depth and distance from coasts protected much of the deep-ocean fauna from the effect of fishing. Massive investments in the development of fishing capacity has led to fleets that now operate in all parts of the world's oceans, including polar areas, at great depths, and in low-productivity tropical zones. These trawl catches are extracted from easily depleted accumulations of long-lived species. The biomass of large pelagic fishes exploited by long liners, purse seiners, and drift netters have also plummeted. **Some fisheries that collapsed in recent decades show no signs of recovering**, such as Newfoundland cod stocks in the northwest Atlantic and orange roughy in New Zealand. [18]

Oil spills, depletions of marine mammals and seabirds, and ocean dumping also contribute to degradation in marine systems, especially at local and regional scales. Although major oils spills are infrequent, their impacts are severe when they do occur. Overfishing and pollution affect marine mammals and seabirds through declining food availability. An estimated 313,000 containers of low-intermediate radioactive waste dumped in the Atlantic and Pacific Oceans since 1970 pose a significant threat to deep-sea ecosystems should the containers leak. [18]

Coastal ecosystems are among the most productive yet highly threatened systems in the world. Approximately 35% of mangroves for which data are available and 20% of coral reefs are estimated to have been destroyed, and a further 20% of corals degraded globally since 1960. Degradation is also a severe problem, both from pressures originating within the coastal zones and from the negative impacts of upstream land uses. Upstream freshwater diversion has meant a 30% decrease worldwide in water and sediment delivery to estuaries, which are key nursery areas and fishing grounds. [19] Knowledge of cold-water corals is limited, and new large reefs are still being discovered. Cold-water coral reefs are estimated to have high species diversity, the biggest threat to which comes from fishery trawling activities.

The main indirect drivers of coastal ecosystem change are related to development activities on the land, particularly in areas adjacent to the coast. Approximately 17% of the world lives within the boundaries of the MA coastal system (up to an elevation of 50 meters above sea level and no further than 100 kilometers from a coast), and approximately 40% live in the full area within 100 kilometers of a coast. The absolute number is increasing through a combination of in-migration, high reproduction rates, and tourism. Physical demand on coastal space is increasing through urban sprawl, resort and port development, and aquaculture, the impacts of which extend beyond the direct footprints due to pollution, sedimentation, and changes in coastal dynamics. Destructive fishing practices, overharvesting, climate change, and associated sea level rise are also important threats to coastal habitats, including forests, wetlands, and coral reefs.

Nearly half of the coastal population has no access to improved sanitation and thus faces increasing risks of disease as well as decreasing ecosystem services as a result of pollution by human wastes. Harmful algal blooms and other pathogens affecting the health of both humans and marine organisms are on the rise. [19] Nitrogen loading to the coastal zone has doubled worldwide and has driven coral reef community shifts. Alien species invasions have also altered coastal ecosystems and threaten both marine species and human well-being. [18]

Island Systems

The ability of island systems to meet the rising demands of local populations for services has declined considerably, such that some islands are now unable to meet such demands without importing significant services from elsewhere. **Biodiversity loss and habitat destruction on islands can have more immediate and serious repercussions than on continental systems,** as a consequence of the relatively restricted genetic diversity, small population sizes and narrow distribution ranges of plants and animals on islands. Many studies show that specialization, coupled with isolation and endemism, make island ecosystems especially sensitive to disturbances. Island species have become extinct at rates that have exceeded those observed on continents, and the most important driver of wild population declines and species extinction on islands has been the introduction of invasive alien species. Although the idea that islands are more susceptible to biological invasion is poorly supported by current information, the impacts of invasive species once they are established are usually more rapid and more pronounced on islands. [23]

In recent years tourism, especially nature-based tourism, has been the largest area of economic diversification for inhabited islands. However, unplanned and unregulated development has resulted in ecosystem degradation, including pollution, and loss of coral reefs, which is undermining the very resource on which the tourism sector is based. Alternative, more environmentally and culturally sensitive forms of tourism ("ecotourism") have developed in some areas. [23]

Cultivated Systems: Croplands, Planted Pastures, and Agroforestry

Cultivated lands are ecosystems highly transformed and managed by humans for the purpose of providing food and fiber, often at the expense of other ecosystem services. **More land was converted to cropland in the 30 years after 1950 than in the 150 years between 1700 and 1850, and one quarter of Earth's terrestrial surface is now occupied by cultivated systems.** (See Figure C6.) Within this area, one fifth is irrigated. [26]

As the demand for food, feed, and fiber has increased, farmers have responded both by expanding the area under cultivation (extensification) and by raising yields per unit land and per unit time (intensification). **Over the past 40 years, in global aggregate, intensification has been the primary source of increased output,** and in many regions (including in the European Union, North America, Australia, and recently China) the extent of land under cultivation has stabilized or even contracted. However, countries with low productivity and high population pressure—conditions that apply in much of sub-Saharan Africa—continue to rely mainly on expansion of cultivated areas for increasing food productivity. In Asia (outside of China), almost no high-productivity land remains available for the expansion of agriculture. Area expansion usually brings more marginal land (steeper slopes, poorer soils, and harsher climates) into production, often with unwelcome social and environmental consequences. Urban expansion is a growing cause of displacement of cultivation, but the area involved remains small in global terms. [26]

Increases in the yields of crop production systems due to increased use of inputs over the past 40 years have reduced the pressure to convert other ecosystems into cropland. Twenty million square kilometers of natural ecosystem have been protected from conversion to farmland since 1950 due to more intensive production. On the other hand, intensification has increased pressure on inland water ecosystems due to increased water withdrawals for irrigation and to nutrient and pesticide leakage from cultivated lands, with negative consequences for freshwater and coastal systems, such as eutrophication. Intensification also generally reduces biodiversity within agricultural landscapes and requires higher energy inputs in the form of mechanization and the production of chemical fertilizers. Especially in systems that are already highly intensified, the marginal value of further increased production must be weighed against the additional environmental impacts. [26]

The intrinsic capacity of cultivated systems to support crop production is being undermined by soil erosion and salinization and by loss of agricultural biodiversity, but their effect on food production is masked by increasing use of fertilizer, water, and other agricultural inputs. (See Figure C7.) [8, 22, 26]

National policies, international agreements, and market forces play a significant role in determining the fate of ecosystems services as a consequence of cultivation. They all influence farmer choices about the scale and type of cultivation as well as the level and mix of production inputs that, in turn, influence trade-offs among the mix and level of ecosystem services that cultivated systems can deliver. [26]

Urban Systems

Urban areas currently cover less than 3% of the total land area of Earth, but they contain an increasing fraction of the world's population. Currently about half of the world's people live in urban areas. The urban requirements for ecosystem services are high, but it could be just as stressful if the same number of people, with similar consumption and production patterns, were dispersed over the rural landscape. In general, **the well-being of urban dwellers is higher than that of their rural neighbors,** as measured by wealth, health, and education indicators. Urban centers facilitate human access to and management of certain ecosystem services through, for example, the scale economies of piped water systems. [27]

Nevertheless, urban developments pose significant challenges with respect to ecosystem services and human well-being. The problems include inadequate and inequitable access to ecosystem services within urban areas, degradation of ecosystems adjoining urban areas, and pressures on distant ecosystems resulting from production, consumption, and trade originating in urban areas. [27]

In affluent countries, the negative impacts of urban settlements on ecosystem services and human well-being have been delayed and passed on to future generations or displaced onto locations away from the urban area. While urban developments in other parts of the world have been quite different, this trend and its political implication remain significant. [27]

Interrelated problems involving local water, sanitation, waste, and pests contribute a large share of the urban burden of disease, especially in low-income settlements. The consumption and production activities driving long-term, global ecosystem change are concentrated in urban centers, especially upper-income settlements. [27]

Urbanization is not inherently bad for ecosystems: ecosystems in and around urban areas can provide a high level of biodiversity, food production, water services, comfort, amenities, cultural values, and so on if well managed. When the loss of ecosystem services due to urban activities is systematically addressed,

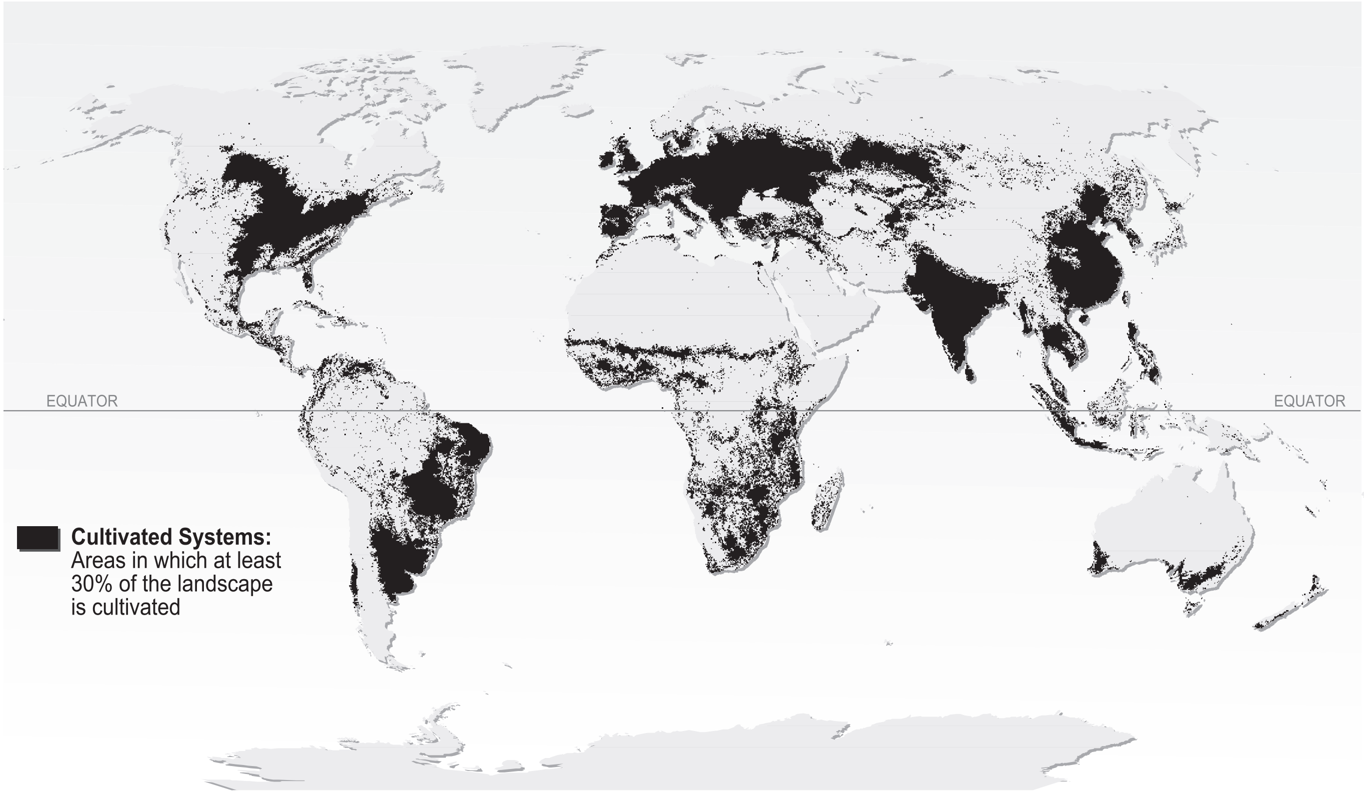

Figure C6. Extent of Cultivated Systems in 2000. Cultivated systems (defined in the MA to be areas in which at least 30% of the landscape comes under cultivation in any particular year) cover 24% of the terrestrial surface.

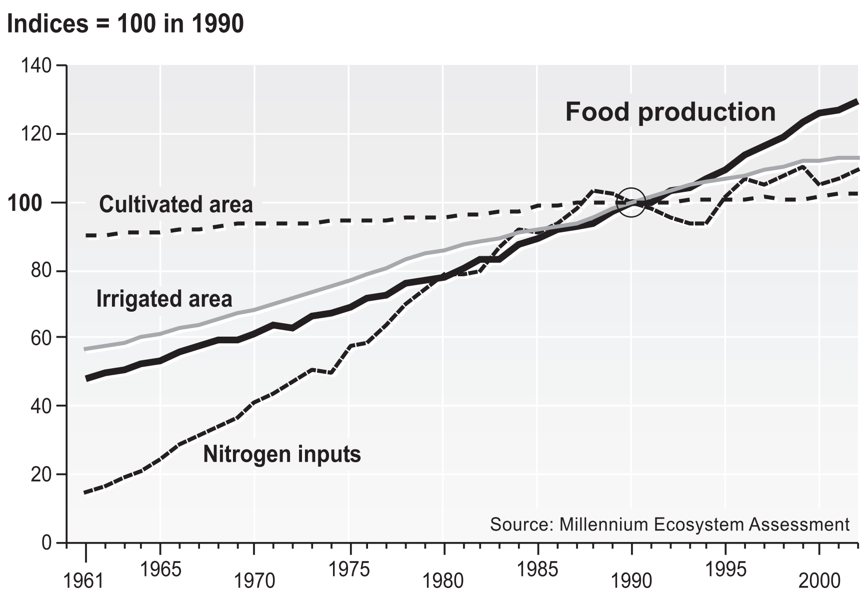

Figure C7. Trends in the Factors Related to Global Food Production since 1961. There have been significant trade-offs in cultivated systems between food production and water availability for other uses (due to irrigation), as well as water quality (due to increased nutrient loading). The role of improved crop varieties has also been extremely significant since 1961.

these losses can be greatly reduced. With a few exceptions, however, there is little evidence of cities taking significant steps to reduce their global ecosystem burdens. A city may be sustained by ecosystem services derived from an area up to 100 times larger than the city itself. [27]

Polar Systems

Direct, locally caused impacts of human activities on polar regions have been modest, and the most significant causes of change mainly originate outside the polar region. These global drivers must be addressed if loss of polar ecosystem services and human well-being is to be avoided, but in the immediate term, mitigation of impacts is the most feasible and urgent strategy. Polar regions have a high potential to continue providing key ecosystem services, particularly in wetlands, where biodiversity and use of subsistence resources are concentrated. [25]

The climate has warmed more quickly in portions of the Arctic (particularly in the western North American Arctic and central Siberia) and Antarctic (especially the Antarctic peninsula) than in any other region on Earth. **As a consequence of regional warming, ecosystem services and human well-being in polar regions have been substantially affected** (*high certainty*). Warming-induced thaw of permafrost is widespread in Arctic wetlands, causing threshold changes in ecosystem services, including subsistence resources and climate feedbacks (energy and trace gas fluxes) and support for industrial and residential infrastructure.

Regional warming interacts with socioeconomic change to reduce the subsistence activities of indigenous and other rural people, the segment of society with greatest cultural and economic dependence on these resources. Warming has reduced access to marine mammals due to there being less sea ice and has made both the physical and the biotic environment less predictable. Industrial development has further reduced the capacity of ecosystems to support subsistence activities in some locations. The net effect is generally to increase the economic disparity between rural subsistence users and urban residents in polar regions. [25]

Changes in polar biodiversity are affecting the resources on which Arctic people depend for their livelihoods. Important changes include increased shrub dominance in Arctic wetlands, which contributes to summer warming trends and alters forage available to caribou; changes in insect abundance that alter food availability to wetland birds and energy budgets of reindeer and caribou; increased abundance of snow geese that are degrading Arctic wetlands; and overgrazing by domestic reindeer in parts of Fennoscandia and Russia. There has also been a reduction of top predators in Antarctic food webs, altering marine food resources in the Southern Ocean. [25]

Increases in persistent organic pollutants and radionuclides in subsistence foods have increased health risks in some regions of the Arctic, but diet changes associated with the decline in harvest of these foods are usually a greater health risk. [25]

Mountain Systems

Mountain systems straddle all geographical zones and contain many different ecosystem types. Ninety percent of the 720 million people in the global mountain population live in developing and transition countries, with one third of them in China. **Almost all of the people living above 2,500 meters (about 70 million people) live in poverty and are especially vulnerable to food insecurity.**

Human well-being in lowland areas often depends on resources originating in mountain areas, such as timber, hydroelectricity, and water. Indeed, river basins from mountain systems supply nearly half of the human population with water, including in some regions far from the mountains themselves, and **loss of ecosystem functions in mountains increases environmental risks in both mountains and adjacent lowland areas.** However, there is rarely a systematic reinvestment of benefits derived from mountain systems in the conservation of upland resources. Mountains often represent political borders, narrow key transport corridors, or refuges for minorities and political opposition, and as such they are often focal areas of armed conflicts. [24]

The compression of climatic zones along an elevation gradient in mountains results in large habitat diversity and species richness in mountains, which commonly exceeds that found in lowlands. Rates of endemism are also relatively high in mountains due to topographic isolation. Mountains occupy about one fifth of the terrestrial surface but host a quarter of terrestrial biodiversity, nearly half of the world's biodiversity "hotspots," and 32% of the global area designated for biodiversity protection. Mountains also have high ethnocultural diversity. Scenic landscapes and clean air make mountains target regions for recreation and tourism. [24]

Mountain ecosystems are unusually exposed and sensitive to a variety of stresses, specifically climate-induced vegetative changes, volcanic and seismic events, flooding, loss of soil and vegetation caused by extractive industries, and inappropriate agricultural practices. On average, glaciers have lost 6–7 meters of depth (thickness) over the last 20 years, and this reduction in glacier volume is expected to have a strong impact on dry-season river flows in rivers fed largely by ice melt. **The specialized nature of mountain biota and low temperatures in mountain systems make recovery from disturbances typically very slow.** [24]

Limits, Trade-offs, and Knowledge

- **The growing demand for provisioning services, such as water, food, and fiber, has largely been met at the expense of supporting, regulating, and cultural ecosystem services.**
- **For some provisioning services, notably fresh water and wild-harvested fish, demand exceeds the available supply in large and expanding parts of the world.**
- **Some ongoing, large-scale human-induced ecosystem changes, such as those involving loss of biodiversity, climate change, excessive nutrient supply, and desertification, are effectively irreversible. Urgent mitigation action is needed to limit the degree of change and its negative impacts on human well-being.**
- **Enough is known to begin to make wiser decisions regarding protection and use of ecosystem services. Making this information available to decision-makers is the purpose of the Millennium Ecosystem Assessment.**

Limits and Thresholds in Coupled Human-Ecological Systems

The current demand for many ecosystems services is unsustainable. If current trends in ecosystem services are projected, unchanged, to the middle of the twenty-first century, there is a high likelihood that widespread constraints on human well-being will result. This highlights the need for globally coordinated adaptive responses, a topic further explored in the MA *Scenarios* and *Policy Responses* volumes.

Some limits to the degree of acceptable ecosystem change represent the level of tolerance by society, reflecting the trade-offs that people are willing (or forced) to make between different aspects of well-being. They are "soft limits," since they are socially determined and thus move as social circumstances change. Many such limits are currently under international negotiation, indicating that some key ecosystem services are approaching levels of concern. Examples are the amounts of fresh water allocated to different countries in shared basins, regional air quality norms, and the acceptable level of global climate change.

Other limits are a property of the ecological system itself and can be considered "hard limits." Two types of hard limit are of concern. The first is nonlinearity, which represents a point beyond which the loss of ecosystem services accelerates, sometimes abruptly. An example is the nitrogen saturation of watersheds: once the absorptive capacity of the ecosystem is exceeded, there is a sudden increase in the amount of nitrogen leaking into the aquatic environment. The second type is a true system threshold that, if crossed, leads to a new regime from which return is difficult, expensive, or even impossible. An example is the minimum habitat area required to sustain a viable population of a given species. If the area falls below this, eventual extinction is inevitable. We have fallen below this limit for many thousands of species (*medium certainty*).

Abrupt and possibly irreversible change may not be widely apparent until it is too late to do much about it. The dynamics of both ecological and human systems have intrinsic inertia—the tendency to continue changing even when the forces causing the change are relieved. The complexity of coupled human–ecological systems, together with our state of partial knowledge, make it hard to predict precisely at what point such thresholds lie. The overexploitation of wild fisheries is an example of a threshold that has already been crossed in many regions. [6, 13, 18, 25]

Thresholds of abrupt and effectively irreversible change are known to exist in the climate-ocean-land system (*high certainty*), although their location is only known with *low to medium certainty*. For example, it is *well established* that a decrease in the vegetation cover in the Sahara several thousand years ago was linked to a decrease in rainfall, promoting further loss of cover, leading to the current dry Sahara. It is *speculated* that a similar mechanism may have been involved in the abrupt decrease in rainfall in the Sahel in the mid-1970s. There are potential thresholds associated with climate feedbacks on the global carbon cycle, but large uncertainties remain regarding the strength of the feedback processes involved (such as the extent of warming-induced increases in soil respiration, the risk of large-scale dieback of tropical forests, and the effects of CO_2, nitrogen, and dust fertilization on carbon uptake by terrestrial and marine ecosystems). [12, 13, 22, 25]

Current human-induced greenhouse gas emissions to the atmosphere are greater than the capacity of global ecosystems to absorb them (*high certainty*). The oceans and terrestrial ecosystems are currently absorbing only about half of the carbon emissions resulting from fossil fuel combustion. As a result, the atmospheric concentration of CO_2 is rising, along with other greenhouse gases, leading to climate change. Although land use management can have a significant impact on CO_2 concentrations in the short term, future trends in atmospheric CO_2 are likely to depend more on fossil fuel emissions than on ecosystem change. [13]

Nitrogen additions to the environment are approaching critical limits in many regions. The increasing extent of oxygen-poor "dead zones" in freshwater or coastal ecosystems that have received elevated inputs of nutrients—nitrogen and phosphorus, in particular—over long periods of time is a symptom of the degree to which the nutrient retention capacity of terrestrial and freshwater systems has been overloaded. [12]

The capacity of Earth as a whole to render other waste products of human activities relatively harmless is unknown. It is *well established* that at high loading rates of wastes such as persistent organic pollutants, heavy metals, and radionuclides, the local ecosystem capacity can be overwhelmed, allowing waste accumulation to the detriment of human well-being and the loss of ecosystem biodiversity [15]. A potential nonlinear response, currently the subject of intensive scientific research, is the atmospheric capacity to cleanse itself of air pollution (in particular, hydrocarbons and reactive nitrogen compounds). This capacity depends on chemical reactions involving the hydroxyl radical, the atmospheric concentration of which has declined by about 10% (*medium certainty*) since preindustrial times. [13]

Understanding the Trade-offs Associated with Our Actions

The growth in human well-being over the last several decades has come in large part through increases in provisioning services, usually at the expense of other services. In particular:

- The substantial increase in the production of food and fiber has expanded the area of cultivated systems (including plantation forests) at the expense of semi-natural ecosystems such as forests, rangelands, and wetlands. It has largely been achieved as a result of large inputs of nutrients, water, energy, and pesticides, with deleterious consequences for other ecosystems and the global climate.
- Clearing and transformation of previously forested land for agricultural and timber production, especially in tropical and sub-tropical forests, has reduced the land's capacity to regulate flows of water, store carbon, and support biological diversity and the livelihoods of forest-dwelling people.
- Harvesting of fish and other resources from coastal and marine systems (which are simultaneously under pressure from elevated flows of nutrients, sediments, and pollutants from the land) has impaired these systems' capacity to continue to deliver food in the future.

This assessment has shown that although we have many of the conceptual and analytical tools to illustrate the existence of trade-offs, the detailed information required to quantify adequately even the main trade-offs in economic terms is generally either lacking or inaccessible. An example of a tool useful for trade-off analysis is the valuation of ecosystem services, but such valuations have only been done for a few services and in a few places. The MA has also shown that failure to fully comprehend the trade-offs associated with particular actions has, in many instances, resulted either in a net decrease in human well-being or in an increase that is substantially less than it could have been. Examples of this include the loss of non-wood products and watershed services from overlogged forests, the loss of timber and the declines in offshore fisheries and storm protection from conversion of mangroves to aquaculture, and the loss of wetland products from conversion to intensive agriculture. (See Figure C8.) The continued tendency to make decisions on a sectoral basis prevents trade-offs from being fully considered.

Several independently derived international goals and commitments are interconnected via the ecosystems they affect. Thoughtful and informed consideration of trade-offs and synergies would be best achieved by coordinated implementation. An example of the importance of ecosystem service trade-offs in the pursuit of human well-being is provided by the Millennium Development Goals. In meeting the goal of reducing hunger, for instance, progress toward the goal of environmental sustainability could be compromised, and vice versa. A narrowly sectoral approach often simply displaces problems to other sectors. Ecosystem approaches, as adopted by the Convention on Biological Diversity, the Ramsar Convention on Wetlands, the Food and Agriculture Organization, and others, show promise for improving the future condition of services and human

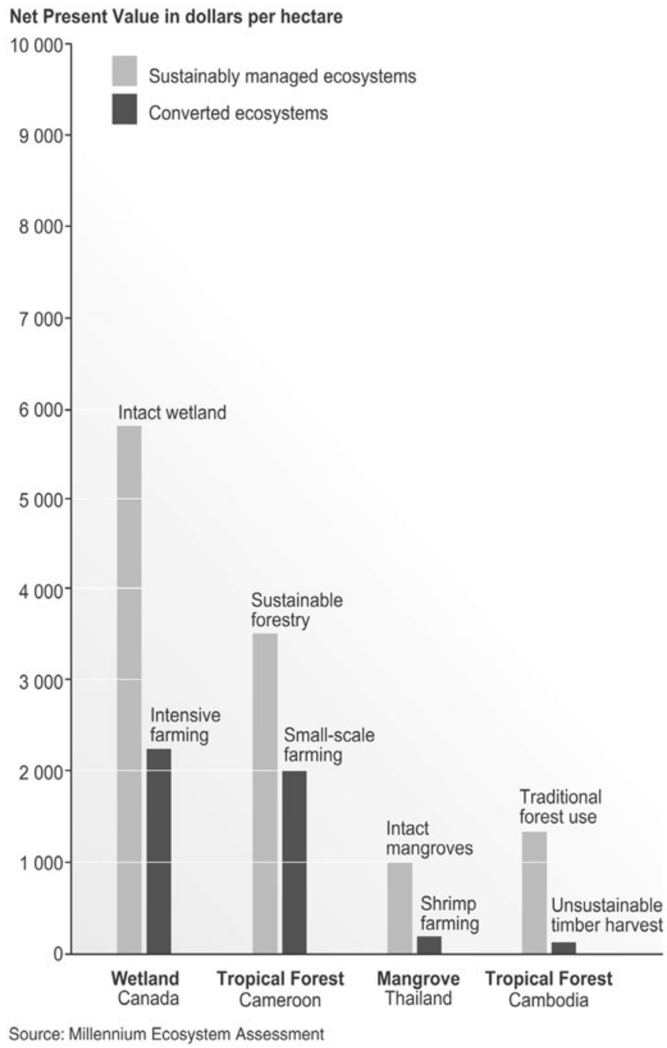

Figure C8. Economic Benefits under Alternate Management Practices. In each case, the net benefits from the more sustainably managed ecosystem are greater than those from the converted ecosystem even though the private (market) benefits would be greater from the converted ecosystem. (Where ranges of values are given in the original source, lower estimates are plotted here.)

well-being as a whole, specifically by balancing the objectives of economic development and ecosystem integrity. In managing ecosystems, a balance needs to be found between provisioning services on the one hand and supporting, regulating, cultural and amenity services on the other hand. [7, 28]

Knowledge and Uncertainty

The experience of this assessment has been that it is hard to demonstrate, quantitatively and unequivocally, the widely accepted and intuitive link between ecosystem changes and changes in human well-being. There are several reasons for this. First, the impacts of ecosystem change on well-being are often subtle, which is not to say unimportant; impacts need not be blatant to be significant. Second, human well-being is affected by many factors in addition to the effects of ecosystem services. Health outcomes, for example, are the combined result of ecosystem condition, access to health care, economic status, and myriad other factors. Unequivocally linking ecosystem changes to changes in well-being, and vice versa, is especially difficult when the data are patchy in both cases, as they usually are. Analyses linking well-being and ecosystem condition are most easily carried out at a local scale, where the linkages can be most clearly identified, but information on ecosystems and human well-being is often only available in highly aggregated form, for instance at the national level. Spatially explicit data with sub-national resolution would greatly facilitate future assessments. [2]

The availability and accuracy of data sources and methods for this assessment were greatest for provisioning services, such as crop yield and timber production. Direct data on regulating, supporting, and cultural services such as nutrient cycling, climate regulation, or aesthetic value are difficult to obtain, making it necessary to use proxies, modeled results, or extrapolations from case studies. Data on biodiversity have strong biases toward the species level, large organisms, temperate systems, and species used directly by people. [2, 4, 28]

Knowledge for quantifying ecosystem responses to stress is equally uneven. Methods to estimate crop yield responses to fertilizer application, for example, are well developed, but methods to quantify relationships between ecosystem services and human well-being, such as the effects of altered levels of biodiversity on the incidence of diseases in humans, are at an earlier stage of development. Thousands of novel chemicals, including long-lived synthetic pharmaceuticals, are currently entering the biosphere, but there are few systematic studies to understand their impact on ecosystems and human well-being. [2, 28]

Observation systems relating to ecosystem services are generally inadequate to support informed decision-making. Some previously more-extensive observation systems have declined in recent decades. For example, substantial deterioration of hydrographic networks is occurring throughout the world. The same is true for standard water quality monitoring and the recording of biological indicators. [7]

Both "traditional" and "formal" knowledge systems have considerable value for achieving the conservation and sustainable use of ecosystems. The loss of traditional knowledge has significantly weakened the linkages between ecosystems and cultural diversity and cultural identity. This loss has also had a direct negative effect on biodiversity and the degradation of ecosystems, for instance by exceeding traditionally established norms for resource use. This knowledge is largely oral. As significant is the loss of languages, which are the vehicle by which cultures are communicated and reproduced. [17]

A Call for Action

Despite the gaps in knowledge, **enough is known to indicate the need for urgent collective action, building on existing activities, to mitigate the further loss of ecosystem services.** It is *well established* that inadequate access to ecosystem services currently is an important factor in the low well-being of a large fraction of the global population and is likely to constrain improvements in well-being in the future.

Urgency is indicated because in situations where the probability of effectively irreversible, negative impacts is high, where the human and natural systems involved have high inertia, and where knowledge of the consequences is incomplete, early action to reduce the rate of change is more rational than waiting until conditions become globally intolerable and potentially irreversible. **Collective action is required** because uncoordinated individual action is necessary but insufficient to mitigate the many issues that have large-scale underlying causes, mechanisms, or consequences. Coordinated action at all levels of social organization—from local to global—is called for if the many islands of local failure are not to coalesce into expanding regions of degradation and if problems with global reach are to be managed. Coordinated action is also required to enable islands of local success to be expanded and propagated in distant locations.

The history of human civilization has many examples of social upheaval associated with ecosystem service failure at the local or regional scale. There are many current examples where the demands on ecosystems are exceeding the limits of the system to supply ecosystem services. Global-scale examples are given in this report, and local and regional examples are found in the *Multiscale Assessments* volume. **Two things are different now compared with any other time in history: human impacts are now ubiquitous and of greater intensity than at any time in the past, and in most cases we can no longer plead ignorance of the consequences.** Whereas in the past, natural disasters, pollution, or resource depletion led to local hardships, realignment of power, and the regional migration of people to better-serviced areas, in the present era the impacts are global in reach. Displacement of the problem to other places and future generations, or starting afresh in a new place, are no longer viable options.

A turning point in the growth of the human population on Earth is likely by mid-century. As the *Scenarios* and *Policy Responses* volumes show, the opportunity and technical means exist to provide food, water, shelter, a less-hazardous environment, and a better life to the existing population, and even to the additional 3 billion people likely to inhabit Earth by the middle of the twenty-first century, but we are currently failing to achieve this. We are also undermining our capacity to do so in the future by failing to take actions that will reduce the risk of adverse changes in Earth's ecological systems that will be difficult and costly to reverse.

Reducing the pressure on critical systems and services will be neither easy nor cost-free, but it is certain that net human well-being is better served by maintaining ecosystems in a condition that is capable of providing adequate levels of essential services than by trying to restore such functions at some future time.