CHAPTER 2

TAKING STOCK OF ECOSYSTEMS

This chapter takes on the critical question: *What condition are the world's ecosystems in?* As Chapter 1 makes clear, the capacity of ecosystems to produce goods and services ranging from food to clean water is fundamentally important for meeting human needs and, ultimately, influences the development prospects of nations. Although policy makers have ready access to information about the condition of their nation's economy, educational programs, or health care system, comparable information about the condition of ecosystems is unavailable. In fact, no nation or global institution has ever undertaken a comprehensive assessment of how well ecosystems are meeting human needs.

We know a good deal about environmental conditions in many places, and we have a fair understanding of the pressures many ecosystems face. But this information lacks the coherence and global coverage needed to provide a clear picture of the state of major ecosystems worldwide.

To help fill this information gap, this chapter presents the results of a first-of-its-kind assessment: the Pilot Analysis of Global Ecosystems (PAGE). The PAGE study assessed five of the world's major ecosystem types.

- ***Agricultural ecosystems*** or "agroecosystems" cover 28 percent of the land surface (excluding Antarctica and Greenland) and account for $1.3 trillion in output of food, feed, and fiber and for 99 percent of the calories humans consume.

- ***Coastal ecosystems*** (including marine fisheries) cover approximately 22 percent of the total land area in a 100-km band along continental and island coastlines, as well as the ocean area above the continental shelf. The coastal zone is home to roughly 2.2 billion people or 39 percent of the world's population and yields as much as 95 percent of the marine fish catch.

- ***Forest ecosystems*** cover 22 percent of the land surface (excluding Antarctica and Greenland) and contribute more than 2 percent of global GDP through the production and manufacture of industrial wood products alone.

- ***Freshwater systems*** cover less than 1 percent of Earth's surface but they are the source of water for drinking, domestic use, agriculture, and industry; freshwater fish and mollusks are also a major source of protein for humans and animals.

- ***Grassland ecosystems*** (including shrublands) cover 41 percent of the land surface (excluding Antarctica and Greenland) and are critical producers of protein and fiber from livestock, particularly in developing countries.

Together these five ecosystem types, which overlap in some places, cover the bulk of Earth's land area and a significant portion of the ocean area. They are also home to much of the world's population. Other ecosystems, such as polar zones, high mountains, ocean areas beyond the continental shelves, and even urban ecosystems account for the remainder of the area and are important in their own right (see the Appendix to this Chapter). But the condition of the goods and services produced by these five major ecosystems will largely determine how well Earth's living systems meet human needs today and in the future.

A Unique Approach

The PAGE study is unique in that it evaluated the state of five ecosystems by examining the condition of a range of goods and services these ecosystems produce:

- food and fiber production,
- provision of pure and sufficient water,
- maintenance of biodiversity,
- storage of atmospheric carbon, and
- provision of recreation and tourism opportunities.

This "goods and services approach" makes explicit the link between the biological capacity of ecosystems and human well-being.

Notably, the PAGE analysis considered not just the current level of production of goods and services, but also the *capacity* of the ecosystem to continue to produce these goods and services in the future. For example, in evaluating food production in the coastal and marine assessment, PAGE researchers looked not only at the current marine fish catch, but also at trends in the condition of the fish stocks that contribute to this catch. In this way, the PAGE study–to the extent possible–addressed the question of the sustainability of current patterns of ecosystem use (Box 2.1 The Difficulty of Assessing Ecosystems).

A Global Synthesis of Current Information

The first objective of PAGE was to review existing environmental assessments and compile available data into a globally comprehensive package. PAGE researchers synthesized information from dozens of sources:

- national, regional, and global data sets on food and fiber production;
- sectoral assessments of agriculture, forestry, biodiversity, water, and fisheries;
- national state-of-the-environment reports;
- national and global assessments of ecosystem extent and change;
- biological assessments of particular species or environments.
- scientific research articles; and
- various national and international data sets.

For each of the five ecosystem types, PAGE researchers first assembled the best information available on the extent of the

Box 2.1 The Difficulty of Assessing Ecosystems

It is enormously challenging to measure the overall condition or health of an ecosystem. The ecosystem "indicators" most readily available, and that have shaped our current understanding of ecosystems, are far from complete. Each provides only a partial description of the bigger picture, like the parable of the five blind men giving different descriptions of the same elephant because each can feel only a small part of the whole animal. These indicators include:

- *pressures* on ecosystems, including such factors as population growth, increased resource consumption, pollution, and overharvesting;

- *extent* of ecosystems—their physical size, shape, location, and distribution; and

- *production* or output of various economically important goods by the system, such as crops, timber, or fish.

Each of these indicators is important, but collectively they provide only a narrow view of ecosystem condition and how well ecosystems are being managed. Indicators of pressure, for example, reveal little about the actual health of the system. With proper management, an ecosystem can withstand significant pressures without losing productivity. Indeed, some agroecosystems have withstood the pressure of intensive cultivation for generations, but have sustained productivity with the help of organic fertilizers and crop rotation. And although growing populations may increase pressures on forests or fisheries, examples abound of community-based management systems that maintained the productivity of ecosystems even in the face of significant population growth.

Similarly, changes in ecosystem extent—such as loss of forests and expansion of agriculture—may indicate that the form of land use and the predominant vegetation have changed, but don't reveal how well the remaining forest or agroecosystem is functioning. And information about the production or output of various ecosystem goods and services doesn't provide a complete picture because production information is rarely available for nonmarketed commodities such as water filtration or storm protection; and the nonmarketed commodities are sometimes the most valuable services ecosystems provide.

Most important, none of these traditional indicators provides information about the underlying capacity of ecosystems to continue to supply their life-sustaining goods and services. The history of the world's fisheries illustrates this problem well. Routinely in fisheries around the world, overfished stocks have collapsed after several years or decades of bountiful harvests. The high production in the good years thus revealed nothing about the health of the fishery; it merely foreshadowed the exhaustion of the resource. Similarly, food production statistics don't reveal evidence of the degradation of agroecosystems that might result from excessive soil erosion or nutrient depletion, since some degradation can be offset by increased fertilization and new crop varieties. With time, though, the diminished capacity of the agricultural lands will increase production costs and may ultimately take land out of production.

Indicators of ecosystem capacity are not easy to obtain. Such indicators must probe the underlying biological state of the ecosystem, including physical factors such as soil fertility or water's dissolved oxygen content that lie at the base of the ecosystem's ability to function. For example, data about the size and structure of some marine fish stocks are available. When these basic population data are combined with knowledge of breeding cycles, the availability of basic nutrients, and large-scale ocean trends like El Niño, the result can lead to an estimate of the maximum sustainable yield for the monitored fish stocks—in other words, the maximum amount of fish that can be harvested without risking depletion of the resource. If calculated carefully, this represents a true measure of the ecosystem's capacity to sustainably produce fish.

Unfortunately, the basic biological data needed to judge ecosystem capacity are often available only for limited areas or species. Even when these data are available, the complex interactions between the elements of the ecosystem and how they affect ecosystem capacity are often unclear. Capacity indicators thus represent the frontier of ecosystem assessment and one of its most problematic aspects.

ecosystem and any modifications to the ecosystem, such as conversion to agriculture or urban areas. PAGE researchers asked:

- Where is the ecosystem located?
- What are its dominant physical characteristics?
- How has it changed through time?
- What pressures and changes is it experiencing today?

They then concentrated on assembling the best indicators of production and condition of the various goods and services produced by each ecosystem:

- What is the quantity of the service being produced (and its value, where possible)?
- Is the capacity of the ecosystem to provide that service being enhanced or diminished through time?

An International Collaboration

Many organizations collaborated to produce the PAGE study:

- Centro Internacional de Agricultura Tropical (CIAT)
- Global Runoff Data Centre, Germany
- International Fertilizer Development Center (IFDC)
- International Food Policy Research Institute (IFPRI) (agroecosystem coordinator)
- International Institute for Applied Systems Analysis (IIASA)
- International Potato Center (CIP)
- International Soil Reference and Information Centre (ISRIC)
- Food and Agriculture Organization of the United Nations (FAO)
- MRJ Technologies, USA
- Ocean Voice International
- UN Environment Programme
- UN Development Programme
- US Geological Survey, EROS Data Center
- University of Maryland, USA
- University of New Hampshire, USA
- University of Umeå Sweden
- World Bank
- World Conservation Monitoring Centre (WCMC)
- World Resources Institute (PAGE coordinator)

Essentially, for each good and service, the PAGE study asked: *Why is it important?* and *What shape is it in?* To the extent possible, researchers also included information about the plausible future condition of the ecosystem.

The results of the PAGE study were subjected to a thorough peer review by more than 70 scientific experts around the world.

The "Big Picture," but with Limitations

The goal of PAGE was not only to provide "state of the art" information about the condition of global ecosystems, but also to help identify gaps in data and information. In addition, PAGE was designed to demonstrate, on a global level, the utility of an *integrated assessment approach*–one that simultaneously assesses the full range of both goods and services an ecosystem produces rather than focusing on just one or two, such as timber production or biodiversity.

The PAGE findings provide a "big picture" view of ecosystem condition and change at a global or continental scale and indicate how these ecosystem characteristics are linked to development prospects. PAGE did not attempt to produce the more detailed site-specific data and information needed at a national scale by resource managers. Nor did it examine specific trade-offs among various goods and services (except for a few illustrative cases), since that type of analysis is most meaningful at smaller scales, such as a nation or river basin, where these choices are actually made.

Although the PAGE study strove to be as integrated as possible in its approach, it is not, strictly speaking, an "integrated assessment." A truly *integrated* ecosystem assessment would focus not on categories such as "forests" and "grasslands," as PAGE has done, but instead on spatially contiguous regions, such as an entire nation, or even a river basin. The Amazon River Basin ecosystem, for example, includes agroecosystems, coastal areas, grasslands, forests, and freshwater habitats. An integrated assessment of the Amazon would examine the array of goods and services produced from this mosaic of land uses and land cover and the trade-offs among them, rather than examine each in isolation (see Box 4.3 The Need for Integrated Ecosystem Assessments).

Nonetheless, at a global scale, the broad ecosystem categories used by PAGE provide a useful way to present information. Moreover, these categories are useful to some of the environmental institutions charged with the conservation and sustainable use of ecosystems. For example, these are the categories used by the Convention on Biological Diversity, the treaty signed by the international community in 1992.

PAGE FINDINGS: The Ecosystem Scorecard

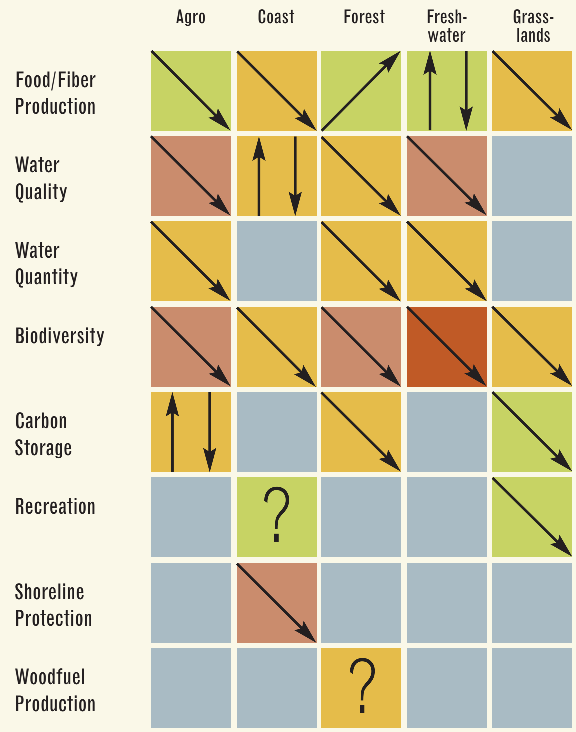
In spite of the narrowness of current ecosystem indicators, we must use them in judicious combination to assemble a picture of ecosystem status. Thus, the PAGE study has negotiated carefully through the various indicators available on ecosystem pressures, production, underlying biological condition, and physical extent to arrive at its findings.

For summary purposes, PAGE researchers chose to represent their findings as two separate "scores" for each of an ecosystem's primary goods or services (see the Ecosystem Scorecard). The *Condition* score (indicated by color) reflects how the ecosystem's ability to yield goods and services has changed over time by comparing the current output and quality of these goods and services with output and quality 20–30 years ago. It is drawn from indicators of production such as crop harvest data, wood production, water use, and tourism, as well as data on biological conditions, such as species declines, biological invasions, or the amount of carbon stored in the vegetation and soils of a given area.

The *Changing Capacity* score reflects the trend in an ecosystem's biological capacity—its ability to continue to provide a good or service in the future. It integrates information on ecosystem pressures with trends in underlying biological factors such as soil fertility, soil erosion and salinization, condition of fish stocks and breeding grounds, nutrient loading and eutrophication of water bodies, fragmentation of forests and grasslands, and disruption of local and regional water cycles.

In all cases, the ecosystem scores represent expert judgments that integrate a number of different variables, and accommodate gaps in the data sets. Although far from perfect, the Condition and Changing Capacity scores, when taken together, offer a reasonable picture of how ecosystems are serving us today, and their trend for the future, given current pressures.

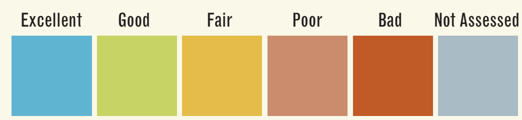
Scorecard



Key

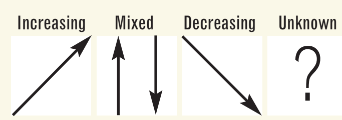
Condition assesses the current output and quality of the ecosystem good or service compared with output and quality of 20–30 years ago.

Condition



Changing Capacity assesses the underlying biological ability of the ecosystem to continue to provide the good or service.

Changing Capacity



Scores are expert judgments about each ecosystem good or service over time, without regard to changes in other ecosystems. Scores estimate the predominant global condition or capacity by balancing the relative strength and reliability of the various indicators. When regional findings diverge, in the absence of global data, weight is given to better-quality data, larger geographic coverage, and longer time series. Pronounced differences in global trends are scored as "mixed" if a net value cannot be determined. Serious inadequacy of current data is scored as "unknown."

PAGE Findings: What Shape Are the World's Ecosystems In?

The results of the PAGE study confirm that humans have dramatically altered the capacity of ecosystems to deliver goods and services, with the most significant changes taking place over the past century. For some goods and services, such as food production, we have greatly increased the capacity of ecosystems to provide what we need, while for others, such as water purification and biodiversity conservation, we have greatly degraded their capacity. The balance sheet of the positive and negative impacts of our management of ecosystems is shown in the Ecosystem Scorecard and summarized below.

FOOD PRODUCTION

People have dramatically increased food production from the world's ecosystems, in part by converting large areas to highly managed agroecosystems–croplands, pastures, feedlots–that provide the bulk of the human food supply. The condition of agroecosystems from the standpoint of food production is mixed. Although crop yields are still rising, the underlying condition of agroecosystems is declining in much of the world. Soil degradation is a concern on as much as 65 percent of agricultural land. Historically, inputs of water, fertilizers, and technologies such as new seed varieties and pesticides have been able to more than offset declining ecosystem conditions worldwide (although with significant local and regional exceptions), and they may continue to do so for the foreseeable future. But how long can that kind of compensation continue? The diminishing capacities of agroecosystems will make that task ever more challenging.

The outlook for fish production–also a major source of food–is more problematic. The condition of coastal ecosystems from the standpoint of food production is only fair and becoming worse. Twenty-eight percent of the world's most important marine fish stocks are depleted, overharvested, or just beginning to recover from overharvesting. Another 47 percent are being fished at their biological limit and are, therefore, vulnerable to depletion. Freshwater fisheries present a mixed picture; we are currently overexploiting most native fish stocks, but introduced species have begun to enhance the harvest in some water bodies, and production from aquaculture ponds is growing steadily. Overall, the pattern of increasing dependence on aquaculture and the decline of natural fish stocks will have serious consequences for many of the world's poor who depend on subsistence fishing.

WATER QUANTITY

Dams, diversions, irrigation pumps, and other engineering works have profoundly altered the amount and location of water available for both human uses and for sustaining aquatic ecosystems. People now withdraw annually about half of the water readily available for use from rivers. Dams and engineering works have strongly or moderately fragmented 60 percent of the world's large river systems; they have so impeded flows, that the length of time it takes the average drop of river water to reach the sea has tripled. The changes we have made to forest cover and other ecosystems such as wetlands also have altered water availability and affected the timing and intensity of floods. For example, tropical montane forests, which play key roles in regulating water quantity in the tropics, are being lost more rapidly than any other tropical forest type. Freshwater wetlands, which store water and moderate flood flows, have been reduced by as much as 50 percent worldwide.

WATER QUALITY

Water quality is degraded directly through chemical and nutrient pollution and indirectly when the capacity of ecosystems to filter water is degraded and when land-use changes increase soil erosion. Nutrient pollution from fertilizer-laden runoff is a serious problem in agricultural regions around the world; it has resulted in eutrophication and human health hazards in coastal regions, particularly in the Mediterranean, Black Sea, and northwestern Gulf of Mexico. The frequency of harmful algal blooms, linked to nutrient pollution, has increased significantly in the past 2 decades. We have greatly exceeded the capacity of many freshwater and coastal ecosystems to maintain healthy water quality. And although developed countries have improved water quality to some extent in the past 20 years, water quality in developing countries–particularly near urban and industrial areas–has been degraded substantially. Decreasing water quality poses a particular threat to the poor who often lack ready access to potable water and are most subject to the diseases associated with polluted water.

CARBON STORAGE

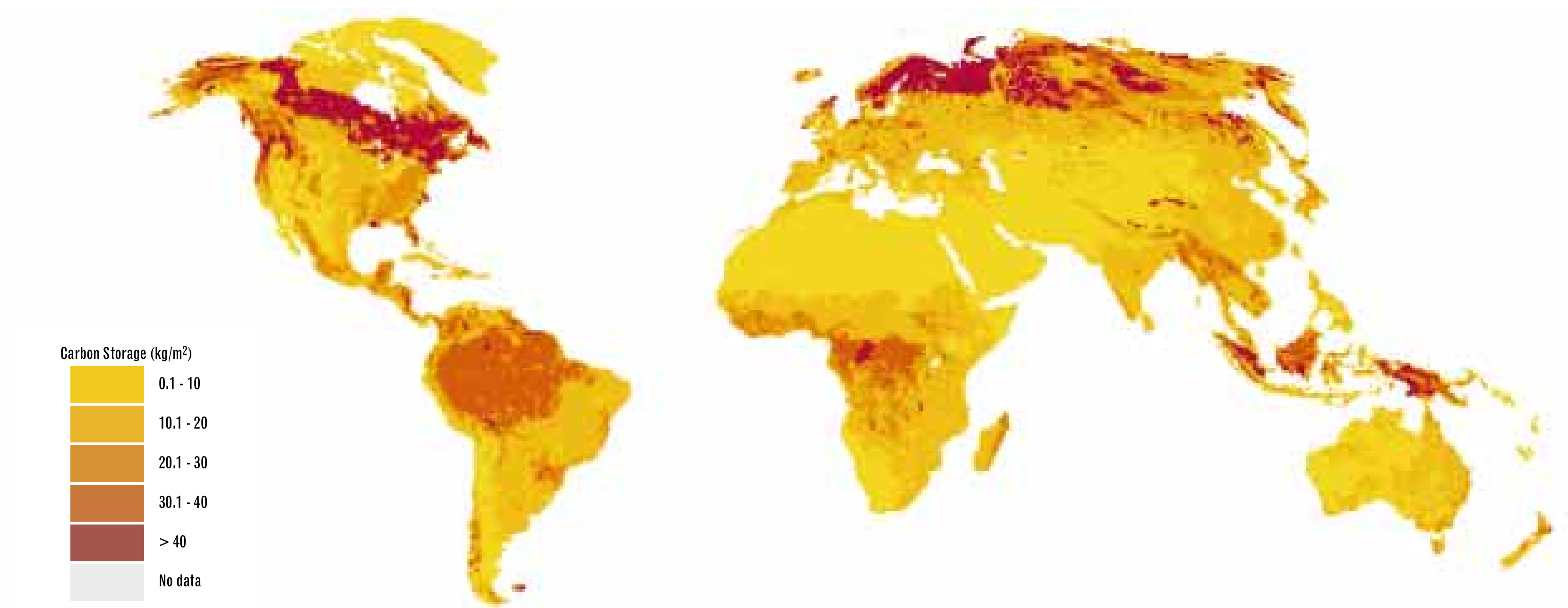
The plants and soil organisms in ecosystems remove carbon dioxide (CO_2)–the most important greenhouse gas–from the atmosphere and store it in their tissues. This carbon storage process helps to slow the buildup of CO_2 in the atmosphere. Unfortunately, the steps we have taken to increase production of food and other commodities from ecosystems have had a net negative impact on their capacity to store carbon. This is principally the result of converting forests to agroecosystems; agroecosystems support less vegetation overall and therefore store less carbon. Such land-use changes are in fact an important source of carbon emissions, contributing approximately 20 percent of global annual carbon emissions.

Ecosystems nonetheless still store significant carbon (Box 2.2 Terrestrial Storage of Carbon). Of the carbon currently stored in terrestrial systems, 38–39 percent is stored in forests and 33 percent in grasslands. Agroecosystems, which overlap grasslands and forests somewhat, store 26–28 percent. How we manage these ecosystems–whether we promote afforestation and other carbon-storing strategies or increase the forest

Box 2.2 Terrestrial Storage of Carbon

Carbon stored in terrestrial ecosystems plays a large role in the global carbon cycle. To map the distribution of terrestrial carbon storage, PAGE researchers combined recent satellite maps of Earth's vegetation with estimates of how much carbon various types of vegetation and soil store. As the map shows, the highest quantities of stored terrestrial carbon are located in the tropics and in the boreal region. In the tropics, a larger portion of the carbon is found in the vegetation, while in boreal regions, especially peatlands, most carbon is stored in the soils. Boreal peatlands are especially important carbon storage areas. Unforested lands generally store less carbon than forested ecosystems.

Global Terrestrial Storage of Carbon



Sources: Matthews et al. [PAGE] 2000. The map is a combination of two maps: a map of carbon stored in above- and below-ground live vegetation based on USGS/EDC (1999b) and a map of carbon stored in soils based on Batjes (1996) and Batjes and Bridges (1994).

Box 2.3 Are We Altering Earth's Basic Chemical Cycles?

Tracking the changes in Earth's chemical cycles—carbon, nitrogen, and water cycles—is essential to understanding the condition of ecosystems. These cycles serve as the basic metabolism of the biosphere, affecting how every ecosystem functions and linking them all on a global level. Human-induced changes in these global processes can alter climate patterns and affect the availability of basic nutrients and water that sustain plant and animal life.

The Carbon Cycle

Carbon dioxide (CO_2) concentrations in the atmosphere rose 30 percent from 1850 to 1998, from 285 parts per million to 366 parts per million (IPCC 2000:4) (see Box 1.6 Carbon Storage, p. 15). This rise in atmospheric CO_2 levels is largely the result of increased CO_2 emissions from burning fossil fuels. However, changes in use and management of ecosystems have also played a major role by releasing carbon that had been stored in vegetation and soil. About 33 percent of the carbon that has accumulated in the atmosphere over the past 150 years has come from deforestation and changes in land use (IPCC 2000:4).

Climate models tell us that rising carbon concentrations in the atmosphere will alter Earth's climate, affecting precipitation, land and sea temperatures, sea level, and storm patterns. The extent and structure of ecosystems will change as they transform in response to these basic physical parameters. Changing climate will also affect the rate of greenhouse gas emissions from some ecosystems. For example, models suggest that a warmer climate in the Arctic will elevate the rate of decomposition of the vast peat reserves in tundra and taiga ecosystems, increasing the release of CO_2 into the atmosphere.

Elevated atmospheric CO_2 can, in turn, have more direct impacts on ecosystems. Because plants depend on CO_2 for growth, elevated CO_2 concentrations will have a "fertilizer effect," increasing the growth rate of some plants and changing some of the chemical and physical characteristics of their cells. Some species will benefit more than others, and this in turn will alter the composition of biological communities.

Climate change could also have a profound impact on growing patterns and yields in agriculture. PAGE researchers estimated that a warmer climate could raise cereal production by 5 percent in mid- to high-latitude regions (mostly developed countries) but might decrease cereal yields in low-latitude regions by 10 percent (particularly in African developing countries).

The Nitrogen Cycle

Although we are more familiar with the influence humans have had on the carbon cycle, human influence on the global nitrogen cycle is more profound and already more biologically significant. In most natural systems, lack of nitrogen is an important limiting factor for plant growth, which is what accounts for significant increases in crop yields in response to nitrogen fertilizers. However, as explained in Chapter 1, the production and use of fertilizers, burning of fossil fuels, and land clearing and deforestation also increase—far beyond natural levels—the amount of nitrogen available to biological systems (Vitousek et al. 1997:5). This added nitrogen has caused serious problems, particularly in freshwater and coastal ecosystems where excess nitrogen stimulates growth of algae, sometimes depleting available oxygen to the point where other aquatic organisms suffocate, a process known as eutrophication.

The Freshwater Cycle

The scale of human impact on freshwater cycles is also massive. Humans currently appropriate more than half of accessible freshwater runoff, and by 2025, demand is projected to increase to more than 70 percent of runoff (Postel et al. 1996:7, 787). A substantial amount—70 percent—of the water currently withdrawn from all freshwater sources is used for agriculture (WMO 1997:9). By shifting water from freshwater systems to agroecosystems, crop production increases, but at significant cost to downstream ecosystems and downstream users. Some of the water diverted from rivers or directly consumed does return to rivers but, typically, carrying with it pollution in the form of agricultural nutrients or chemicals, or human or industrial waste. But as much as 60 percent of water withdrawn from rivers is lost to downstream uses (Postel 1993:56; Seckler 1998:4).

Global Cycles, Global Impacts

The importance of these global cycles to the functioning of ecosystems cannot be overstated. There is no question that sound management of Earth's ecosystems will require changes in the use of resources at a local level; but it is not enough to only examine and assess the condition of ecosystems at the local level. Some of the most important features of Earth's ecosystems—with the most profound influence on the future role of ecosystems in meeting human needs—can only be fully understood on regional and even global levels. Thus, it is vital that we examine and assess the condition of ecosystems at those levels.

conversion rate—will have a significant impact on future increases or decreases in atmospheric carbon dioxide.

BIODIVERSITY

The erosion of global biodiversity over the past century is alarming. Major losses have occurred in virtually all types of ecosystems, much of it simply by loss of habitat area. Forest cover has been reduced by at least 20 percent and perhaps by as much as 50 percent worldwide; some forest ecosystems, such as the dry tropical forests of Central America, are virtually gone. More than 50 percent of the original mangrove area in many countries is gone; wetlands area has shrunk by about half; and grasslands have been reduced by more than 90 percent in some areas. Only tundra, arctic, and deep-sea ecosystems have emerged relatively unscathed.

Even if ecosystems had retained their original spatial extent, many species would still be threatened by pollution, overexploitation, competition from invasive species, and habitat degradation. In terms of the health of species diversity, freshwater ecosystems are far and away the most degraded, with 20 percent of freshwater fish species extinct, threatened, or endangered in recent decades. Forest, grassland, and coastal ecosystems all face major problems as well. The rapid rise in the incidence of diseases affecting marine organisms, the increased prevalence of algal blooms, and the significant decreases in amphibian populations all attest to the severity of the threat to global biodiversity.

Apart from the loss of medicines, useful genetic materials, and ecotourism revenues this erosion of biodiversity represents, it also threatens the basis of ecosystem productivity. The diversity of species undergirds the ability of an ecosystem to provide most of its other goods and services. Reducing the biological diversity of an ecosystem may well diminish its resilience to disturbance, increase its susceptibility to disease outbreaks, and thus threaten its stability and integrity.

RECREATION AND TOURISM

The capacity of ecosystems to provide recreational and tourism opportunities was assessed only for coastal and grassland ecosystems. It is likely that the demand for these services will grow significantly in coming years, but the condition of the service is declining in many areas because of the overall degradation of biodiversity as well as the direct impacts of urbanization, industrialization, and tourism itself on the ecosystems being visited.

The Bottom Line

Overall, there are numerous signs that the capacity of ecosystems to continue to produce many of the goods and services we depend on is decreasing. In all five ecosystem types PAGE analyzed, ecosystem capacity is decreasing over a range of goods and services, not just one or two. PAGE results confirm that major modifications of ecosystems—through deforestation, conversion, nutrient pollution, dams, biological invasions, and regional-scale air pollution—continue to grow in scale and pervasiveness. Furthermore, human activities are significantly altering the basic chemical cycles that all ecosystems depend on (Box 2.3 Are We Altering Earth's Basic Chemical Cycles?). This strikes at the foundation of ecosystem functioning and adds to the fundamental stresses that ecosystems face at a global scale.

This downward trend in global ecosystem capacity is not impeding high production levels of some goods and services today. Food and fiber production have never been higher, and dams have allowed unprecedented control of water supplies. But this wealth of production is, in many instances, the product of intensive management that threatens to reduce the productivity of ecosystems in the longer term. Our use of technology—whether it is artificial fertilizer, more efficient fishing gear, or water-saving drip-irrigation systems—has also helped mask some of the decrease in biological capacity and has kept production levels of food and fiber high. However, services like maintaining biodiversity and high water quality and carbon storage show reductions in output that technology cannot so easily mask. In sum, the PAGE findings starkly illustrate the trade-offs we have made between high commodity production and impaired ecosystem services, and indicate the dangers these trade-offs pose to the long-term productivity of ecosystems.

The remaining sections of this chapter present an ecosystem-by-ecosystem discussion of the conclusions of the PAGE study.

The Pilot Analysis of Global Ecosystems

Technical Reports Available in Print and On-Line at http://www.wri.org/wr2000

Agroecosystems
Stanley Wood, Kate Sebastian, and Sara Scherr, *Pilot Analysis of Global Ecosystems: Agroecosystems*, *A joint study by International Food Policy Research Institute and World Resources Institute*, International Food Policy Research Institute and World Resources Institute, Washington, D.C.
December 2000 / 100 pages / paperback / ISBN 1-56973-457-7 / US$20.00

Coastal Ecosystems
Lauretta Burke, Yumiko Kura, Ken Kassem, Mark Spalding, and Carmen Revenga, *Pilot Analysis of Global Ecosystems: Coastal Ecosystems,* World Resources Institute, Washington, D.C.
December 2000 / 100 pages / paperback / ISBN 1-56973-458-5 / US$20.00

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AGROECOSYSTEMS

Agroecosystems provide the overwhelming majority of crops, livestock feed, and livestock on which human nutrition depends. In 1997, global agriculture provided 95 percent of all animal and plant protein and 99 percent of the calories humans consumed (FAO 2000). Agroecosystems also contribute a large percentage of the fiber we use–cotton, flax, hemp, jute, and other fiber crops.

Globally, agroecosystems have been remarkably successful, when judged by their ability to keep pace with food, feed, and fiber demands (Box 2.4 Taking Stock of Agroecosystems). Per capita food production is higher today than 30 years ago, even though the global population doubled since then. However, agriculture faces an enormous challenge to meet the food needs of an additional 1.7 billion people–the projected population increase–over the next 20 years.

Historically, agricultural output has increased mainly by bringing more land into production. But the amount of land remaining that is both well suited for crop production (especially for annual grain crops) and not already being farmed is limited. A further limitation is the growing competition from other forms of land use such as industrial, commercial, or residential development. Indeed, in densely populated parts of India, China, Indonesia, Egypt, and Western Europe, limits to expansion were reached many years ago. Approximately 2.8 billion people live in or near agroecosystems (not including adjacent urban areas) (Wood et al. [PAGE] 2000).

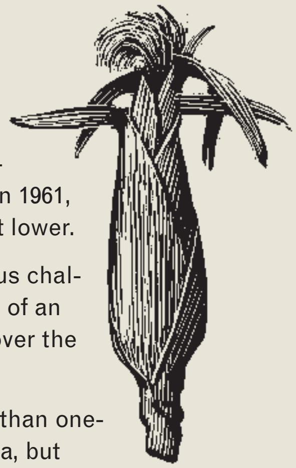
Intensifying production–obtaining more output from a given area of agricultural land–has thus become essential. In some regions, particularly in Asia, farmers have successfully intensified production by raising multiple crops each year, irrigating fields, and using new crop varieties with shorter growth cycles. On high-quality, nonirrigated lands, farmers have intensified production mainly by abandoning or shortening fallow periods and moving to continuous cultivation, with the help of modern technologies. Agricultural intensification is widespread even on lower-quality lands, particularly in developing nations. Intensification has also been significant around major cities (and to an unexpected extent, within cities), principally to produce high-value perishables such as dairy products and vegetables for urban markets, but also to meet subsistence needs.

The unprecedented scale of agricultural expansion and intensification has raised concerns about the state of agroecosystems. First, there is growing concern about their productive capacity–can agroecosystems withstand the stresses imposed by intensification? These stresses include increased erosion, soil nutrient depletion, salinization and waterlogging of soils, and reduction of genetic diversity among major crops. There is also concern about the negative impacts of agriculture on other ecosystems–impacts that are often accentuated by intensification. Examples include the harmful effects of increased soil erosion on downstream fisheries

(continues on p. 56)

Box 2.4 Taking Stock of Agroecosystems

Highlights

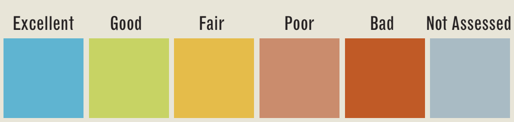


- Food production has more than kept pace with global population growth. On average, food supplies are 24 percent higher per person than in 1961, and real prices are 40 percent lower.
- Agriculture faces an enormous challenge to meet the food needs of an additional 1.7 billion people over the next 20 years.
- Agroecosystems cover more than one-quarter of the global land area, but almost three-quarters of the land has poor soil fertility and about one-half has steep terrain, constraining production.
- While the global expansion of agricultural area has been modest in recent decades, intensification has been rapid, as irrigated area increased, fallow time has decreased, and the use of purchased inputs and new technologies has grown and is producing more output per hectare.
- About two-thirds of agricultural land has been degraded in the past 50 years by erosion, salinization, compaction, nutrient depletion, biological degradation, or pollution. About 40 percent of agricultural land has been strongly or very strongly degraded.

Key

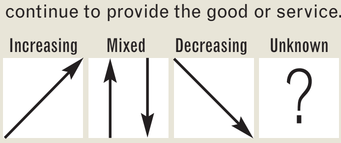
Condition assesses the current output and quality of the ecosystem good or service compared with output and quality of 20–30 years ago.

Condition



Changing Capacity assesses the underlying biological ability of the ecosystem to continue to provide the good or service.

Changing Capacity



Scores are expert judgments about each ecosystem good or service over time, without regard to changes in other ecosystems. Scores estimate the predominant global condition or capacity by balancing the relative strength and reliability of the various indicators. When regional findings diverge, in the absence of global data weight is given to better-quality data, larger geographic coverage, and longer time series. Pronounced differences in global trends are scored as "mixed" if a net value cannot be determined. Serious inadequacy of current data is scored as "unknown."

Conditions and Changing Capacity

FOOD PRODUCTION

Since 1970, livestock products have tripled and crop outputs have doubled, a sign of rising incomes and living standards. Food production, which was worth US$1.3 trillion in 1997, is likely to continue to increase significantly as demand increases. Nonetheless, soil degradation is widespread and severe enough to reduce productivity on about 16 percent of agricultural land, especially cropland in Africa and Central America and pastures in Africa. Although global inputs and new technologies may offset this decline in the foreseeable future, regional differences are likely to increase.

WATER QUALITY

Production intensification has limited the capacity of agroecosystems to provide clean freshwater, often significantly. Both irrigated and rainfed agriculture can threaten downstream water quality by leaching fertilizers, pesticides, and manure into groundwater or surface water. Irrigated agriculture also risks both soil and water degradation through waterlogging and salinization, which decreases productivity. Salinization is estimated to reduce farm income worldwide by US$11 billion each year.

WATER QUANTITY

Irrigation accounts for fully 70 percent of the water withdrawn from freshwater systems for human use. Only 30–60 percent is returned for downstream use, making irrigation the largest net user of freshwater globally. Although only 17 percent of agroecosystems now depend on irrigation, that share has grown; irrigated area increased 72 percent from 1966 to 1996. Competition with other kinds of water use, especially for drinking water and industrial use, will be stiffest in developing countries, where populations and industries are growing fastest.

BIODIVERSITY

Agricultural land, which supports far less biodiversity than natural forests, has expanded primarily at the expense of forest areas. As much as 30 percent of the potential area of temperate, subtropical, and tropical forests has been lost to agriculture through conversion. Intensification also diminishes biodiversity in agricultural areas by reducing the space allotted to hedgerows, copses, or wildlife corridors and by displacing traditional varieties of seeds with modern high-yield but uniform crops. Nonetheless, certain practices, including fallow periods and shade cropping, can encourage diversity as well as productivity.

CARBON STORAGE

In agricultural areas the amount of carbon stored in soils is nearly double that stored in the crops and pastures that the soils support. Still, the share of carbon stored in agroecosystems (about 26–28 percent of all carbon stored in terrestrial systems) is about equal to the share of land devoted to agroecosystems (28 percent of all land). Agricultural emissions of both carbon dioxide and methane are increasing because of conversion to agricultural uses from forests or woody savannas, deliberate burning of crop stubble and pastures to control pests or promote fertility, and paddy rice cultivation.

Data Quality

FOOD PRODUCTION

Value, yield, input, and production data are from the Food and Agriculture Organization (FAO) national tables, 1965-97. Consistency and reliability vary across countries and years. Ecosystem analysis requires more spatially disaggregated information. Fertility constraints are spatially modeled from the soil mapping units of FAO's Soil Map of the World. Global and regional assessments of human-induced soil degradation are based primarily on expert opinion. Developing reliable, cost-effective methods for monitoring soil degradation would help to both mitigate further losses and target restoration efforts.

WATER QUALITY

There are no globally consistent indicators of water quality that relate specifically to agriculture. In agricultural watersheds, the quantity of pesticides and nutrients—nitrogen and phosphorus—are good indicators of pollution from leaching and surface runoff. In mixed-use catchments it is much more difficult to separate from other sources such as human effluents and pesticides applied in gardens and public recreation areas. Pesticide data are more expensive to monitor. Data on suspended solids from soil erosion are also scarce and difficult to interpret.

WATER QUANTITY

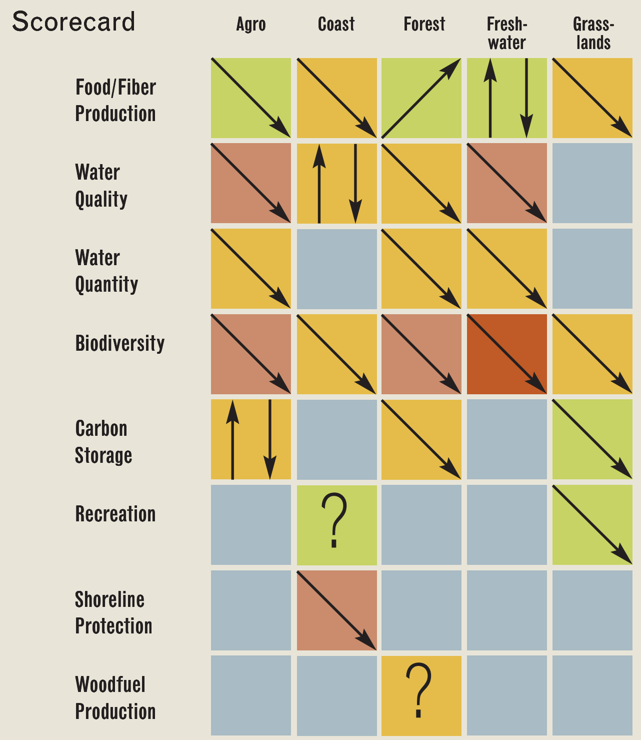
Irrigated area is assessed using the Kassel University global spatial data, which indicate the percentage and area of land equipped for irrigation but has some inconsistencies in scale, age, and reliability of source. Irrigation water use data are derived from country-specific tabular data sets on irrigated area, water availability and use, and water abstraction. Little crop-specific information is available on irrigated area and production. Global estimates of rainfall from the University of East Anglia are based on spatial extrapolations of monthly data from climate stations over a 30-year period. Even though the resolution of these data is coarse, it allows assessment of both spatial and temporal variability.

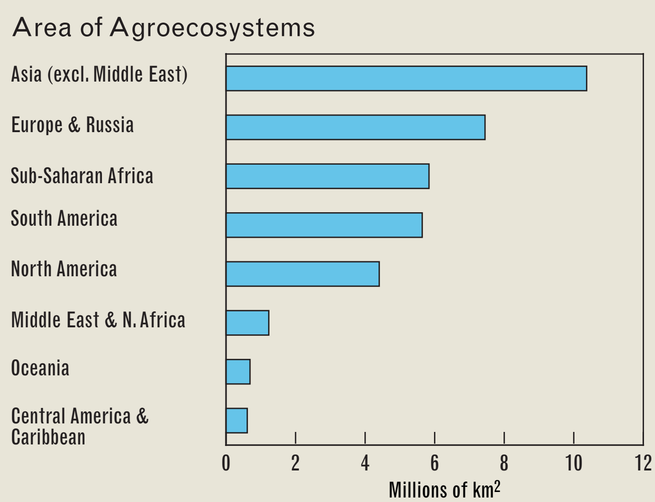
BIODIVERSITY

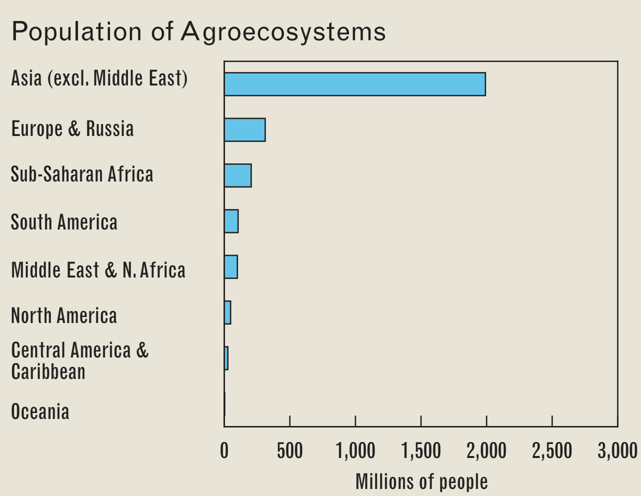
World Wildlife Fund for Nature (WWF) global spatial data describe potential natural habitats and ecoregions. These were developed from expert opinion and input maps of varying resolution and data, but the data do provide a general understanding of the spatial patterns of natural habitats. Genetic diversity data are compiled from major germplasm-holding institutions. Area adoption data for modern varieties of cereals are compiled from survey and agricultural census.

CARBON STORAGE

Storage capacity is modeled for vegetation and soils based on carbon storage capacity by land cover type at a resolution of half a degree for a single point in time. Data would be improved by better characterization of agricultural land-cover types and their vegetation content. Soil carbon data were derived for Latin America using FAO and the International Soil Reference and Information Centre's Soil and Terrain database.







and reservoirs and the damage to both aquatic ecosystems and human health from fertilizer and pesticide residues in water sources, in the air, and on crops. Agricultural practices also have even broader consequences for biodiversity and for alteration of the global carbon, nitrogen, and hydrological cycles (Thrupp 1998; Conway 1997).

Characterizing Agroecosystems

EXTENT AND GROWTH

Agriculture is one of the most common land uses on the planet and agroecosystems are quite extensive. Determining their exact extent depends on how they are defined.[1] The PAGE study, making use of satellite imagery, defined agricultural areas as those where at least 30 percent of the land is used for cropland or highly managed pasture (Box 2.5 The Global Extent of Agriculture). Using this definition, agroecosystems cover approximately 28 percent of total land area (excluding Greenland and Antarctica). This includes some overlap with forest and grassland ecosystems because land-use is often quite fragmented spatially, with agricultural plots forming part of a mosaic of uses–agriculture alongside forest or grassland areas. The Food and Agriculture Organization of the United Nations (FAO) reports an even greater percentage of land in agriculture–37 percent (FAO 2000). FAO's figures are derived from national production statistics rather than from satellite data and include all permanent pasture.

The actual area of agroecosystems probably falls somewhere between these estimates. Since the satellite data are based on only 1 year of data, areas that were not cultivated that year but are still used for agricultural purposes (for example, an area under fallow or regions that alternate year to year between cropland and pasture) may be underestimated in the satellite images. It is also more difficult to detect extensive pastures and some perennial crops using satellite data because of their similarity to natural grasslands and forests.

According to FAO, 69 percent of agroecosystems consist of permanent pasture, with the remainder of the area under crops. However, this global average masks very large differences among regions in the balance between crops and pastureland. In some regions, pastureland predominates: pastures make up 89 percent of the agroecosystem area in Oceania, 83 percent in Sub-Saharan Africa, 82 percent in South America, and 80 percent in East Asia. In other regions, croplands occupy much larger areas: 92 percent of agroecosystem area in South Asia and 84 percent in Southeast Asia. In India, crops cover 94 percent of the agroecosystem area. On croplands, annual crops such as wheat, rice, maize, and soybeans occupy 91 percent of the area, with the remainder in permanent crops, such as tea, coffee, sugarcane, and most fruits (FAO 2000).

Most agricultural production, with the exception of dairy and perishable vegetable production, is derived from intensively managed croplands located away from major concentrations of population. However, since the 1980s, the growth of urban and periurban agriculture has accelerated, especially in developing countries. By the early 1990s, approximately 800 million people globally were actively engaged in urban agriculture, using a variety of urban spaces including homesites, parks, rights-of-way, rooftops, containers, and unbuilt land around factories, ports, airports, and hospitals (FAO 1999a). Urban residents, who would otherwise spend a high proportion of income on food, engage in agriculture to increase their own food security and nutrition or as an income source. An estimated 200 million urban dwellers produce food for sale (Cheema et al. 1996).

FAO statistics show that the total area in agriculture expanded slowly between 1966 and 1996, from 4.55 Bha to 4.92 Bha–about an 8 percent increase (FAO 2000). This low growth rate masks a more dynamic pattern of land-use changes, with land conversion to and from agriculture taking place at much higher rates. It is these aggregate changes, for which data are scarce, that are most relevant from an ecosystem perspective.

Despite global growth, agricultural area has actually decreased in many industrialized countries. Both the United States and Western Europe have progressively been taking land out of agriculture for the last 30 years, and Oceania for the last 20. During this period, these three regions have removed a total of 49 Mha from agricultural production. Agricultural land has also decreased significantly in Eastern Europe, largely because of liberalization of production and marketing and poor economic conditions. South Asia's total agricultural area has remained constant for more than 20 years at approximately 223 Mha. However, expansion of agricultural area is still significant in some regions. Agricultural land increased by almost 0.8 percent/year during 1986–96 in China and Brazil and by 1.38 percent/year in West Asia (FAO 2000).

INTENSIFICATION

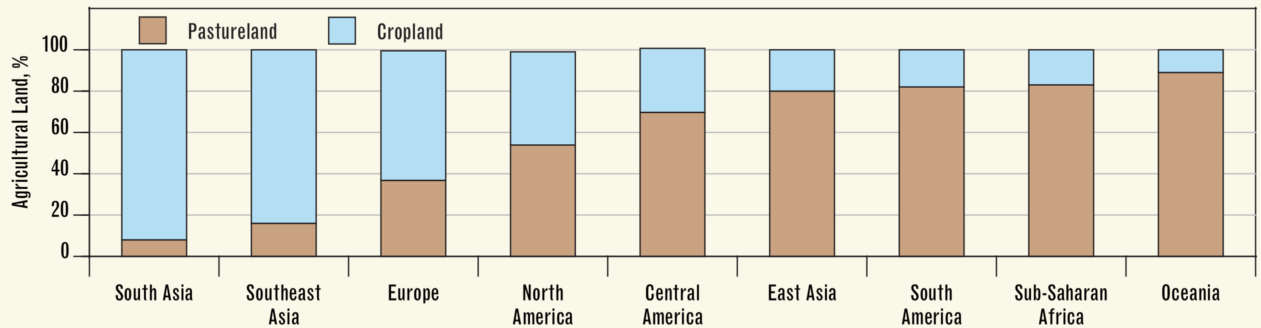
Although the net global expansion of agricultural area has been modest in recent decades, intensification has been rapid. Irrigated area grew significantly over the past 3 decades, from 153 Mha in 1966 to 271 Mha in 1998. Globally, irrigated land accounts for only 5.5 percent of all agricultural land–17.5 percent of cropland–but in some regions irrigation is much more extensive. For example, China and India together contain 41 percent of the global irrigated area and Western Europe and the United States contain another 12.5 percent. In contrast, the arid and semiarid regions of Sub-Saharan Africa and Oceania (primarily Australia), contain only 3 percent of the world's irrigated land (FAO 2000) (Box 2.6 Intensification of Agriculture).

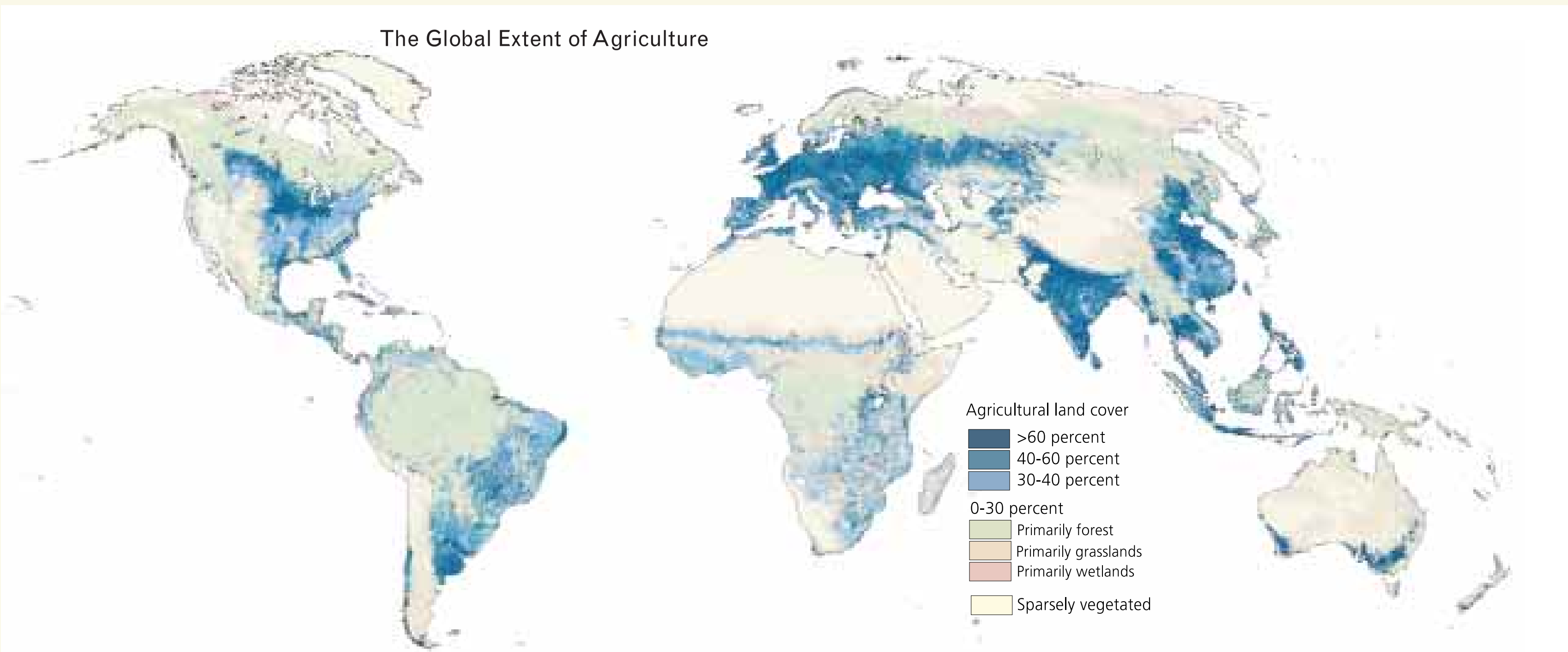
(continues on p. 60)

Box 2.5 The Global Extent of Agriculture

Agricultural lands cover about 36 Mha, 28 percent, of Earth's land area (excluding Greenland and Antarctica). Although agricultural area has increased worldwide in the past 30 years, it has decreased in many industrialized countries. Globally, about 31 percent of agroecosystems are croplands and 69 percent are pasture, but actual proportions of each vary widely among regions.

Composition of Agricultural Land



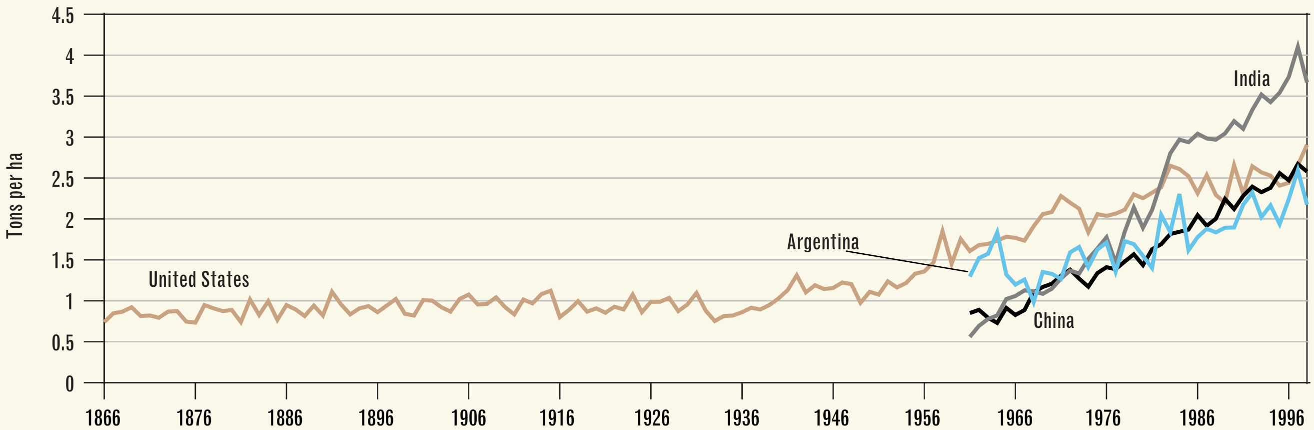


Sources: Wood et al. [PAGE] 2000. The map is based on Global Land Cover Characteristics Database Version 1.2 (Loveland et al. [2000]) and USGS/EDC (1999a). The figure is based on FAOSTAT (1999).

Box 2.6 The Intensification of Agriculture

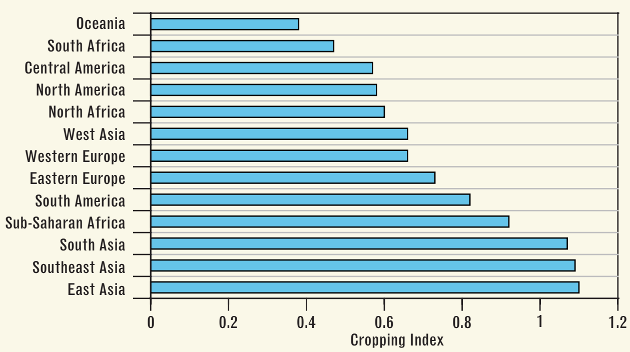
As population has grown and good agricultural land has become scarcer, inputs such as water, fertilizer, pesticides, and labor have been applied more intensively to increase output. In Asia, where population pressures are greatest, virtually all of the cropland is harvested each year, sometimes two to three times a season, as the use of irrigation, new varieties of quick-growing seeds, and fertilizers has replaced traditional practices of leaving land fallow to restore

Wheat Yields, 1866–1997

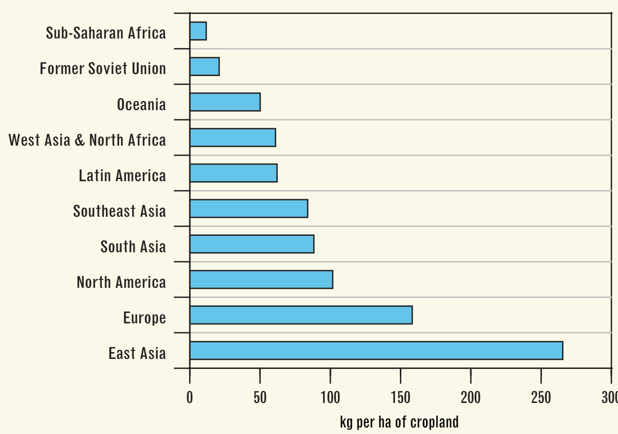


Intensification of Cropping, 1995–97

The cropping index is the harvested area of land planted in annual crops divided by the total area of such land. A value of more than 1 indicates more than one crop harvested per year per hectare.

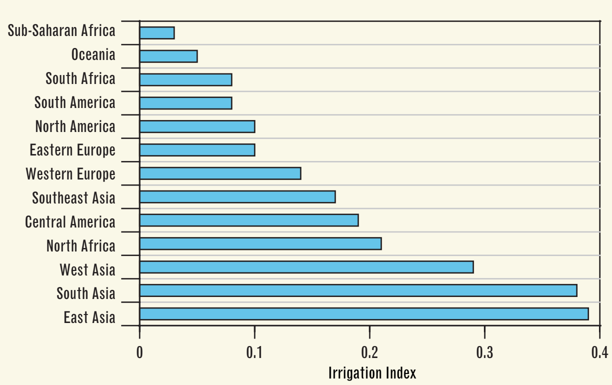


Use of Commercial Fertilizer, 1995–97

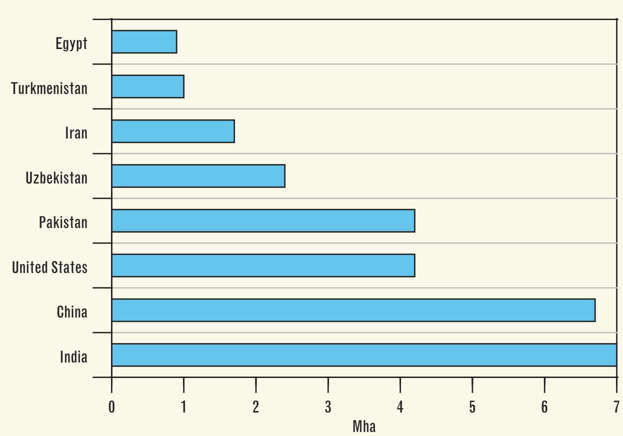


Intensification of Irrigation, 1995–97

The irrigation index is the irrigated area of cropland divided by the total area of cropland.



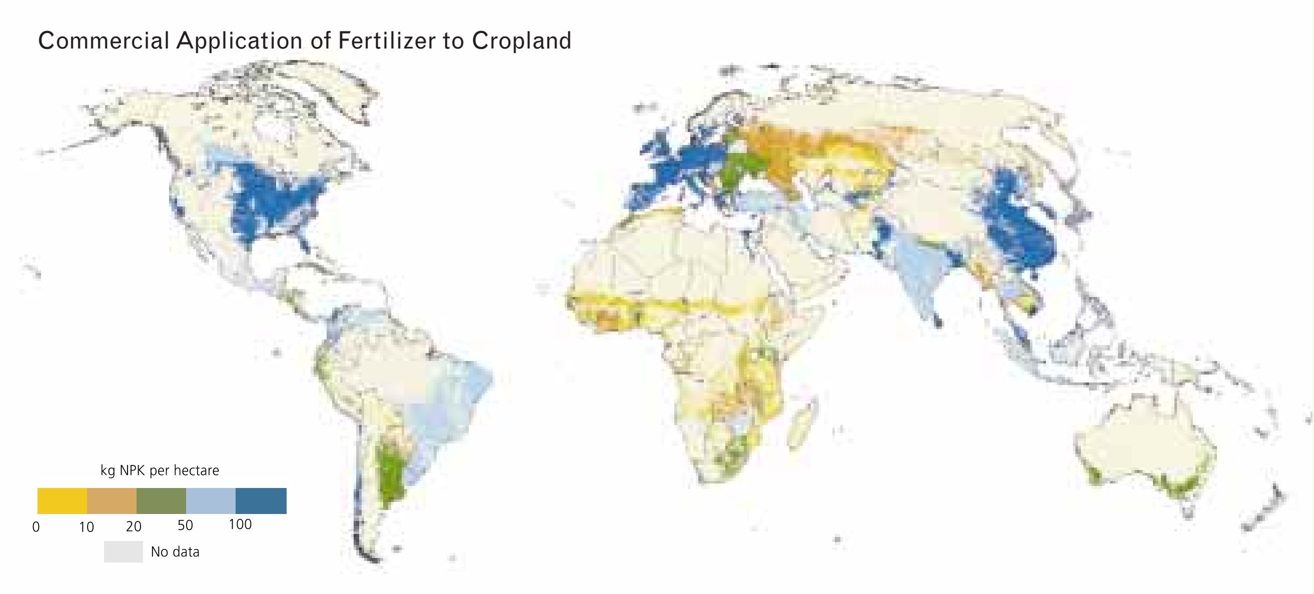
Irrigated Land Damaged by Salt, 1987

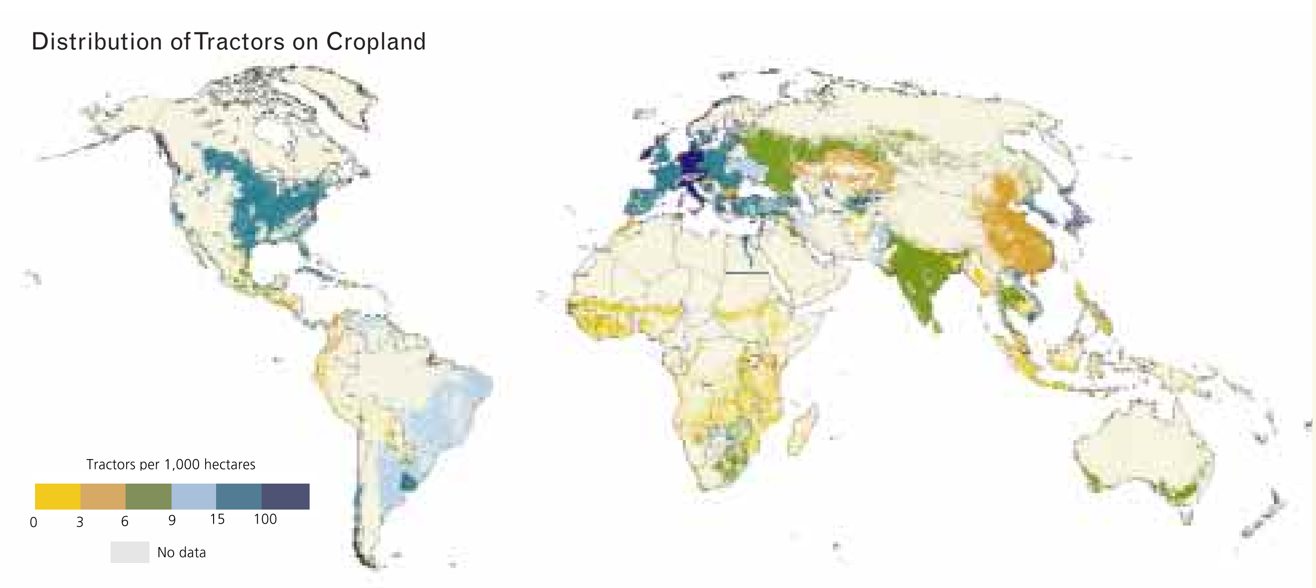


fertility. Even marginal lands in Africa are in continuous use to meet demands for food, although water and fertilizer inputs are much lower there.

Many agroecosystems are vulnerable to the stresses imposed on them by intensification. There is much local evidence of soil salinization caused by poorly managed irrigation systems, loss in soil fertility through overcultivation, compaction by tractors or livestock, and lowering of water tables through overpumping for irrigation.

Continued agricultural intensification need not lead inexorably to environmental degradation, however. Farming communities in all parts of the world have responded to degradation, particularly when it affects their livelihoods, with measures such as planting trees to control erosion, regulating cultivation around local water sources, restricting pesticides and other pollutants, rehabilitating degraded soils, and adopting new technologies. (See Chapter 3, Regaining the High Ground: Reviving the Hillsides of Machakos, Kenya.)





Sources: Wood et al. [PAGE] 2000. The maps are based on FAOSTAT 1999. They show national values within the global extent of agriculture, augmented by additional irrigated areas (Döll and Siebert 1999). Wheat yields are from USDA-NASS (1999). Irrigated land damaged by salt is based on Postel (1999:93). All other figures are based on FAOSTAT (1999).

Production intensity is also reflected in the use of inputs such as tractors and fertilizers. The current global consumption of fertilizer totals about 137 million tons/year (1997), representing a dramatic increase in consumption during the last 50 years (FAO 2000).

In recent years, irrigation growth rates have slowed considerably and growth in fertilizer consumption has moderated. Following a decline from the late 1980s to the mid-1990s, total fertilizer consumption is again increasing and is currently around 6 percent below its 1988 peak (FAO 2000).

SOIL AND SLOPE CONSTRAINTS

Despite the high productivity of global agriculture and the rapid intensification of production on some lands, many of the world's agricultural lands offer less than optimal conditions. Steep slopes (more than 8 percent incline) or poor soil conditions limit production on a significant portion of agricultural land. Soil fertility constraints include high acidity, low potassium reserves, high sodium concentrations, low moisture-holding capacity, or limited depth. If more than 70 percent of agricultural land in a particular region has one or more of these constraints, it is said to have "significant" soil constraints.

Using these definitions, 81 percent of agricultural land has significant soil constraints and around 45 percent of agricultural land is steep. Approximately 36 percent of agricultural land is characterized by both significant soil constraints and slopes of 8 percent or more. Areas with both steep slopes and significant soil constraints make up 30 percent of temperate, 45 percent of subtropical, and 39 percent of tropical agricultural land. Average agricultural yields are generally lower and degradation risks are generally higher in these areas than in more ecologically favored environments. Nonetheless, these marginal lands represent a significant share of global agriculture and support roughly one-third of the world's population (Wood et al. [PAGE] 2000).

Assessing Goods and Services

FOOD, FEED, AND FIBER

Economic Importance

The food, fiber, and animal feed that the world's agroecosystems produce is worth approximately $1.3 trillion per year[2] (Wood et al. [PAGE] 2000). Agriculture is most important to the economies of low-income countries, accounting for 31 percent of their GDP, and more than 50 percent of GDP in many parts of Sub-Saharan Africa. In middle-income countries, agriculture accounts for 12 percent of GDP. But in the high-income countries of Western Europe and North America, where other economic sectors dominate, the contribution of agriculture to GDP is just 1–3 percent, even though the value of the agricultural output in these countries represents 79 percent of the total market value of world agricultural products (Box 2.7 The Economic Value of Agricultural Production).

Conventional measures of agriculture's share of GDP actually understate agriculture's contribution to economies. For example, agricultural GDPs in the Philippines, Argentina, and the United States comprise 21 percent, 11 percent, and 1 percent of those countries' total GDPs, respectively; yet the total value of agriculture, including manufacturing and services further along the marketing chain, comprises 71 percent, 39 percent, and 14 percent of their respective total GDPs (Bathrick 1998:10).

Beyond the economic value of the food produced, agroecosystems also provide employment for millions. Agricultural labor represents the livelihood, employment, income, and cultural heritage of a significant part of the world's population. In 1996, of the 3.1 billion people living in rural areas, 2.5 billion–44 percent of the world population–were estimated to be living in households dependent on agriculture. The labor force directly engaged in agriculture is an estimated 1.3 billion people–about 46 percent of the total labor force. In North America, only 2.4 percent of the labor force is directly engaged in agriculture, while in East, South, and Southeast Asia as well as in Sub-Saharan Africa, agricultural labor accounts for 56–65 percent of the labor force (FAO 2000).

Human Nutrition

Agriculture was developed for a simple but fundamental purpose–to provide adequate human nutrition. Globally, agroecosystems produce enough food to provide every person on the planet with 2,757 kcal each day, which is sufficient to meet the minimum human requirement for nutrition (FAO 2000). However, many people do not have adequate access to that food, and an estimated 790 million people are chronically undernourished. In Sub-Saharan Africa, 33 percent of the population is undernourished; in the Caribbean 31 percent; and in South Asia 23 percent (FAO 1999b:29)

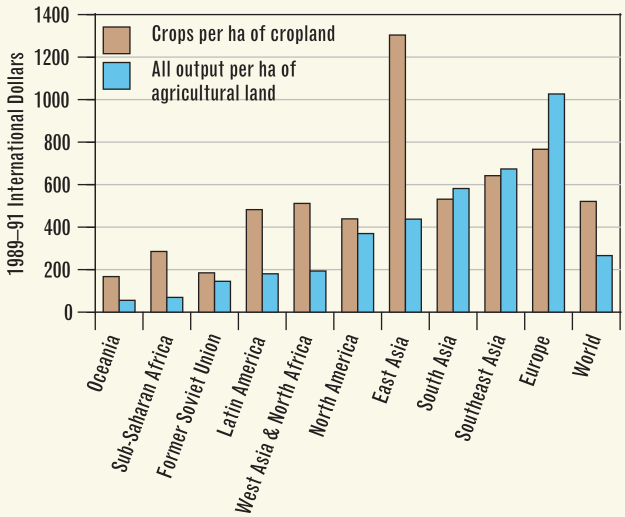
Global demand for food is still increasing significantly, driven by population growth, urbanization, and growth in per capita income. One of the most notable changes in demand is the dramatic increase in meat consumption, particularly in the developing world. This has been dubbed the "livestock revolution." Between 1982 and 1994, global meat consumption grew by 2.9 percent per year, but it grew five times faster in developing countries than in developed countries, where meat consumption is already high (Delgado et al. 1999:9–10).

Between 1995 and 2020, global population is expected to increase by one-third, totaling 7.5 billion people. Global demand for cereals is projected to increase by 40 percent, with 85 percent of the increase in demand coming from developing countries. Meat demand is projected to increase

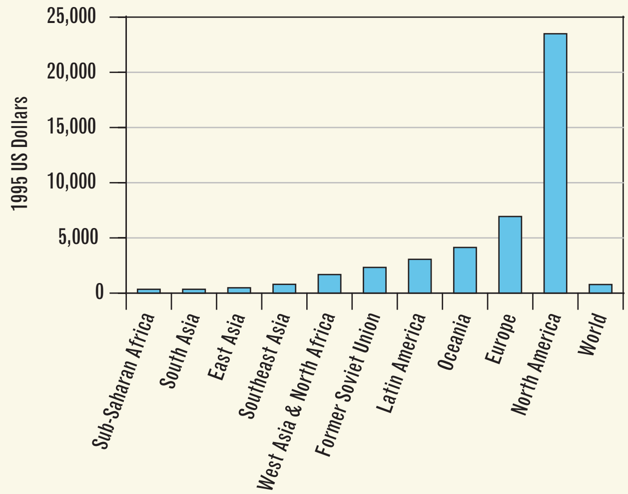
Box 2.7 The Economic Value of Agricultural Production

The total value of output from agroecosystems is US$1.3 trillion per year. Worldwide, 46 percent of the total labor force works in agriculture, and almost half the total population lives in rural communities that depend on agriculture. Cropland generally has more valuable outputs per hectare than pasture, except in Europe, South Asia, and Southeast Asia, where pastures support intensive livestock production. Output per worker varies dramatically from region to region, reflecting difference in level of commercialization of agriculture and opportunities for off-farm employment.

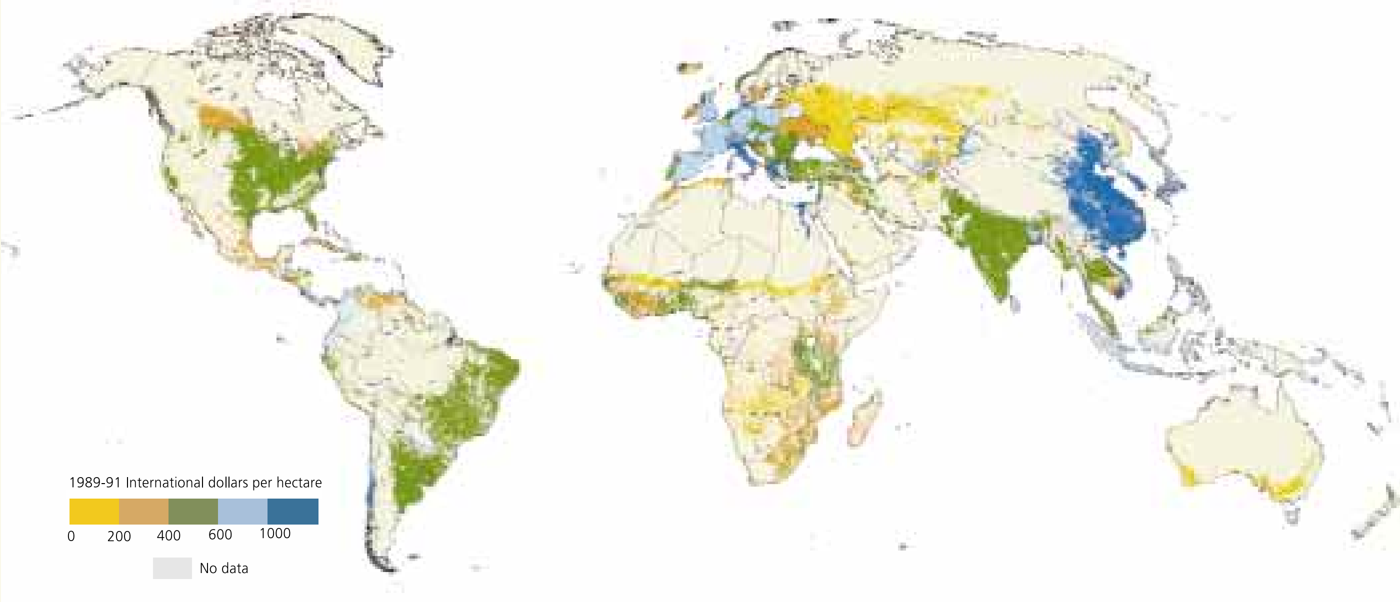
Value of Production per Hectare, 1995–97



Value of Agricultural GDP per Agricultural Worker, 1995–97



The Value of Crops per Hectare of Cropland, 1995–97



Sources: Wood et al. [PAGE] 2000. The map shows national values within the global extent of agriculture, augmented by additional irrigated areas (Döll and Siebert 1999). Value of production table and map are based on FAO (1997) and FAOSTAT (1999). Value of agricultural production weights the output of 134 primary crop and 23 primary livestock commodity quantities by their respective international agricultural prices for 1989–91. Value of crop production is based on the 134 primary crops only. Value of agricultural GDP per agricultural worker is based on World Bank (2000) and FAOSTAT (1999).

by 58 percent, with approximately 85 percent of the increase coming from developing countries. Demand for roots and tubers is expected to grow 37 percent, with 97 percent of this increase coming from the developing world (Pinstrup-Andersen et al. 1999:5–12). And, if significant progress is made in alleviating poverty during this period, there will be an additional increase in demand as the poor and malnourished use their increased income to buy food they previously could not afford.

Productive Capacity

Changes in Yield Growth. Rapid yield growth in most major crops has been instrumental in meeting the food needs of growing populations, particularly in the second half of this century. Recently, however, the growth of cereal crop yields has been slowing, raising concerns that future production may not be able to keep pace with demand. Moreover, there is evidence from some parts of the world that maintaining the growth in yields, or even holding yields at current levels, requires proportionately greater amounts of fertilizer input, implying that the quality of the underlying soil resource may be deteriorating.

These trends must be interpreted cautiously. Even if yields continue to grow rapidly, this does not necessarily indicate that agroecosystems are in good shape, since increased inputs like fertilizer and pesticides could mask underlying depletion of soil nutrients. Nor does a slowdown in the growth of crop yields prove agroecosystem conditions are worsening, since market factors such as falling commodity prices and high fertilizer prices may also account for slower production. Nonetheless, the declining rate of yield growth is worrisome in a world where the growth in food demand is not expected to slow.

Soil Degradation. One measure of the long-term productive capacity of an agroecosystem is the condition of its soil. Natural weathering processes and human management practices can both affect soil quality. Sustaining soil productivity requires that soil-degrading pressures be balanced with soil-conserving practices. The principal processes of soil degradation are erosion by water or wind, waterlogging and salinization (the buildup of salts in the soil), compaction and crusting, acidification, loss of soil organic matter and soil microorganisms, soil nutrient depletion, and accumulation of pollutants in the soil.

Different types of soil degradation are associated with different types of agricultural land use. For example, salinization is associated most often with intensification of irrigated land, and compaction with mechanized farming in high-quality rain-fed lands. Nutrient depletion is often associated with intensifying production on marginal lands but can occur on any soil if nutrients extracted by crops are not adequately replenished. Water erosion is also often associated with marginal lands that have been extensively cleared and tilled. Soil pollution is a particular problem in periurban agriculture (Scherr 1999).

The 1990 Global Assessment of Soil Degradation (GLASOD), based on a structured survey of regional experts, provides the only continental and global-scale estimates of soil degradation (Oldeman et al. 1991). The GLASOD study suggested that 1.97 Bha had been degraded between the mid-1940s and 1990 (Scherr 1999:17; Wood et al. [PAGE] 2000). This represents 15 percent of terrestrial area (excluding ice-covered Greenland and Antarctica).

To assess the extent and severity of soil degradation on agricultural lands in particular, PAGE researchers overlaid the GLASOD data on the map of agricultural land (land with more than 30 percent agricultural use). This revealed that 65 percent of agricultural lands have some amount of soil degradation. About 24 percent were classified as "moderately degraded" which, according to GLASOD, signifies that their agricultural productivity has been greatly reduced. A further 40 percent of agricultural land fell into the GLASOD categories of "strongly degraded" (lands that require major financial investments and engineering work to rehabilitate) or "very strongly degraded" (lands that cannot be rehabilitated at all) (Wood et al. [PAGE] 2000). Among the most severely affected areas are South and Southeast Asia,[3] where populations are among the densest and agriculture the most extensive (Box 2.8 Soil Degradation in South and Southeast Asia).

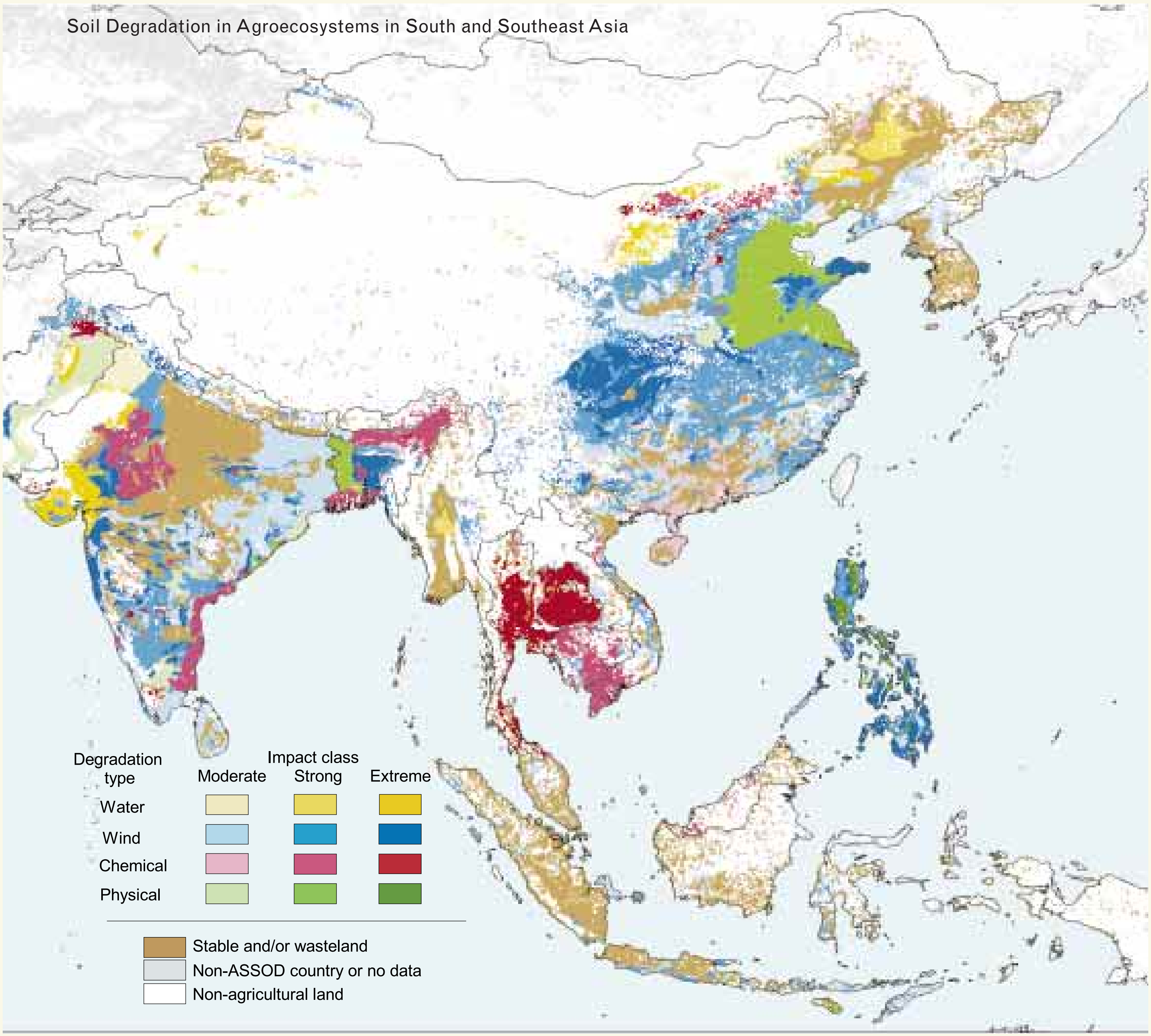
Soil Nutrient Balance. One indicator of soil condition–and productive capacity–is soil nutrient balance. One of the most common management techniques used to maintain the condition of agroecosystems, particularly intensively cultivated systems, is to replenish soil nutrients with organic manures or inorganic fertilizers containing nitrogen, phosphorus, and potassium. Too little replenishment can lead to soil nutrient mining–the progressive loss of nutrients as crops draw on them for growth. Too much replenishment (overfertilization) can lead to leaching of excess nutrients and the consequent soil and water pollution problems as these unused nutrients find their way into surrounding soils and freshwater systems.

An estimate of the nutrient balance of an agroecosystem can be obtained by measuring the nutrient inputs (inorganic and organic fertilizers, nutrients from crop residues, and nitrogen fixation by soybeans and other legumes) and outputs (nutrient uptake in the main crop products and the crop residue). PAGE researchers calculated these nutrient balances at the national level for individual crops in Latin America and the Caribbean (Henao 1999) and found that for most of the crops and cropping systems, the nutrient balance is significantly negative–in other words, soil fertility is declining (see Box 2.9 Hot Spots and Bright Spots).

The observed increases in production in recent decades must therefore be due to a combination of area expansion,

Box 2.8 Soil Degradation in South and Southeast Asia

South and Southeast Asia, where agricultural production systems are among the most intensive in the world, have soils that are among the most degraded. In these regions, soils are significantly steeper, more subject to erosion, and more likely to be salinized, acidic, depleted of potassium, and saturated with aluminum than the soils of most other regions.



Sources: Wood et al. [PAGE] 2000. The map is based on Van Lynden and Oldeman (1997), and Global Land Cover Characteristics Database Version 1.2 (Loveland et al. [2000]). It shows soil degradation within the extent of agriculture.

improved varieties, and other factors that mask or offset the effects of soil degradation. By overlaying nutrient balance with trends in yields, it is possible to identify potential degradation "hot spots" where yield growth is slowing and soil fertility is declining. Areas where the capacity of agroecosystems to produce food appears most threatened include northeast Brazil and sections of Argentina, Bolivia, Colombia, and Paraguay.

Soil nutrient balances are also available for most of Sub-Saharan Africa at continental, national, and district levels (Smaling et al. 1997:47–62). Findings there also suggest widespread nutrient depletion.

Productivity Losses. The cumulative productivity loss from soil degradation over the past 50 years has been roughly estimated, using GLASOD figures, to be about 13 percent for cropland and 4 percent for pasture lands (Oldeman 1998:4). The economic and social impacts of this degradation have been far greater in developing countries than in industrialized countries. In industrialized countries, soil quality plays a relatively less important role in overall agricultural productivity because of the high level of fertilizer and other inputs used. Furthermore, the most important grain-producing areas in industrialized countries typically have deep, geologically "new" soils that can withstand considerable degradation without having yields affected.

Soil degradation has more immediate impacts on the food supply in developing countries. Agricultural productivity is estimated to have declined significantly on approximately 16 percent of agricultural land, especially on cropland in Africa and Central America, pastures in Africa, and forests in Central America. The GLASOD study estimates that almost 74 percent of Central America's agricultural land (defined by GLASOD as cropland and planted pastures) is degraded, as is 65 percent of Africa's and 38 percent of Asia's (Scherr 1999:18). Detailed studies based on predictive models for Argentina, Uruguay, and Kenya calculated yield reductions between 25 and 50 percent over the next 20 years (Mantel and van Engelen 1997:39–40).

Subregional studies have documented significant aggregate declines in crop yields due to degradation in many parts of Africa, China, South Asia, and Central America (Scherr 1999). Crop yield losses in Africa from 1970 to 1990 due to water erosion alone are estimated to be 8 percent (Lal 1995:666). Estimates of the economic losses associated with soil degradation in eight African countries range from 1 to 9 percent of agricultural GDP (Bøjö 1996:170). Total annual economic loss from degradation in South and Southeast Asia is estimated to be 7 percent of the region's agricultural GDP (Young 1994:75). Given that more than half of all land in this region is not affected by degradation, the economic effects in the degraded areas appear to be quite significant. Economic losses from erosion in different regions of Mexico vary from approximately 3 to 13 percent of agricultural GDP (McIntire 1994:124).

The Bottom Line for Food Production. At a global level there is little reason to believe that crop production cannot continue to grow significantly over the next several decades. That said, the underlying condition of many of the world's agroecosystems, particularly those in developing countries, is not good. Soil degradation data, while coarse, suggest that erosion and nutrient depletion are undermining the long-term capacity of agricultural systems on well over half of the world's agricultural land. And competition for water will further magnify the issue of resource constraints to food production. Although nutrient inputs, new crop varieties, and new technologies may well offset these declining conditions for the foreseeable future, the challenge of meeting human needs seems destined to grow ever more difficult.

WATER QUANTITY AND QUALITY

Agriculture is perhaps the most significant human influence on the world's water cycle, affecting quantity, timing, and quality of water available to freshwater systems. At a global scale, agriculture accounts for the greatest proportion of total freshwater withdrawals of any sector of human activity. Agriculture also has the highest consumptive use of water (use that results in returning water to the atmosphere, rather than back to streams or groundwater). Approximately 70 percent–2,800 km^3–of the 4,000 km^3 of water humans withdraw from freshwater systems each year (Shiklomanov 1997:69) is used for irrigation (WMO 1997:9).

This volume of water irrigates 271 Mha of croplands (FAO 2000). Although this number represents only 17 percent of total cropland, it produces 40 percent the world's crops (WMO 1997:9). Of the water used for irrigation, 50–80 percent is returned to the atmosphere or otherwise lost to downstream users (Shiklomanov 1993:19). As a consequence, irrigation can significantly decrease river flows and aquifer levels and can shrink lakes and inland seas.

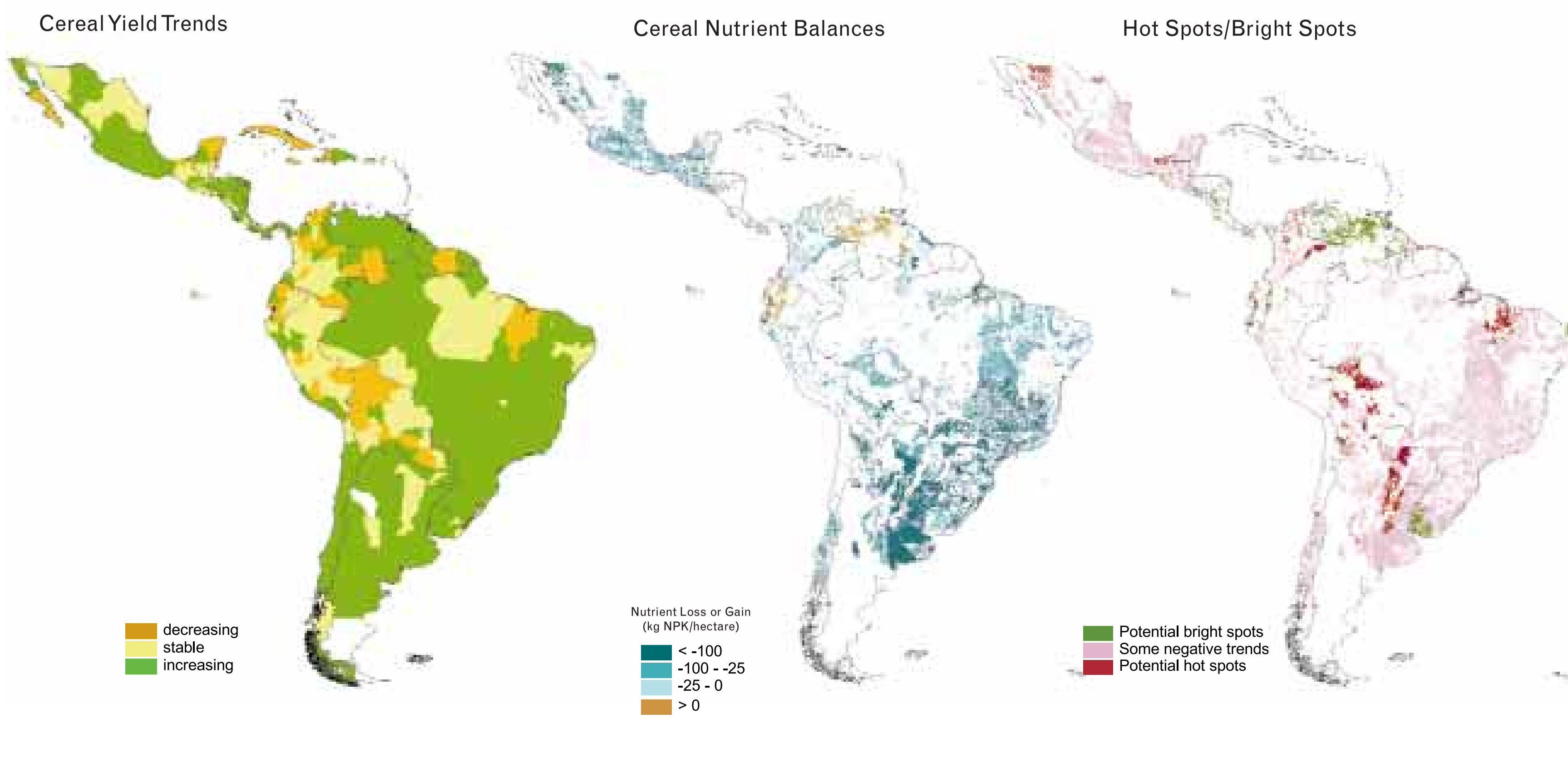
The Aral Sea represents an extreme case of the ecological damage agricultural water diversions can inflict. Withdrawals to irrigate cotton and other crops shrank the sea to one-third of its original volume by the early 1990s, thus increasing its salinity. Fish species and fishing livelihoods were lost before steps were taken to restore some of the flows (WRI 1990:171; Gleick 1998:189).

For 82 percent of the world's agroecosystems, rainfall is the sole source of water for agricultural production. Although rain-fed agriculture has less sweeping impacts on freshwater flows than irrigated agriculture, it can still affect the quantity and timing of downstream flows. These impacts are highly site-specific, depending on the type of agriculture, the soil's slope and condition, and the patterns and intensity of rainfall.

Both irrigated and rain-fed agriculture can pose threats to water quality from the leaching of fertilizer, pesticides, and ani-

Box 2.9 Hot Spots and Bright Spots in Latin American Agroecosystems

Cereal yields have generally been increasing in Latin America over the past 20 years (left map), but at the expense of stocks of nutrients in the soils in which cereals and other crops are grown. In fact, most Latin American agricultural soils show a negative "nutrient balance," meaning that more nutrients are lost through plant growth and harvest than are replaced through additions of fertilizer, manure, or legume cover crops (center map). Combining these maps yields a picture of agricultural "hot spots"—areas where yield growth is slowing and soil fertility is declining (right map). Hot spots where agricultural capacity appears to be most threatened are in northeast Brazil and parts of Argentina, Bolivia, Columbia, and Paraguay. Some "bright spots"—where yields are stable or increasing and nutrient balances are positive—also appear, but cover a much smaller area.



Sources: Wood et al. [PAGE] 2000. Cereal yield trends are based on subnational 1975-98 data for rice, wheat, maize, and sorghum. Nutrient balances are based on national balances of applied nutrients less extraction by cereal crops. They were allocated to specific geographic areas using subnational production statistics and information on climate, soil, and elevation. Map of hots pots and bright spots combines the map of cereal yield trends and the map of cereal nutrient balances.

mal manure into groundwater or surface water. Sediment from erosion can also greatly degrade surface water quality. Irrigated agriculture also creates problems associated with excess water in the soil profile: waterlogging and salinization. Both problems can decrease productivity and lead to abandonment of the affected land. In India, China, and the United States–countries that rely heavily on irrigation–an average of 20 percent of irrigated land suffers from salinization. According to one estimate, salinization costs the world's farmers $11 billion/year in reduced income–almost 1 percent of the total value of agricultural production (Postel 1999:92; Wood et al. [PAGE] 2000).

One measure of the relative impact of various agroecosystems on freshwater systems is their efficiency of water use. Seckler et al. (1998) calculated average irrigation efficiency–the proportion of irrigation water that is actually consumed by crops for growth, compared with the proportion that evaporates or is otherwise wasted. More efficient irrigation systems require less water to meet crop needs, often by delivering water more directly to plant roots, and they are better timed to meet plant growth requirements.

Globally, irrigation efficiency averaged 43 percent in 1990 (Seckler et al. 1998:25). In general, agroecosystems in arid regions have more efficient irrigation systems. Irrigation efficiency in the driest regions runs as high as 58 percent, whereas regions with abundant water supplies have efficiency as low as 31 percent. Thirty-one percent efficiency means more than two-thirds of irrigation water in these areas is wasted, although some water lost to underground leakage may become available for downstream use (Seckler et al. 1998:25). Irrigation efficiencies in China and India are intermediate–39 percent and 40 percent, respectively.

The increasing competition for water from other sectors poses a challenge for agriculture, especially in developing countries where urban populations and the industrial sector are growing quickly. Both industrial and domestic water demands generally take precedence over agriculture. Indeed, irrigated agriculture may increasingly have to rely on recycled water from industrial facilities and wastewater treatment plants to meet its needs. Many believe that water scarcity and its impact on water services such as irrigation is one of the most immediate natural resource concerns from the perspective of human welfare (Rosegrant and Ringler 1999). Certainly, current trends emphasize the critical importance of developing agroecosystems that use water more efficiently, and that minimize the salinization and waterlogging of soils and the leaching of pesticides, fertilizer, and silt into surface and groundwater.

The Bottom Line for Water Services. Overall, the capacity of agroecosystems to maintain the quantity and quality of incoming water resources, and deliver those to downstream users, is declining. Although the consumptive use of water to produce more food represents an important and legitimate water service within agroecosystems, the deterioration in water quality that accompanies this is an often significant penalty for other ecosystems. Irrigation inefficiency increases water withdrawals and contributes to unsustainable rates of groundwater extraction, reduced river flows, and damage to aquatic ecosystems. Downstream water quality is particularly at risk in areas where farmers apply agrochemicals and animal manure abundantly. Poorly managed irrigation can also directly reduce the productivity of agroecosystems through waterlogging and salinization. Improvements in the efficiency of agricultural water use are increasingly important as both food needs and competing water demands continue to grow.

BIODIVERSITY

Agricultural lands support far less biodiversity than the natural forests, grasslands, and wetlands that they replaced. Even so, the biodiversity harbored in agricultural regions is important in its own right. From a purely agricultural perspective, the diversity of naturally occurring predators, bacteria, fungi, and plants in a region can contribute to agricultural production by helping to control pest and disease outbreaks, improving soil fertility and soil physical properties, and improving the resilience of agroecosystems to natural disasters such as floods and droughts. Moreover, the genetic diversity found in traditional crop varieties and in wild species provides a reservoir of genetic material that breeders can use to develop improved crop and animal varieties.

The expansion of agricultural land has, nonetheless, had major impacts on biodiversity. Using maps of the potential habitat that would naturally occur in a region, based on climate and soil characteristics, PAGE researchers estimated the percentage of different habitat types that had been converted to agriculture. Among the most heavily affected natural habitats, 46 percent of the potential area of temperate broadleaf and mixed forests is now agricultural land, accounting for 24 percent of total agricultural land. Close behind, 43 percent of the potential area of tropical deciduous forest (similar to rainforest, but with distinct dry seasons and more open canopy) has been converted to agriculture, accounting for 10 percent of total agricultural land. These types of forest are far more biodiverse than agroecosystems.

Within agroecosystems, different management practices can further alter biodiversity. Intensification tends to greatly diminish the capacity of agroecosystems to support biodiversity by fragmenting and reducing the area of hedgerows, copses, wildlife corridors, and other refuges and natural habitats within the agricultural landscape. Pesticides and other agrochemicals can also be toxic to wildlife and soil microorganisms, including many beneficial birds, pollinators, and carnivorous insects. On the positive side, the increasing use of trees on agricultural lands can increase their biodiversity potential. In Latin America, Sub-Saharan Africa, and South and Southeast Asia, trees are a significant and often a growing part of the agricultural landscape (Wood et al. [PAGE] 2000).

In addition to on-farm tree planting, positive trends include the increasing adoption of "no tillage cultivation," where disturbance of the soil is greatly minimized, helping to preserve soil integrity and minimize erosion. The use of integrated pest management, where pesticides are used more sparingly and in combination with nonchemical pest controls to protect crops, is also expanding. Further, the growth of high-yielding, intensive production systems has a positive side, too, in that it has forestalled the conversion of at least 170 Mha of natural habitat in the tropics (Nelson and Maredia 1999) and perhaps as much as 970 Mha worldwide (Golkany 1999).

In terms of genetic diversity, global agriculture focuses on relatively few species and thus begins from a somewhat narrow base. More than 90 percent of the world's caloric intake comes from just 30 crops, and only 120 crops are economically important at a national scale (FAO 1998:14). Nonetheless, there has traditionally been immense genetic diversity within these crop species, and this diversity has historically helped to maintain the productivity of agroecosystems and is a source of genetic material for modern plant breeding.

Today, however, crop genetic diversity is tending toward decline. Modern crop varieties are taking on more uniform characteristics, and these varieties are planted over large areas in monocultures. This tendency is not limited to high-income countries where the commercialization of agriculture is most prevalent. Modern crop varieties are displacing traditional varieties throughout the world, threatening the loss of an enormous genetic resource and increasing the vulnerability of large areas of homogeneous crops to pest and disease attack. Across all developing countries, modern rice varieties were being grown on 74 percent of the planted area in 1991, modern wheat on 74 percent in 1994, and modern maize on 60 percent in 1992 (Morris and Heisey 1998:220).

The Bottom Line for Biodiversity. Through habitat conversion, landscape fragmentation, the specialization of crop species, and intensification, agriculture plays an important role in shaping global patterns of biodiversity. Currently, the capacity of agroecosystems to support biodiversity is highly degraded, particularly in areas of intensive agriculture. Approaches to enhance biodiversity in agricultural regions while still maintaining or increasing production are only now beginning to develop. Better agricultural practices will almost certainly constitute central elements in any strategy to preserve global biodiversity in the 21st century.

CARBON STORAGE

Carbon is of fundamental importance to the fertility of agroecosystems. The organic matter content of soil, and its stability over time, are key indicators of long-term soil quality and fertility. The level of soil organic matter affects the water retention and tilth of soils, as well as the richness of the soil biota.

Typically, when natural ecosystems such as forest or savanna are converted to agriculture, their soils quickly lose a significant percentage of their soil organic matter. Successful agriculture can arrest this decline and rebuild soil organic matter to its original levels through appropriate crop rotations and the application of nutrients (particularly from organic sources), or through such practices as zero or minimum tillage. On the other hand, excessive tilling, removing crop residues from fields, and practices that promote soil erosion will accelerate loss of organic matter.

Carbon in agroecosystems–in both soils and vegetation–also plays an important role in the global carbon cycle. Except for some production systems in the tropics, agricultural soils generally store more carbon than do the crops or pastures they support. Agricultural vegetation stores an average of 5–6 kg of carbon per square meter (kgC/m^2), while agricultural soils store an average of 7–11 kgC/m^2 (Wood et al. [PAGE] 2000). Together, the vegetation and soils in agroecosystems contain approximately 26–28 percent of all the carbon stored in terrestrial ecosystems.

Land-use change and land management practices, of which agricultural activities are an important part, emit an estimated 1.6 GtC to the atmosphere annually, about 20 percent of human-related greenhouse gas emissions (IPCC 2000:5). There are many distinct agricultural sources of carbon emissions. Prime sources of carbon dioxide include conversion of forests and woody savannas to agricultural land, and deliberate burning of crop stubble and pastures to control pests and diseases and promote soil fertility. Other activities produce methane–another carbon-based molecule that is a more powerful greenhouse gas than CO_2. Livestock rearing and paddy rice cultivation are both major methane sources.

Some researchers believe that the net release of carbon dioxide from agriculture could decrease between 1990 and 2020 (Sombroek and Gommes 1996), while emissions of methane will continue to climb, pushed by the continuing growth in the number of livestock. Emissions of nitrous oxide (N_2O), an even more potent greenhouse gas derived from nitrogen fertilizers, is also rising rapidly.

There is a growing belief that agriculture can play a much greater role in reducing global carbon emissions and in increasing carbon storage. For example, control of agricultural burning, improved diets for cattle and other livestock, and soil conservation can reduce emissions. Meanwhile, better cultivation practices, mixing trees into agricultural systems, and planting improved pasture grasses can help store more carbon. Recent studies show that conservation programs and the adoption of no tillage cultivation in the United States increased carbon storage in U.S. croplands by around 138 MtC/year during the 1980s (Houghton et al. 1999:577).

The Bottom Line for Carbon Storage. Agroecosystems store about 26–28 percent of total terrestrial carbon—mostly in the soil. Improved nutrient management, reduced soil erosion, and the widely adopted use of minimum tillage cultivation tend to increase soil organic matter and, hence, can play some role in increasing carbon storage capacity in agricultural soils. On the other hand, livestock rearing and rice cultivation are significant and growing sources of carbon emissions tied to agriculture, and agricultural burning and land conversion remain prime sources as well.

COASTAL ECOSYSTEMS

The continental margins, where coastal ecosystems reside, are regions of remarkable biological productivity and high accessibility. This has made them centers of human activity for millennia. Coastal ecosystems provide a wide array of goods and services: they host the world's primary ports of commerce; they are the primary producers of fish, shellfish, and seaweed for both human and animal consumption; and they are also a considerable source of fertilizer, pharmaceuticals, cosmetics, household products, and construction materials.

Encompassing a broad range of habitat types and harboring a wealth of species and genetic diversity, coastal ecosystems store and cycle nutrients, filter pollutants from inland freshwater systems, and help to protect shorelines from erosion and storms. On the other side of shorelines, oceans play a vital role in regulating global hydrology and climate and they are a major carbon sink and oxygen source because of the high productivity of phytoplankton. The beauty of coastal ecosystems makes them a magnet for the world's population. People gravitate to coastal regions to live as well as for leisure, recreational activities, and tourism.

Extent and Modification

Many different definitions of *coastal zone* are in use. For the purpose of the ecosystem analysis, PAGE researchers define coastal regions as "the intertidal and subtidal areas above the continental shelf (to a depth of 200 m) and adjacent land area up to 100 km inland from the coast." The PAGE analysis of coastal ecosystems also includes marine fisheries because the bulk of the world's marine fish harvest–as much as 95 percent, by some estimates–is caught or reared in coastal waters (Sherman 1993:3). Only a small percentage comes from the open ocean (Box 2.10 Taking Stock of Coastal Ecosystems).

EXTENT

Because the world's coastal ecosystems are defined by their physical characteristics (their proximity to the coast) rather than a distinct set of biological features, they encompass a much more diverse array of habitats than do the other ecosystems in the PAGE study. Coral reefs, mangroves, tidal wetlands, seagrass beds, barrier islands, estuaries, peat swamps, and a variety of other habitats each provides its own distinct bundle of goods and services and faces somewhat different pressures.

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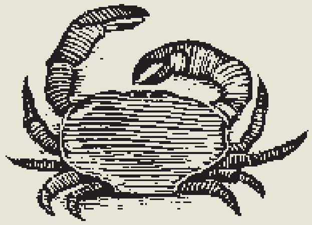
Box 2.10 Taking Stock of Coastal Ecosystems



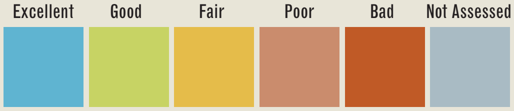
Highlights

- Almost 40 percent of the world's population lives within 100 km of a coastline, an area that accounts for only 22 percent of the land mass.
- Population increase and conversion for development, agriculture, and aquaculture are reducing mangroves, coastal wetlands, seagrass areas, and coral reefs at an alarming rate.
- Fish and shellfish provide about one-sixth of the animal protein consumed by people worldwide. A billion people, mostly in developing countries, depend on fish for their primary source of protein.
- Coastal ecosystems have already lost much of their capacity to produce fish because of overfishing, destructive trawling techniques, and destruction of nursery habitats.
- Rising pollution levels are associated with increasing use of synthetic chemicals and fertilizers.
- Global data on extent and change of key coastal habitats are inadequate. Coastal habitats are difficult to assess from satellite data because areas are small and often submerged.

Key

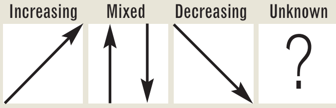
Condition assesses the current output and quality of the ecosystem good or service compared with output and quality of 20–30 years ago.

Condition



Changing Capacity assesses the underlying biological ability of the ecosystem to continue to provide the good or service.

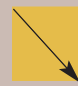
Changing Capacity



Scores are expert judgments about each ecosystem good or service over time, without regard to changes in other ecosystems. Scores estimate the predominant global condition or capacity by balancing the relative strength and reliability of the various indicators. When regional findings diverge, in the absence of global data weight is given to better-quality data, larger geographic coverage, and longer time series. Pronounced differences in global trends are scored as "mixed" if a net value cannot be determined. Serious inadequacy of current data is scored as "unknown."

Conditions and Changing Capacity

FOOD PRODUCTION



Global marine fish production has increased sixfold since 1950, but the rate of increase annually for fish caught in the wild has slowed from 6 percent in the 1950s and 1960s to 0.6 percent in 1995–96. The catch of low-value species has risen as the harvest from higher-value species has plateaued or declined, masking some effects of overfishing. Approximately 75 percent of the major fisheries are fully fished or overfished, and fishing fleets have the capacity to catch many more fish than the maximum sustainable yield. Some of the recent increase in the marine fish harvest comes from aquaculture, which has more than doubled in production since 1990.

WATER QUALITY

As the extent of mangroves, coastal wetlands, and seagrasses declines, coastal habitats are losing their pollutant-filtering capacity. Increased frequency of harmful algal blooms and hypoxia indicates that some coastal ecosystems have exceeded their ability to absorb nutrient pollutants. Although some industrial countries have improved water quality by reducing input of certain persistent organic pollutants, chemical pollutant discharges are increasing overall as agriculture intensifies and industries use new synthetic compounds. Furthermore, while large-scale marine oil spills are declining, oil discharges from land-based sources and regular shipping operations are increasing.

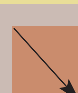
BIODIVERSITY

Indicators of habitat loss, disease, invasive species, and coral bleaching all show declines in biodiversity. Sedimentation and pollution from land are smothering some coastal ecosystems, and trawling is reducing diversity in some areas. Commercial species such as Atlantic cod, five species of tuna, and haddock are threatened globally, along with several species of whales, seals, and sea turtles. Invasive species are frequently reported in ports and enclosed seas, such as the Black Sea, where the introduction of Atlantic comb jellyfish caused the collapse of fisheries.

RECREATION

Tourism is the fastest-growing sector of the global economy, accounting for $3.5 trillion in 1999. Some areas have been degraded by the tourist trade, particularly coral reefs, but the effects of tourist traffic on coastal ecosystems at a global scale are unknown.

SHORELINE PROTECTION



Human modification of shorelines has altered currents and sediment delivery to the benefit of some beaches and detriment of others. Coastal habitats with natural buffering and adaptation capacities are being modified by development and replaced by artificial structures. Thus, the impact from storm surges has increased. Furthermore, rising sea levels, projected as a result of global warming, may threaten some coastal settlements and entire small island states.

Data Quality

FOOD PRODUCTION

Global data on fish landings are underreported in many cases or are not reported by species, which makes assessing particular stocks difficult. Data are fragmentary on how many fish are unintentionally caught and discarded, how many boats are deployed, and how much time is spent fishing, which obscures the full impact of fishing on ecosystems. Many countries fail to report data on smaller vessels and their fish landings.

WATER QUALITY

Global data on extent and change of wetlands and seagrasses are lacking, as are standardized and regularly collected data on coastal or marine pollution. Monitoring of nutrient pollution by national programs is uneven and often lacking. Current information relies heavily on anecdotal observation. Effective national programs are in place in some countries to monitor pathogens, persistent organic pollutants, and heavy metals, but data are inconsistent. No data are available on oil pollution from nonpoint sources.

BIODIVERSITY

Detailed habitat maps are available for only some areas. Loss of mangrove, coastal wetlands, and seagrasses are reported in many parts of the world, but little is documented quantitatively. Species diversity is not well inventoried, and population assessments are available only for some key species, such as whales and sea turtles. Data on invasive species are limited by difficulty in identifying them and assessing their impact. Few coral reefs have been monitored over time. Information on the ecological effects of trawling is poorly documented.

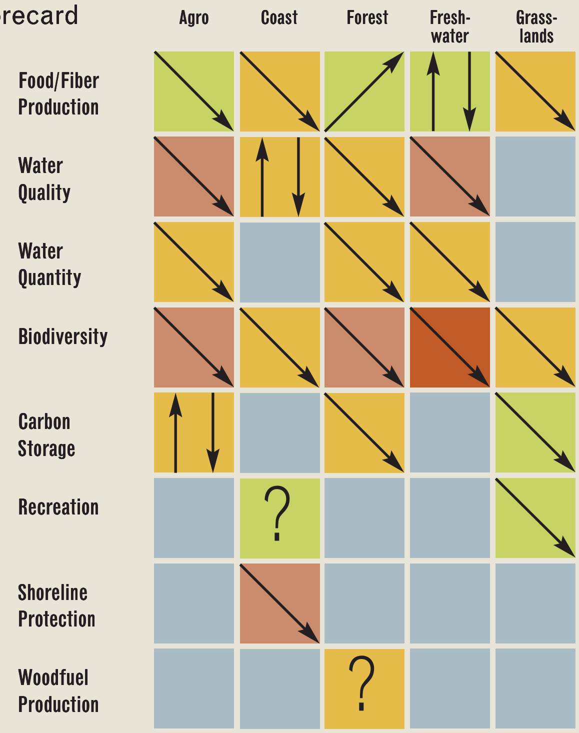
RECREATION

Typically, only national data on tourism are available, rather than data specific to coastal zones. Not all coastal countries report tourism statistics, and information on the impacts of tourism and the capacity of coastal areas to support tourism is very limited.

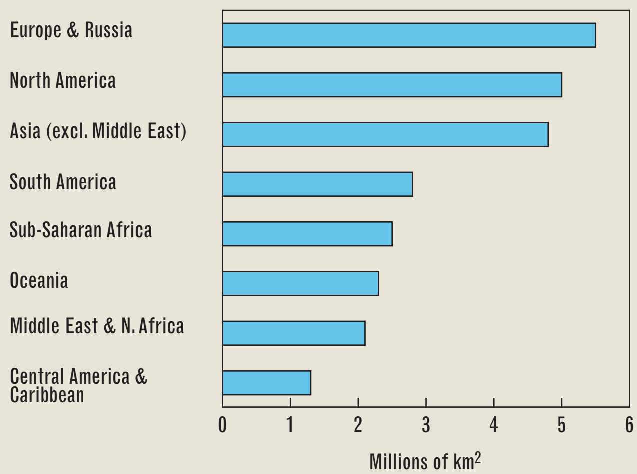
SHORELINE PROTECTION

Information on conversion of coastal habitat and shoreline erosion is inadequate. Information is lacking on long-term effects of some coastal modifications on shorelines. Predictions of sea level rise and storm effects as a result of climate change are speculative.

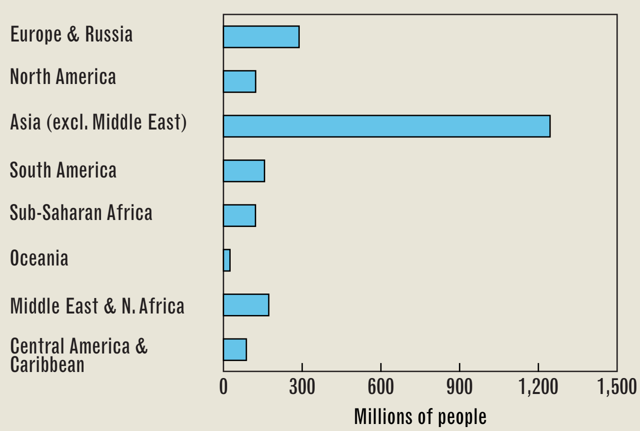
Scorecard



Area within 100 km² of a Coast



Population within 100 km² of a Coast



The extent of coastal ecosystems and how they have been modified over time is less well known than are the extents of the other ecosystems examined in the PAGE study. Individual coastal habitats such as wetlands or coral reefs tend to cover relatively small areas, and detailed mapping is necessary to accurately measure extent or change in these areas. Until the advent of satellite imagery, such mapping was beyond the capacity of most nations. Even today, high-resolution mapping of these systems is imperfect and expensive and has not been attempted at a global scale for the entire 1.6 million km of coastlines (Burke et al. [PAGE] 2000).

MODIFICATIONS

In the absence of such maps, PAGE researchers used satellite imagery to estimate how much coastal area remains in natural vegetation (dunes, wetlands, wooded areas, etc.) versus how much is now urban and agricultural land. Overall, 19 percent of all lands within 100 km of the coast is classified as highly altered, meaning they have been converted to agricultural or urban uses, 10 percent semialtered (involving a mosaic of natural and altered vegetation), and 71 percent are unaltered (Burke et al. [PAGE] 2000) (Box 2.11 Coastal Population and Altered Land Cover).

Mangroves and Coral Reefs

More detailed information is available about the extent and modification of a few coastal habitats, such as mangroves and coral reefs, than is known about the extent of coastal ecosystems. Mangroves line approximately 8 percent of the world's coastline (Burke et al. [PAGE] 2000) and about one-quarter of tropical coastlines, covering a surface area of approximately 181,000 km^2 (Spalding et al. 1997:23). Some 112 countries and territories have mangroves within their borders (Spalding et al. 1997:20). Although scientists cannot determine exactly how extensive mangroves were before people began to alter coastlines, based on historical records, anywhere from 5 to nearly 85 percent of original mangrove area in various countries is believed to have been lost. Extensive losses have occurred in the last 50 years. For example, much of the estimated 84 percent of original mangroves lost to Thailand were lost since 1975 (MacKinnon 1997:167; Spalding et al. 1997:66); Panama lost 67 percent of its mangroves just during the 1980s (Davidson and Gauthier 1993) (Box 2.12 Mangroves). Overall, it is estimated that half of the world's mangrove forests have been destroyed (Kelleher et al. 1995:30). Although the net trend is clearly downward, in some regions mangrove area is actually increasing as a result of plantation forestry and small amounts of natural regeneration (Spalding et al. 1997:24).

Knowledge of the extent and distribution of coral reefs is probably greater than for any other marine habitat. Rough global maps of coral reefs have existed since the mid-1800s because of the hazard they posed to ships. WCMC has compiled a coarse-scale (1:1,000,000) map of the world's shallow coral reefs; more detailed maps exist for many countries. Worldwide, an estimated 255,000 km^2 of shallow coral reefs exist, with more than 90 percent in the Indo-Pacific region (Spalding and Grenfell 1997:225, 227) (Box 2.13 Coral Reefs). Adding deep water reefs would make the total reef area much higher–perhaps more than double the area–but these deeper reefs are poorly mapped.

Both reef-building corals and coral reef fish show broadly similar patterns in the distribution of species richness, with highest species diversity in the Indo-Pacific region and lower diversity in the Atlantic. Currently, on a global basis, coral reef degradation is a more serious problem than outright loss of coral through, for example, land reclamation and coral mining. Nonetheless, coral area has been significantly reduced in some parts of the world.

Other Coastal Ecosystems

No comprehensive global information, and only limited reliable national information, is available to document change in seagrass habitats, peat swamps, or other types of coastal wetlands besides mangroves. Where data do exist, however, the habitat loss is often dramatic. For example, 46 percent of Indonesia's and as much as 98 percent of Vietnam's peat swamps are believed to have been lost (MacKinnon 1997:104, 175). Similarly, the extent of change in seagrass habitats is thought to be high. In the United States, more than 50 percent of the historical seagrass cover has been lost from Tampa Bay, 76 percent from the Mississippi Sound, and 90 percent from Galveston Bay because of population growth and changes in water quality (NOAA 1999:19).

PRESSURES ON COASTAL ECOSYSTEMS

Along with direct loss of area, a variety of other factors are significantly altering coastal ecosystems. Chief among these are population growth, pollution, overharvesting, and the looming threat of climate change.

Population

Globally, the number of people living within 100 km of the coast increased from roughly 2 billion in 1990 to 2.2 billion in 1995–39 percent of the world's population (Burke et al. [PAGE] 2000). However, the number of people whose activities affect coastal ecosystems is much larger than the actual coastal population because rivers deliver pollutants from inland watersheds and populations to estuaries and surrounding coastal waters. As coastal and inland populations continue to grow, their impacts–in terms of pollutant loads and the development and conversion of coastal habitats–can be expected to grow as well.

Pollution

A vast range of pollutants affects the world's coasts and oceans. These can be broadly classified into toxic chemicals (including organic chemicals, heavy metals, and radioactive

(continues on p. 76)

Box 2.11 Coastal Population and Altered Landcover

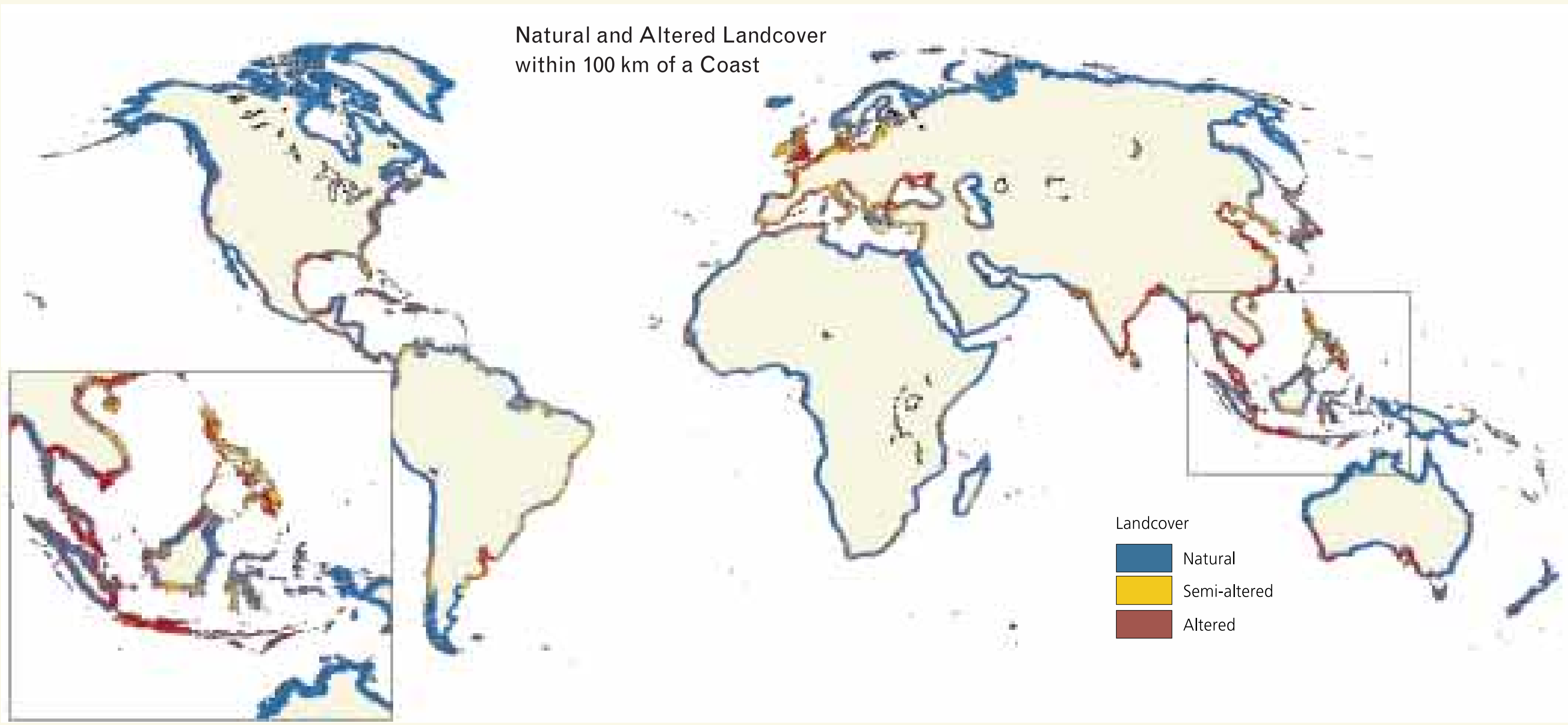
In 1990, 2 billion people lived within 100 km of the sea. By 1995, coastal areas were home to 200 million more, or 39 percent of the population.

Concentrated coastal populations are having a profound impact on marine coastal ecosystems. Much of the shoreline has been developed to meet needs for shelter, subsistence, commerce, and recreation. Even inland populations have an impact on coastal ecosystems. Coastal problems such as algal blooms and eutrophication can be attributed to added pollutants and nutrients from inland freshwater systems.

Overall, 29 percent of all lands within 100 km of a coastline is classified as altered—19 percent is highly altered, converted to agricultural and urban uses; and 10 percent is semialtered, with natural vegetation and cropland interspersed. Some 71 percent remains unaltered.

Population Living Near a Coastline, 1995

Proximity to Coastline	Population (cumulative totals in thousands)	Percentage of Total Population
Within 25 km	1,143,828	20
Within 50 km	1,645,634	29
Within 100 km	2,212,670	39



Sources: Burke et al. [PAGE] 2000. The map is based on Global Land Cover Characteristics Database Version 1.2 (Loveland et al. [2000]). The table is based on CIESIN (2000).

Box 2.12 Mangroves

Mangroves line 8 percent of the world's coasts and about one-quarter of the world's tropical coastlines, covering a surface area of approximately 181,000 km^2 (Spalding et al. 1997:23). Adapted to conditions of varying salinity and water level, they flourish in sheltered coastal areas, such as river estuaries.

Mangroves are crucial to the productivity of tropical fisheries because they act as spawning grounds for a wide range of fish species. They also provide local communities with timber and fuelwood and help stabilize coastlines.

Historical records indicate that the original extent of mangrove forests has declined considerably under pressure from human activity. National proportions of original mangrove cover lost vary from 4 to 84 percent, with the most rapid losses occurring in recent decades. Overall, as much as half of the world's mangrove forests may have been lost (Kelleher et al. 1997:30)

Excessive cutting for fuel and timber as well as clearance for agriculture and shrimp farming and for coastal development have all contributed to these high loss rates. In a few regions, however, mangrove area is actually increasing as a result of plantation forestry and natural regeneration.

Mangrove Area in Selected Countries

Region and Country	Current Extent (km^2)	Approximate Loss (%)	Period
Africa			
Angola	*1,100*	50	Original extent to 1980s
Cote d'Ivoire	640	60	Original extent to 1980s
Gabon	*1,150*	50	Original extent to 1980s
Guinea-Bissau	*3,150*	70	Original extent to 1980s
Kenya	*610*	4	1971–88
Tanzania	*2,120*	60	Original extent to 1980s
Latin America and the Caribbean			
Costa Rica	*413*	–6	1983–90
El Salvador	*415*	8	1983–90
Guatemala	161	31	1960s–90s
Jamaica	106	30	Original extent to 1990s
Mexico	5,315	65	1970s–90s
Panama	*1,581*	67	1983–90
Peru	51	25	1982–92
Asia			
Brunei	200	20	Original extent to 1986
Indonesia	*24,237*	55	Original extent to 1980s
Malaysia	*2,327*	74	Original extent to 1992–93
Myanmar	*4,219*	75	Original extent to 1992–93
Pakistan	*1,540*	78	Original extent to 1980s
Philippines	*1,490*	67	1918–80s
Thailand	1,946	84	Original extent to 1993
Vietnam	2,525	37	Original extent to 1993
Oceania			
Papua New Guinea	*4,627*	8	Original extent to 1992–93

Source: Burke et al. [PAGE] 2000. The table is based on *World Resources 1990–91*; UNEP Kenya Coastal Zone Database (1997), Spalding et al. (1997), Davidson and Gauthier (1993), MacKinnon (1997), World Bank (1989), and BAP Planning (1993). Current extent estimates in italics are not in agreement with recent estimates in the Data Tables in this volume, because of differences in year assessed and methodology.

Box 2.13 Coral Reefs

Coral reefs exist mostly in shallow tropical waters with minimal silt content. Shallow coral reefs occupy only 255,000 km^2 of the world's surface. Nonetheless, they support nearly 1 million species of plants and animals (Reaka-Kudla 1997; Spalding and Grenfell 1997:225). Besides harboring rich biodiversity, coral reefs provide an accessible area for small-scale fishing and help to protect coastlines from storm damage.

Coral reefs are most extensive around the islands and coasts of the Western Pacific and Southeast Asia, which together encompass two-thirds of the world's coral ecosystems. These areas are also the richest in species diversity.

Coral ecosystems are extremely vulnerable to the direct and indirect effects of human activity. In many parts of the world, reef area has been reduced by land reclamation, coastal development, and coral mining. Such direct threats can be combated by extending protected-area status, but the indirect effects of human activity such as increased siltation, pollution, and increases in sea level and temperature are broader in impact and harder to counter.

The mass bleaching of reefs that occurred during the 1997–98 El Niño was the most extensive such event yet recorded. If, as is generally thought, coral bleaching is caused by elevated sea temperatures, global warming is likely to make these events more severe and more threatening to the long-term survival of reefs.

Global and Regional Reef Areas, 1997

Region	Area (thousands of km^2)	Percentage of Total Area
WORLD	255	100.0
Indo-Pacific	233	91.4
Western Pacific (including Hawaii)	105	41.2
Eastern Pacific	3	1.2
Red Sea	17	6.7
Arabian Gulf	3	1.2
Indian Ocean	36	14.1
Southeast Asia	68	26.7
Atlantic	22	8.6
Wider Caribbean	21	8.2
West Africa	1	0.4

Sources: Burke et al. [PAGE] 2000. The map shows observations of coral bleaching from NOAA/NESDIS (2000) and WCMC (1999) and sea surface temperature data from NOAA/NESDIS (2000).

waste), nutrients (including agricultural fertilizers and sewage), sediments, and solid waste. The occurrence of bacterial contamination is a special case, often associated with nutrient pollution. Oil pollution (from spills and seepage) includes toxic, nutrient, and sediment-based pollutants.

Most pollution of coastal waters comes from the land, but atmospheric sources and marine-based sources such as oil leaks and spills from vessels also play a role. Approximately 40 percent of toxic pollution in Europe's coastal waters is thought to stem from atmospheric deposition; the percentage could be even greater in the open ocean (Thorne-Miller and Catena 1991:18; EEA 1998:213).

In some regions, such as North America and Europe, heavy metal and toxic chemical pollution has decreased in recent decades as the use of these compounds has decreased, but toxic chemicals continue to be a major problem worldwide (NOAA 1999:14; EEA 1998:216). Some progress has also been achieved in reducing the volume of oil spilled into the oceans. Both the number of oil spills and total amounts of oil spilled have decreased considerably since the 1970s (ITOPF 1999; Etkin 1998:10). Indeed, spills from vessels, although they can be catastrophic, are not the major source of oil pollution; runoff and routine maintenance of oil infrastructure are estimated to account for more than 70 percent of the total annual oil discharged into the ocean (National Research Council 1985:82).

Nutrient pollution, especially nitrates and phosphates, has increased dramatically this century. Greater use of fertilizers, growth in quantities of domestic and industrial sewage, and increased aquaculture, which releases considerable amounts of waste directly into the water, are all contributing factors (GESAMP 1990:96). Some local improvements in nutrient pollution have been achieved through sewage treatment and bans on phosphate detergents (NOAA 1999:iv; EEA 1999:155). However, the Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) identified marine eutrophication, caused by these nutrients, as one of the most immediate causes of concern in the marine environment (GESAMP 1990:3) (Box 2.14 Pollution in Coastal Areas).

Overharvesting

Forty-five years of increasing fishing pressure have left many major fish stocks depleted or in decline. Yet overfishing is not a new phenomenon; it was recognized as an international problem as long ago as the early 1900s (FAO 1997:13). Prior to the 1950s, however, the problem was much more confined, since only a few regions such as the North Atlantic, the North Pacific, and the Mediterranean Sea were heavily fished and most world fish stocks were not extensively exploited. Since then, the scale of the global fishing enterprise has grown rapidly and the exploitation of fish stocks has followed a predictable pattern, progressing from region to region across the world's oceans. As each area in turn reaches its maximum productivity, it then begins to decline (Grainger and Garcia 1996:8, 42–44) (Box 2.15 Overfishing).

Overexploitation of fish, shellfish, seaweeds, and other marine organisms not only diminishes production of the harvested species but can profoundly alter species composition and the biological structure of coastal ecosystems. Overharvest stems in part from overcapacity in the world fishing fleet. Worldwide, 30–40 percent more harvest capacity exists than the resource can withstand (Garcia and Grainger 1996:5). A recent review of Europe's fisheries by the European Union indicates that the fishing fleet plying European waters would need to be reduced by 40 percent to bring it into balance with the remaining fish supply (FAO 1997:65).

Trawling. Not only is harvesting excessive, but many modern harvesting methods are destructive as well. Modern trawling equipment that is dragged along the sea bottom to catch shrimp and bottom-dwelling fish such as cod and flounder can devastate the seafloor community of worms, sponges, urchins, and other nontarget species as it scoops through the sediment and scrapes over rocks. Extent of damage to seabottom habitats that have been swept by trawling equipment may be light, with effects lasting only a few weeks, or intensive, with some impacts on corals, sponges, and other long-lived species lasting decades or even centuries (Watling and Norse 1998:1185–1190).

One global estimate puts the area swept by trawlers at 14.8 million km^2 of the seafloor (Watling and Norse 1998:1190). To better estimate the percentage of the continental shelf areas affected by trawling, PAGE researchers mapped the total area of trawling grounds for 24 countries for which sufficient data were available. These countries include about 41 percent of the world's continental shelves. The PAGE analysis shows that trawling grounds covered 57 percent of the total continental shelf area of these countries (Burke et al. [PAGE] 2000) (Box 2.16 Trawling).

Bycatch. Another destructive practice associated with commercial fishing comes from the "bycatch" or unintended catch of nontarget species as well as juvenile or undersized fish of the target species. Some of these fish are kept for sale, but many are discarded and eventually thrown back to the sea, where most die of injuries and exposure. Fisheries experts estimate that bycatch accounts for roughly 25 percent of the global marine fish catch–some 20 million metric tons per year (FAO 1999a:51). In certain fisheries, bycatch can outweigh the catch of target species. For example, in the shrimp capture fishery, discards may outweigh shrimp by a ratio of 5 to 1 (Alverson et al. 1994:24).

Climate Change

Global climate change may compound other pressures on coastal ecosystems through the additional effects of warmer ocean temperatures, altered ocean circulation patterns,

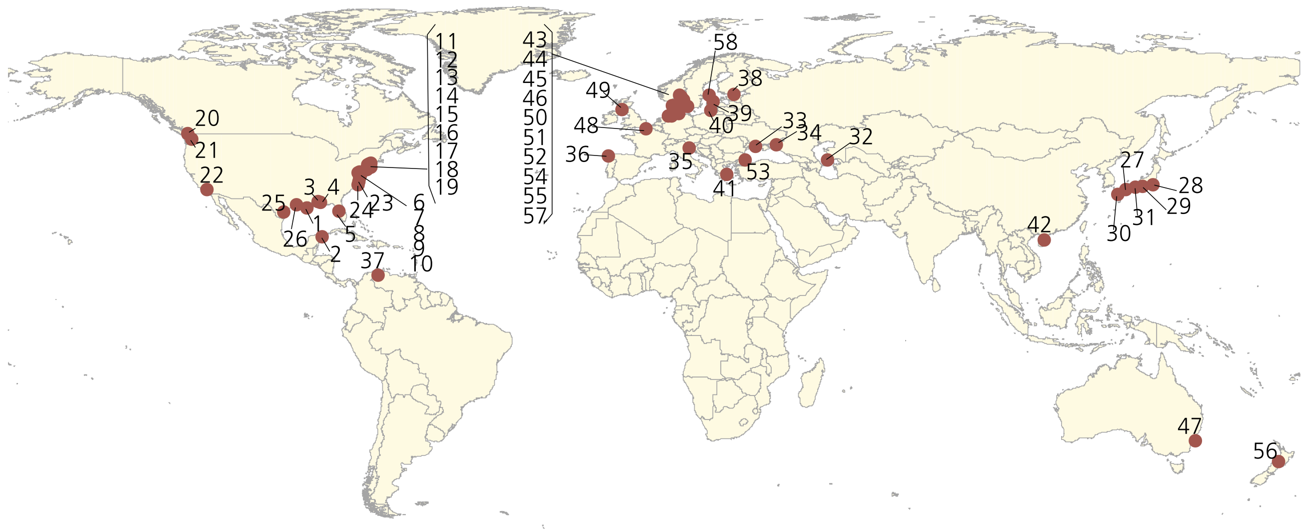
Box 2.14 Pollution in Coastal Areas

Marine nutrient pollution, especially from nitrates and phosphates, has increased dramatically this century largely because of increased use of agricultural fertilizers and growing discharges of domestic and industrial sewage (GESAMP 1990:96). Excessive nutrient concentrations in water can stimulate excessive plant growth—eutrophication. As the plant matter becomes more abundant, its decomposition can reduce oxygen concentrations in the water to less than the 2 parts per million needed to support most aquatic animal life. This not only jeopardizes native species, it also jeopardizes human health, livelihoods, and recreation.

Harmful algal blooms, which consist of algae that produce harmful biotoxins, can also be fueled by excessive nutrient runoff. More than 60 kinds of algal toxins are known today (McGinn 1999), and the number of incidents annually affecting public health, fish, shellfish, and birds has increased from around 200 in the 1970s to more than 700 in the 1990s (HEED 1998).

Hypoxia, the depletion of dissolved oxygen, is also related to nutrient pollution of coastal waters. Fish leave or avoid hypoxic areas and bottom-dwellers such as shrimp, crabs, snails, clams, starfish, and worms eventually suffocate. Current data suggest that hypoxic zones occur most frequently in enclosed waters adjacent to intensively farmed watersheds and major industrial centers off the coasts of Europe, the United States, and Japan.

Global Distribution of Hypoxic Zones



1 Dead Zone
2 Nichupti Lagoon
3 Mobile Bay
4 Perdido Bay
5 Hillsborough Bay
6 Chesapeake Mainstream
7 Potomac River
8 Rappahannock River
9 York River
10 Pagan River
11 Long Island Sound
12 New York/New Jersey Bight
13 Flushing Bay
14 Raritan Bay
15 Barneqatt Inlet
16 Mullica River Estuary
17 Townsend-Hereford Inlet
18 Great Egg Harbor River
19 New York City
20 Puget Sound
21 Saanich Inlet
22 Los Angeles
23 Pamlico river
24 Cape Fear River
25 Corpus Christi Bay
26 Freeport
27 Seto Inland Sea
28 Tokyo Harbor
29 Mikawa & Ise Bays
30 Omura Bay
31 Osaka Bay
32 Caspian Sea
33 Black Sea NW Shelf
34 Sea of Azov
35 Gulf of Trieste
36 Rias Baixas
37 Fosa de Cariaco
38 Gulf of Finland
39 Baltic Sea Channel
40 Bornholm Basin
41 Elefsis Bay
42 Tolo Harbor, Hong Kong
43 Kattegat
44 Laholm Bay
45 Byfjord
46 Gullmarsfjord
47 Port Hacking
48 Sommone Bay
49 Lough Ine
50 German Bight, North Sea
51 Kiel Bay
52 Wadden Sea
53 Marmara Sea
54 Limfjorden
55 Arhus Bay
56 New Zealand
57 Oslofjiord
58 Stockholm Inner Archipeligo

Source: Burke et al. [PAGE] 2000. The map is based on R.J. Diaz, Virginia Institute of Marine Science, personal communication (1999), updating Diaz and Rosenberg (1995).

Box 2.15 Overfishing

Prior to the 1950s, overfishing was confined to heavily fished regions in the North Atlantic, North Pacific, and Mediterranean Sea. Today overfishing is global, and current harvest trends put fishing, as both a source of food and a source of employment, at risk.

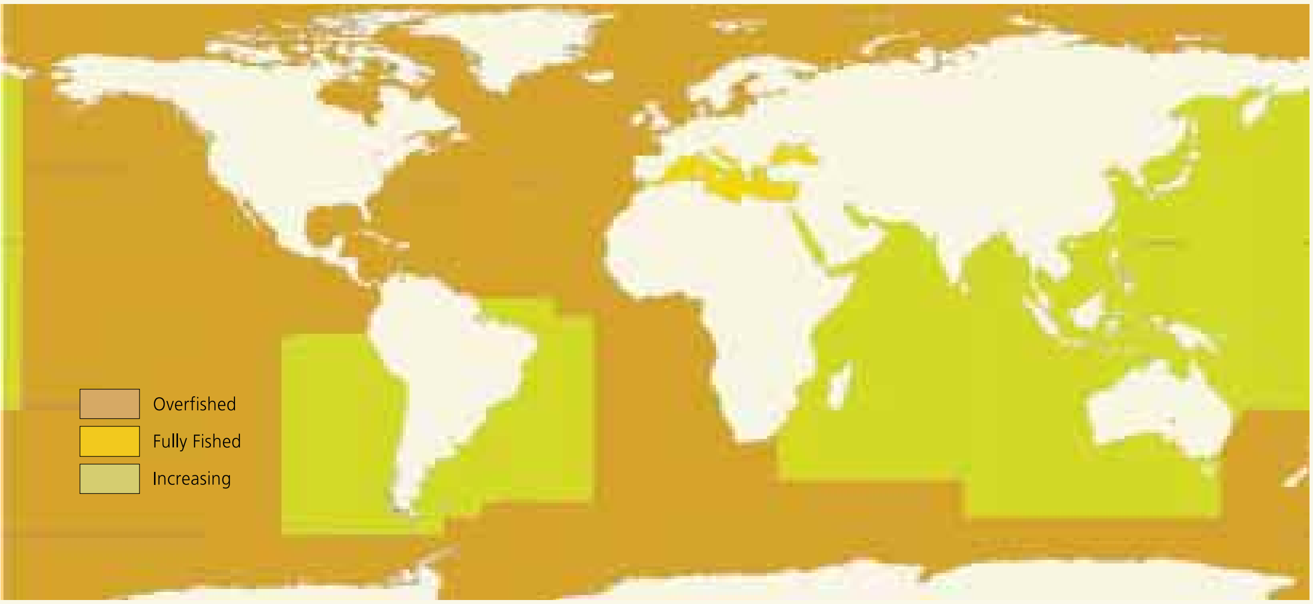
Fish account for one-sixth of all animal protein in the human diet, and around 1 billion people rely on fish as their primary protein source. As demand for fish has increased, many major stocks have declined or have been depleted. FAO reports that as of 1999, more than a quarter of all fish stocks are already depleted as a result of past overfishing or are in imminent danger of depletion from current overharvesting. Almost half of all fish stocks are being fished at their biological limit and are therefore vulnerable to depletion if fishing intensity increased.

Employment within fisheries is likely to change profoundly, especially for small-scale fishers who fish for the local market or for subsistence. Over the past 2 decades, these fishers, who number some 10 million worldwide, have been losing ground as competition from commercial vessels has grown. However, commercial fleets don't face bright prospects, either. Worldwide the fishing industry has 30–40 percent more harvest capacity than fish stocks can support, and the European Union recently estimated that the fleet working in Europe would need to be reduced 40 percent to bring it into balance with the remaining supply of fish.

A History of Decline: Peak Fish Catch vs. 1997 Fish Catch, by Ocean

Fishing Area	1997 Catch (thousand tons)	Maximum Catch (thousand tons)	Year of Maximum Catch
Atlantic			
Northeast	11,663	13,234	1976
Northwest	2,048	4,566	1968
Eastern Central	3,553	4,127	1990
Western Central	1,825	2,497	1984
Southeast	1,080	3,271	1978
Southwest	2,651	2,651	1997
Pacific			
Northeast	2,790	3,407	1987
Northwest	24,565	24,565	1997
Eastern Central	1,668	1,925	1981
Western Central	8,943	9,025	1995
Southeast	14,414	20,160	1994
Southwest	828	907	1992
Indian			
Eastern	3,875	3,875	1997
Western	4,091	4,091	1997
Mediterranean	1,493	1,990	1988
Antarctic	28	189	1971

Fishing Grounds Overfished or Fully Fished, 1994



Source: Burke et al. [PAGE] 2000. The map is based on Grainger and Garcia (1996); analysis is based on landings data collected between 1950 and 1994 for the top 200 species-/fishing-area combinations, which represent 77 percent of the world's marine production, as explained in the technical notes for Data Table 4 in Coastal, Marine, and Inland Waters. Table is based on FAO (1999c, 1999d).

changing storm frequency, and rising sea levels. Changing concentrations of CO_2 in ocean waters may also affect marine productivity or even change the rate of coral calcification (Kleypas et al. 1999). The widespread coral bleaching observed during the 1997–98 El Niño is a dramatic example of the effect of elevated temperatures at the sea surface. Similarly, changes in ocean currents and circulation patterns could dramatically affect the biological composition of coastal ecosystems by changing both the physical characteristics of the habitat–the water temperature and salinity–and the pattern of migration of larvae and adults of different species.

Rising sea level, associated with climate change, is likely to affect virtually all of the world's coasts. During the past century, sea level has risen at a rate of 1.0–2.5 mm per year (IPCC 1996:296). The Intergovernmental Panel on Climate Change (IPCC) has projected that global sea level will rise 15–95 cm by the year 2100, due principally to thermal expansion of the ocean and melting of small mountain glaciers (IPCC 1996:22).

Some of the areas most vulnerable to rising seas are coastal lands whose highest points are within 2 m of sea level, in particular the so-called "lands of no retreat"–islands with more than half of their area less than 2 m above sea level. Rising sea levels will also increase the impact of storm surges. This, in turn, could accelerate erosion and associated habitat loss, increase salinity in estuaries and freshwater aquifers, alter tidal ranges, change sediment and nutrient transport, and increase coastal flooding. River deltas are at risk from flooding as a result of sea-level rise as are saltwater marshes and coastal wetlands if they are blocked from migrating inland by shoreline development (NOAA 1999:20).

Assessing Goods and Services

FOOD FROM MARINE FISHERIES

The forecast for world fisheries is grim despite the fact that fish provided 16.5 percent of the total animal protein consumed by humans in 1997 (Laureti 1999:63). On average this accounts for 6 percent of all protein–plant and animal–that humans eat annually. Approximately 1 billion people rely on fish as their primary source of animal protein (Williams 1996:3). Dependence on fish is highest in developing nations: of the 30 countries most dependent on fish as a protein source, all but four are in the developing world (Laureti 1999:v). In developing countries, production of fish products is almost equal to the production of all major meats–poultry, beef, sheep, and pork (Williams 1996:3).

Global marine fish and shellfish production has increased sixfold from 17 million tons in 1950 to 105 million metric tons in 1997 (FAO 1999c). This rapid growth–particularly in the last 20 years–has come partly from growth in aquaculture, which now accounts for more than one-fifth of the total harvest (marine and inland) (FAO 1999a:10). From 1984 to 1997, aquaculture production in marine and brackish environments tripled and continues to expand rapidly (FAO 1999c). Another 30 percent of the marine harvest consists of small, low-valued fish like anchovies, pilchard, or sardines, many of which are reduced to fish meal and used as a protein supplement in feeds for livestock and aquaculture. Over time, the percentage of the global catch made up by these low-value species has risen as the harvest of high-value species like cod or hake has declined, partially masking the effects of overfishing (FAO 1997:5).

Fish and shellfish production is of global economic importance and is particularly significant for developing countries, where more than half of the export trade in fish products originates (FAO 1999a:21). The value of fishery exports in 1996 amounted to US$52.5 billion, 11 percent of the value of agricultural exports that year (FAO 1999a:20).

Employment

Fishing and aquaculture are major sources of employment as well, providing jobs for almost 29 million people worldwide in 1990 (FAO 1999a:64). Some 95 percent of these fish-related jobs were in developing countries (FAO 1999b). The pattern of employment within the fisheries sector is likely to shift dramatically in coming years, especially for small-scale fishers harvesting fish for local markets and subsistence. Small-scale fishers have been losing ground over the last 2 decades as competition from commercial vessels has grown. Surveys off the west coast of Africa show that fish stocks in the shallow inshore waters where artisanal fishers ply their trade dropped by more than half from 1985 to 1990 because of increased fishing by commercial trawlers (FAO 1995:22). This trend is likely to intensify as fish stocks near shore continue to decrease under heavy fishing pressure.

Ecosystem Condition

The condition of coastal ecosystems, from the standpoint of fisheries production, is poor. Yields of 35 percent of the most important commercial fish stocks declined between 1950 and 1994 (Grainger and Garcia 1996:31). As of 1999, FAO reported that 75 percent of all fish stocks for which information is available are in urgent need of better management–28 percent are either already depleted from past overfishing or in imminent danger of depletion due to current overharvesting, and 47 percent are being fished at their biological limit and therefore vulnerable to depletion if fishing intensity increased (Garcia and DeLeiva 2000).

Another indicator of the condition of coastal fisheries is the relative abundance of fish stocks at different levels of the food web. In many fisheries, the most prized fish are the large predatory species high on the food web, such as tuna, cod, hake, or salmon. When these "top predators" are depleted through heavy fishing pressure, other species lower on the

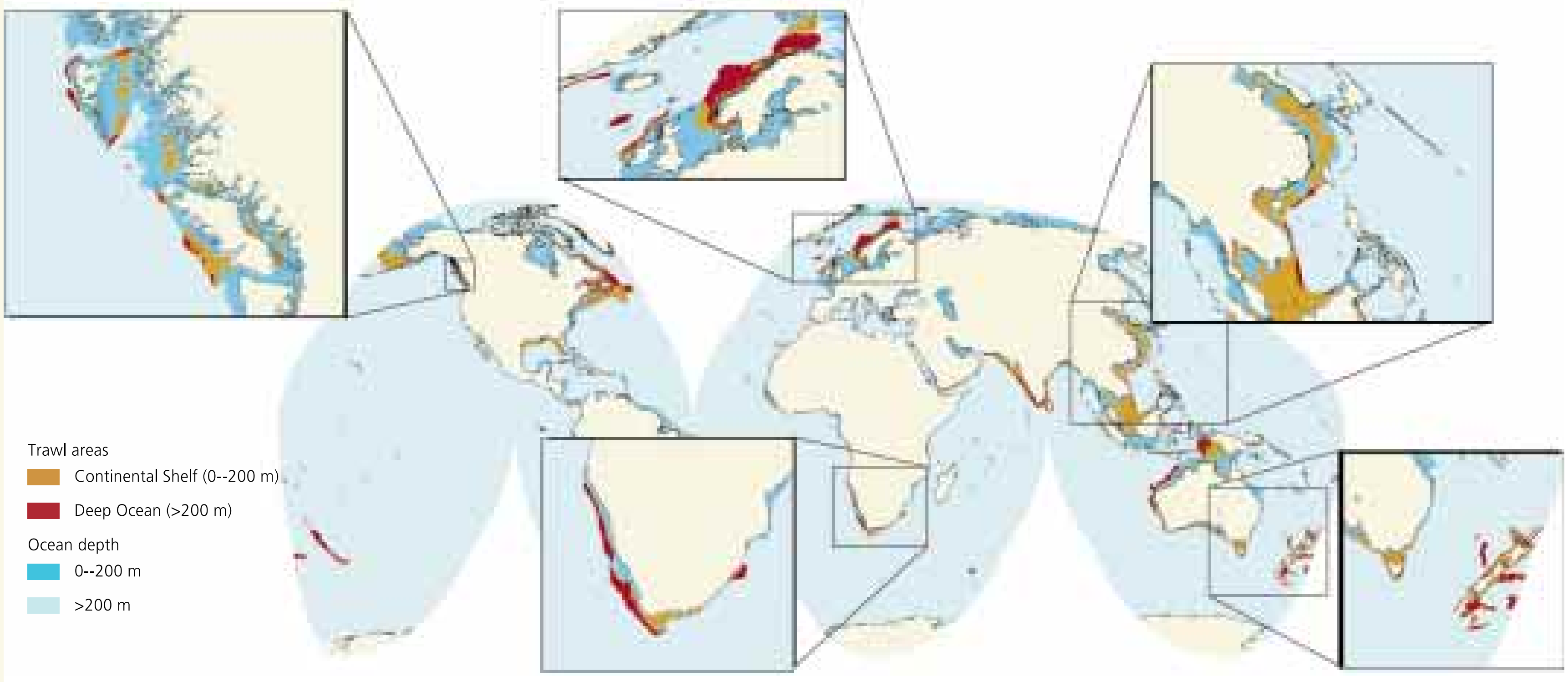
Box 2.16 Trawling

Increasingly, trawling—dragging weighted nets across the sea floor to catch shrimp and bottom-dwelling fish—is taking place beyond the continental shelf. Harvesters are trawling at depths up to 400 m and, in some places, more than 1,500 m. An estimated 14.8 million km^2 of the sea floor is swept by trawlers (Watling and Norse 1998:1190). PAGE researchers mapped the total area of trawling grounds for 24 countries for which sufficient data were available. Trawling grounds in these countries encompass 8.8 million km^2. Extrapolating from these figures suggests that the world's trawling grounds total approximately 20 million km^2, nearly two and one-half times the size of Brazil.

Trawling sea floors is a major source of pressure on the biodiversity of coastal ecosystems. Modern trawling techniques are capable not only of rapidly depleting targeted fish stocks, but also of damaging or destroying nontarget species including corals and sponges. Because deep-living species tend to grow more slowly than shallow-water species, the long-term impact of trawling is magnified as trawl depths increase.

The thick natural carpet of bottom-dwelling plants and animals is important for the survival of the fry of groundfish such as cod, which find protection there (Watling and Norse 1998:1184). Thus, destruction of sea-floor habitats is one of the principal factors in the decline of fishing stocks in heavily trawled areas.

Trawled Areas of the World



Source: Burke et al. [PAGE] 2000. The map is based on McAllister, D., et al. (1999). Data reflect preliminary results of a partial global trawling survey.

food web—plankton eaters—may begin to dominate the fish catch. This pattern of exploitation was described by Pauly et al. (1998) as "fishing down the food web," and it may signal a deterioration in the species structure of the ecosystem.

On behalf of the PAGE study, FAO analyzed global catch statistics for signs of ecosystem change, particularly for signs of "fishing down the food web." The results of the analysis show relatively strong evidence of this exploitation pattern only in the Northern Atlantic. Other regions show shifts in the relative abundance of species; but only in the North Atlantic did fishing practices seem to be the major influence causing this broad-scale ecosystem shift (Burke et al. [PAGE] 2000). In other areas such as the Mediterranean and Baltic Seas, an increase in plankton-eating fish low on the food web may indicate the presence of excess nutrients, which stimulates plankton growth and thus provides a larger food supply for plankton eaters (Caddy et al. 1998).

Continued deterioration of coastal ecosystems and the fish stocks they support could have serious implications for future fish consumption. FAO expects demand for fish and shellfish as a human food source to continue to increase well beyond today's consumption of 93 million tons per year. FAO warns that only under the most optimistic scenario—where aquaculture continues to expand rapidly and overfishing is brought under control so that fish stocks can recover—will there be enough fish to meet global demand (FAO 1999d). If the present deterioration continues, however, a substantial gap between supply and demand will likely develop, raising the price of fish and threatening food security in some regions (Williams 1996:14–15, 25–26).

The Bottom Line for Food Production. Global marine fish stocks still yield significant supplies of fish and shellfish, and marine aquaculture production is growing rapidly. However, current fishing practices show a global pattern of stock depletions and destructive fishing techniques that harm coastal ecosystems. Currently, nearly 75 percent of assessed fish stocks are either overfished or fished at their biological limit and susceptible to overfishing. Other factors, such as water pollution and loss of spawning habitat compound the harm. As a result, the capacity of the world's coastal and marine ecosystems to produce fish for human harvest is highly degraded and is continuing to decline. This could have a significant impact on nutrition and local and national economies in many countries.

WATER QUALITY

Coastal ecosystems provide the important service of maintaining water quality by filtering or degrading toxic pollutants, absorbing nutrient inputs, and helping to control pathogen populations. But the capacity of estuaries and coasts to provide these services can easily be exceeded in at least three ways. First, toxic pollutants can build to levels in fish and shellfish that are harmful to human health. Second, polluted coastal waters can harbor pathogens such as cholera and hepatitis A, which are also significant health hazards. Third, excessive nutrient inputs from agricultural and urban runoff, and sewage effluent, can cause eutrophication, whereby the additional nutrients stimulate rapid growth of algae. This in turn depletes the dissolved oxygen level in the water as it decomposes, which then harms or drives away all but the hardiest species.

Coastal pollution is most commonly measured by how much pollution is being discharged into the sea, such as the number of oil spills or the amount of sewage. However, this does not indicate what effect the pollution is having on coastal ecosystems. Consequently, the PAGE researchers examined several other indicators that better reflect biological changes in coastal ecosystems, although global data are available for relatively few of these indicators.

Oxygen Depletion

One such indicator is oxygen depletion in the water—a condition known as hypoxia. Hypoxia, which is often associated with more severe forms of eutrophication, can be quite harmful to marine organisms, especially sedentary organisms that live on the sea floor. Although historical information on hypoxia is limited, experts believe that the prevalence and extent of hypoxic zones have increased in recent decades (Diaz 1999; Diaz and Rosenberg 1995). One of the most well-known examples of hypoxic conditions is the so-called "Dead Zone" at the mouth of the Mississippi River in the northern Gulf of Mexico. Over the last 4 decades, the amount of nitrogen delivered to the coast by the Mississippi River—which drains the entire midsection of North America—has tripled, helping to create a hypoxic zone that covers 7,800–10,400 km^2 at mid-summer, when the zone is at its worst (Rabalais and Scavia 1999).

Somewhat better historical information exists for algal blooms, which also may be exacerbated by nutrient pollution.

Harmful Algal Blooms

Scientists have assembled information on harmful algal blooms (HABs)—rapid increases in the populations of algae species that produce toxic compounds. More than 60 harmful algal toxins are known today. They are responsible for at least six types of food poisoning, including several that can be lethal (McGinn 1999:21; NRC 1999:52). In the United States, HABs have caused nearly $300 million in economic losses since 1991 from fish kills, public health problems, and lost revenue from tourism and the seafood industry (McGinn 1999:25). From the 1970s to the 1990s, the frequency of recorded HABs has increased from 200 to 700 incidents per year (NRC 1999:52; HEED 1998). Some of this increase may be due to better reporting, since awareness of HABs has been heightened; but much of the increase is real, confirmed in areas with long-term monitoring programs.

Pathogens and Toxic Chemicals

Information about the ecosystem effects of pathogens, toxic chemicals, and persistent organic pollutants is less available than information about nutrient pollution. Limited data are available from some regions of the world–mostly industrialized countries–where programs have been established to monitor shellfish beds to guard against consumption of shellfish contaminated with pathogens. Data from the United States' shellfish monitoring program show gradually improving conditions; 69 percent of U.S. shellfish-growing waters were approved for harvest in 1995, up from 58 percent in 1985 (Alexander 1998:6).

Persistent Organic Pollutants

Persistent organic pollutants (POPs) include a number of chemicals that do not exist naturally in the environment, including polychlorinated biphenyls (PCBs), dioxins and furans, and pesticides such as DDT, chlordane, and heptachlor. POPs persist in the environment and can accumulate through the marine food web or in coastal sediments to a level that is toxic to aquatic organisms and humans.

"Mussel Watch" programs in North America, Latin America and the Caribbean, and France have provided a tool for monitoring changes in POPs (as well as other toxic compounds) in coastal ecosystems. These monitoring programs measure accumulations of toxic compounds in the tissues of mussels, which feed by filtering large quantities of sea water, and thus are prone to accumulate any available toxins. Mussel Watch data indicate that chlorinated hydrocarbons, though still high in coastal sediments near industrial areas and in the fat tissue of top predators such as seals, are now decreasing in some northern temperate areas where restrictions on their use have been enforced for some years (O'Conner 1998; GESAMP 1990:52). However, contamination appears to be rising in tropical and subtropical areas because of the continued use of chlorinated pesticides (GESAMP 1990:37).

The Bottom Line for Water Quality. Although there is relatively little monitoring of the actual condition of coastal waters (as opposed to the pollutants discharged into them), evidence indicates decreasing capacity of coastal ecosystems to maintain clean water in many regions of the world. In particular, the increased frequency of harmful algal blooms and hypoxia suggests that the capacity of ecosystems in these regions to absorb and degrade pollutants has been exceeded. Only within some of the OECD countries is there evidence of water quality improvements, which appear to be the result of reduced input of certain pollutants such as POPs.

BIODIVERSITY

Only 250,000 of the 1.75 million species cataloged to date in all ecosystems are found in marine environments, but experts believe that the majority of marine species have yet to be discovered and classified (Heywood 1995:116; WCMC In preparation). Life first evolved in the sea, and marine ecosystems still harbor an impressive variety of life forms. Of the world's 33 phyla (groups of related organisms), 32 are found in the marine environment, and 15 of these are found only there (Norse 1993:14–15). Coral reefs are one coastal marine ecosystem often singled out for their high biodiversity. Although coral reefs inhabit less than a quarter of 1 percent of the global sea bottom, they are the most diverse marine environment, with 93,000 species identified so far, and many more yet to be found (Reaka-Kudla 1997:88–91).

Evidence abounds of the significant pressures on coastal biodiversity. The loss of coastal habitats such as mangroves, seagrasses, and wetlands is one direct measure of declining condition of biodiversity in coastal habitats. Coral reefs face degradation at a global scale, with loss of area, overfishing of reef fish, and degradation of near-coastal water quality having inevitable consequences for reef biodiversity. A 1998 study that mapped pressures on coral reef ecosystems concluded that 58 percent of the world's reefs are at risk from human activities, with 27 percent at high risk (Bryant et al. 1998:20).

Invasive Species

One of the most significant changes in the condition of coastal biodiversity has been growth in the number and abundance of invasive species. For example, the marine ecosystems in the Mediterranean now contain 480 invasive species, the Baltic 89, and Australian waters contain 124 species (Burke et al. [PAGE] 2000). A principal source of biological invasion is from the ballast water of ships. On any one day, 3,000 different species are thought to be carried alive in the ballast water of the world's ocean fleets (Bright 1999:156).

The introduction of the Leidy's comb jellyfish from the western Atlantic into the waters of the Black Sea in 1982 provides one of the most dramatic examples of how a nonnative species can impact marine ecosystems. Unchallenged by natural predators in the Black Sea, the Leidy's comb jellyfish proliferated to a peak in 1988 of 0.9–1 billion tons wet weight (about 95 percent of the entire wet weight biomass in the Black Sea). These animals devastated the natural zooplankton stocks, which allowed the unleashing of massive algal blooms. Natural food webs were disrupted, ultimately contributing to the collapse of the Black Sea fish harvest (Bright 1999:157; Travis 1993:1366).

Other causes of biological invasion include intentional introduction of nonnative species for fisheries stocking or even for ornamental purposes, accidental introduction from aquaculture, and species migration through artificial canals, most notably through the Suez Canal from the Red Sea into the Mediterranean and vice versa.

Depletion

Another measure of direct change in the condition of coastal ecosystem biodiversity is the reduced abundance of various commercially important fish species. Excessive harvests of fish reduce their populations, sometimes to the point they become threatened with extinction, at least in substantial portions of their original range. The IUCN Red List of threatened species includes species such as the Atlantic cod, Atlantic halibut, five species of tuna, and yellowtail flounder–all species heavily exploited for food (IUCN 1996:70–88).

Disease

Additional evidence of declining condition of coastal biodiversity is found in the incidence of new diseases in coastal organisms (Harvell et al. 1999:1505). These diseases cause mass mortalities among plants, invertebrates, and vertebrates, including kelp, seagrasses, shellfish, corals, and marine mammals such as seals and dolphins. Better detection of new diseases may be a factor in the increase in reported incidents, but a careful review of the evidence shows that the number of new diseases is indeed rising (Harvell et al. 1999:1505).

Corals provide one of the best examples of the increase in disease incidence in marine ecosystems. A recent worldwide survey has documented more than 2,000 individual coral disease incidents from more than 50 countries. The earliest records date back to 1902, but the vast majority have occurred since the 1970s (Green and Bruckner In press). In Florida, for example, more than a fourfold increase in coral disease has been observed at 160 monitoring sites since 1996 (Harvell et al. 1999:1507). Although the exact causes of these diseases remain unclear, researchers have linked them to the increasing vulnerability of corals caused by stresses such as pollution and siltation.

Coral Bleaching

Coral bleaching provides a direct indicator of the condition of coral reefs. Reef-building corals contain microscopic algae (zooxanthellae) living within their tissues in a mutually dependent partnership. This partnership breaks down when corals are stressed, and one of the most common causes of such stress is exposure to higher-than-normal temperatures. When this happens, corals lose the algae from their tissues and become a vivid white color, as if they had been bleached. Although corals may recover from such an event, they may die if the cause of bleaching reaches particularly high levels or persists for a long period. Temperatures just 1–2 °C higher than average in the warm season are sufficient to cause bleaching.

Before 1979, there were no records of mass-bleaching of entire reef systems, but that changed in the last 2 decades. In 1987, 1991, and 1996, mass-bleaching was observed in 6 of the 10 major coral reef provinces of the world. The most recent and widespread bleaching event occurred from late 1997 until mid-1998, during one of the largest El Niño events of this century. Bleaching was recorded in all 10 provinces (Hoegh-Guldberg 1999:8). Coral death reached more than 90 percent in some locations; fortunately, many reefs have since recovered (Salm and Clark 2000:8). Experts believe high water temperatures caused the coral bleaching. There is no way of knowing whether human-induced climate change had any bearing, but researchers believe that the elevated sea temperatures associated with climate change could have this same detrimental effect.

Management Efforts

Evidence of the declining condition of coastal biodiversity has stimulated a number of actions by local communities, NGOs, and national governments to slow the rate of loss of particular habitats and to protect the species that remain. Although PAGE researchers did not attempt to survey the entire array of response measures, one important response has been the rapid growth in the number of marine protected areas. To date, more than 3,600 marine protected areas have been designated throughout the world (WCMC 2000). Even so, the total area under protection still falls well short of the minimum area that many marine scientists believe is necessary for the conservation of marine biodiversity.

The Bottom Line for Biodiversity. The variety of coastal habitats—from coral reefs to kelp beds—gives coastal ecosystems a wide array of species and complex communities. However, many indicators show a significant decline in this biodiversity. Degradation and area loss affect all major habitat types such as mangroves, seagrasses, coral reefs, and coastal wetlands. Invasive species have made significant inroads in many marine environments, especially near ports and other highly trafficked areas. Heavily exploited fish species such as cod and haddock have recently been listed as threatened species. Disease incidence among marine mammals and coral reefs has risen dramatically, as have coral bleaching events. Overall, the capacity of marine ecosystems to support their normal biodiversity has been greatly diminished.

SHORELINE PROTECTION

The economic and human costs of coastal storm damage are growing as more people expand into coastal settlements and put lives and property at risk. Economic losses in Europe from floods and landslides between 1990 and 1996 were four times greater than the losses suffered in the 1980s and more than twelve times those of the 1960s (EEA 1998:274). From 1988 to 1999, the United States sustained 38 weather-related disasters causing damage that reached or exceeded $1 billion each, for a total cost in excess of $170 billion (NCDC 2000). In both Europe and the United States, many of these weather-related natural disasters involved flooding in coastal areas or, in the case of the United States, hurricane impacts in coastal regions. Worldwide, more than 40 million people per year are currently at risk of flooding due to storm surges (IPCC 1996:292).

Healthy coastal ecosystems cannot completely protect communities from the impacts of storms and floods, but they do play an important role in stabilizing shorelines and buffering coastal development from the impact of storms, wind, and waves. For example, Sri Lanka spent US$30 million on revetments, groins, and breakwaters in response to severe coastal erosion that occurred in areas where coral reefs were heavily mined (Berg et al. 1998:630). Japan spent roughly 4.5 trillion yen (US$41 billion) on shoreline protection projects from 1970 to 1998 (Japanese Ministry of Commerce 1998).

For many countries, protection of coastal ecosystems is likely to be one of the most cost-effective means of protecting coastal development from the impact of storms and floods. Clearly, with the substantial loss in extent of various coastal ecosystems, the ability to provide this service of shoreline protection has significantly diminished in most nations.

The Bottom Line for Shoreline Protection. There is no doubt that the dramatic loss of coastal habitats around the world has diminished the capacity of coastal ecosystems to protect human settlements from storms. There are few estimates of how great the economic cost of the loss of this service might be, but losses from storm damage already cost billions of dollars annually. With intensive development of the world's coasts proceeding rapidly, the value of the coastal protection service will undoubtedly rise quickly, too.

COASTAL TOURISM AND RECREATION

Travel and tourism, encompassing transport, accommodation, catering, recreation, and services for travelers, is the world's largest industry and the fastest growing sector of the global economy. The World Travel and Tourism Council projected travel and tourism would generate US$3.5 trillion and account for more than 200 million jobs in 1999—about 8 percent of all jobs worldwide (WTTC 1999). In most countries, coastal tourism is the largest sector of this industry and in a number of countries, particularly small island developing states tourism contributes a significant and growing portion to GDP and foreign exchange. Travel and tourism in coastal zones can promote both conservation and economic development, if properly managed.

Most statistics related to tourism are aggregated by country, and agencies and organizations compiling statistics typically do not distinguish inland from coastal tourism. With this in mind, PAGE researchers chose the Caribbean—where the vast majority of tourism is coastal or marine in nature—to assess the condition of coastal ecosystems with regard to their potential to support the recreation and tourism industry.

In 1998, travel and tourism in the Caribbean accounted for more than US$28 billion or about 25 percent of the region's total GDP. The industry provided more than 2.9 million jobs in 1998 (more than 25 percent of all employment), with projections in excess of 3.3 million jobs by 2005 (WTTC/WETA 1998). The number of tourists arriving in the Caribbean is growing rapidly. Over the next decade, tourist arrivals are expected to increase by 36 percent (Caribbean Tourism Organization 1997).

Ecotourism

Different types of tourism differ in their benefits to local economies as well as in their environmental impacts. In the Caribbean, for example, most of the prosperous hotels are large resorts; nature-based tourism (ecotourism) is a small niche market. Worldwide, relatively few local communities have realized significant benefits yet from nature-based tourism on their own lands or in nearby protected areas. The participation of local communities in nature tourism has been constrained by a lack of relevant knowledge and experience, lack of access to capital for investment, inability to compete with well-established commercial operations, and simple lack of ownership rights over the tourism destinations (Wells 1997:iv).

Protected areas often supply the most valuable part of the nature tourism experience, but capture little of the economic value of tourism in return (Wells 1997:iv). Although many governments have successfully increased tourist numbers by marketing their country's nature tourism destinations, most have not invested sufficiently in managing those natural assets or in building the infrastructure needed to support nature tourism. Thus sensitive sites of ecological or cultural value have been exposed to risk of degradation by unregulated tourism development, too many visitors, and the impact of rapid immigration linked to new jobs and business opportunities (Wells 1997:iv–v) (see Box 1.15 Ecotourism, pp. 34–35).

Tourism Related Pressures

Tourism has a tremendous potential to bring economic prosperity and development, including environmental improvements, to the destinations in which it operates. However, poorly planned and managed tourism can harm the very resources on which it is based. Adverse impacts of tourism in the Caribbean include scarring mountain faces with condominium and road construction; filling wetlands and removing mangrove forests for resort construction; losing beach area and lagoons to pollution and to sand mining, dredging, and sewage dumping; and damaging coral reefs with anchoring, sedimentation, and marina development (UNEP/CEP 1994). A 1996 Island Resources Foundation study found that tourism was a major contributor to sewage and solid waste pollution in virtually every country in the Caribbean, as well as the prime contributor to coastal erosion and sedimentation (IRF 1996). Since the success of tourism in the Caribbean has been built on the appeal of excellent beaches and a high-class marine environment suitable for a range of outdoor activities, this inattention to the harmful impacts of tourism itself directly threatens the industry's growth in the region.

? **The Bottom Line for Tourism and Recreation.** Information is not available to accurately judge whether the capacity of coastal ecosystems to support tourism is being diminished at a global scale. However, in some areas, such as parts of the Caribbean region, there is clear evidence of degradation. Nonetheless, this industry has the potential—and indeed incentive—to bring long-term sustainable benefits to coastal communities without degrading the resource on which it depends.

FOREST ECOSYSTEMS

Forests, woodlands, and scattered trees have provided humans with shelter, food, fuel, medicines, building materials, and clean water throughout recorded history. In recent decades they have become a source of new goods and services including pharmaceuticals, industrial raw materials, personal care products, recreation, and tourism. Forests regulate freshwater quality by slowing soil erosion and filtering pollutants, and they help to regulate the timing and quantity of water discharge. In addition, forests harbor much of the world's biological diversity. Although scientists know that most of the world's species have not yet been identified, they think that at least half and possibly well over two-thirds of these species are found in forest ecosystems–in particular, in tropical and subtropical forests (Reid and Miller 1989:15).

Forests provided an important springboard for industrial and socioeconomic development for northern hemisphere countries. They were often recklessly used, but former forested lands usually became productive in new ways. For example, wide tracts of forest were converted permanently to agriculture. In some areas, such as parts of the eastern United States, forests that had been clear-cut have regrown. For now, the northern hemisphere and temperature zone industrialized countries–with the exception of Japan–are broadly self-sufficient in wood, though tropical woods must still be imported.

Forests are now playing a similar socioeconomic development role in many developing countries. That role is more critical in these nations because forests supply industrial wood both for domestic consumption and for export to obtain foreign currency. At the same time, traditional goods and services–woodfuels, food, and medicines–continue to support the livelihoods of many rural populations. Millions of people in tropical and subtropical countries still depend entirely on forest ecosystems to meet their every need.

From the range of goods and services provided by forest ecosystems, PAGE focused on five of the most important for human development and well-being: timber production and consumption, woodfuel production and consumption, biodiversity, watershed protection, and carbon storage.

(continues on p. 90)

Conditions and Changing Capacity

Box 2.17 Taking Stock of Forest Ecosystems

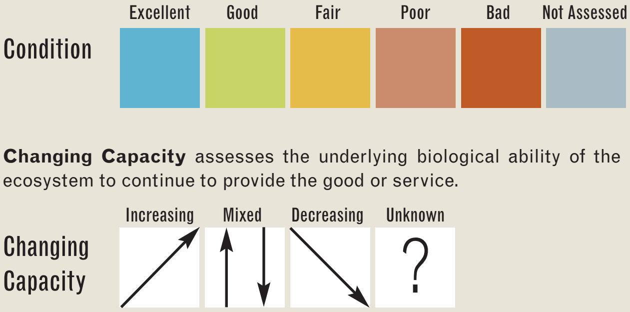
Highlights

- Forests cover about 25 percent of the world's land surface, excluding Greenland and Antarctica. Global forest cover has been reduced by at least 20 percent since preagricultural times, and possibly by as much as 50 percent.
- Forest area has increased slightly since 1980 in industrial countries, but has declined by almost 10 percent in developing countries. Tropical deforestation probably exceeds 130,000 km^2 per year.
- Less than 40 percent of forests globally are relatively undisturbed by human action. The great majority of forests in the industrial countries, except Canada and Russia, are reported to be in "semi-natural" condition or converted to plantations.
- Many developing countries today rely on timber for export earnings. At the same time, millions of people in tropical countries still depend on forests to meet their every need.
- The greatest threats to forest extent and condition today are conversion to other forms of land use and fragmentation by agriculture, logging, and road construction. Logging and mining roads open up intact forest to pioneer settlement and to increases in hunting, poaching, fires, and exposure of flora and fauna to pest outbreaks and invasive species.

Key

Condition assesses the current output and quality of the ecosystem good or service compared with output and quality of 20–30 years ago.

Changing Capacity assesses the underlying biological ability of the ecosystem to continue to provide the good or service.



Scores are expert judgments about each ecosystem good or service over time, without regard to changes in other ecosystems. Scores estimate the predominant global condition or capacity by balancing the relative strength and reliability of the various indicators. When regional findings diverge, in the absence of global data, weight is given to better-quality data, larger geographic coverage, and longer time series. Pronounced differences in global trends are scored as "mixed" if a net value cannot be determined. Serious inadequacy of current data is scored as "unknown."

FIBER PRODUCTION

Fiber production has risen nearly 50 percent since 1960 to 1.5 billion cubic meters annually. In most industrial countries, net annual tree growth exceeds harvest rates; in many other regions, however, more trees are removed from production forests than are replaced by natural growth. Fiber scarcities are not expected in the foreseeable future. Plantations currently supply more than 20 percent of industrial wood fiber, and this contribution is expected to increase. Harvesting from natural forests will also continue, leading to younger and more uniform forests.

WATER QUALITY AND QUANTITY

Forest cover helps to maintain clean water supplies by filtering freshwater and reducing soil erosion and sedimentation. Deforestation undermines these processes. Nearly 30 percent of the world's major watersheds have lost more than three-quarters of their original forest cover. Tropical montane forests, which are important to watershed protection, are being lost faster than any other major forest type. Forests are especially vulnerable to air pollution, which acidifies vegetation, soils, and water runoff. Some countries are protecting or replanting trees on degraded hillslopes to safeguard their water supplies.

BIODIVERSITY

Forests, which harbor about two-thirds of the known terrestrial species, have the highest species diversity and endemism of any ecosystem, as well as the highest number of threatened species. Many forest-dwelling large mammals, half the large primates, and nearly 9 percent of all known tree species are at some risk of extinction. Significant pressures on forest species include conversion of forest habitat to other land uses, habitat fragmentation, logging, and competition from invasive species. If current rates of tropical deforestation continue, the number of all forest species could be reduced by 4-8 percent.

CARBON STORAGE

Forest vegetation and soils hold almost 40 percent of all carbon stored in terrestrial ecosystems. Forest regrowth in the northern hemisphere absorbs carbon dioxide from the atmosphere, currently creating a "net sink" whereby absorption rates exceed respiration rates. In the tropics, however, forest clearance and degradation are together a net source of carbon emissions. Expected growth in plantation area will absorb more carbon, but likely continuation of current deforestation rates will mean that the world's forests remain a net source of carbon dioxide emissions and a contributor to global climate change.

WOODFUEL PRODUCTION

?

Woodfuels account for about 15 percent of the primary energy supply in developing countries and provide up to 80 percent of total energy in some countries. Use is concentrated among the poor. Woodfuel collection is responsible for much local deforestation in parts of Asia, Africa, and Latin America, although two-thirds of all woodfuel may come from roadsides, community woodlots, and wood industry residues, rather than forest sources. Woodfuel consumption is not expected to decline in coming decades, despite economic growth, but poor data make it difficult to determine the global supply and demand.

Data Quality

FIBER PRODUCTION

Generally good global data on industrial roundwood production by country are published annually by the Food and Agriculture Organization (FAO) and the International Tropical Timber Organization (ITTO). Production is recorded by value and by volume in cubic meters per year. Various studies forecast future production and consumption rates. Forest inventory data, recording annual rates of tree growth, tree mortality, size and age of stands, and harvest rates, are generally available for industrial countries but are incomplete and must be estimated for many developing countries. Information on plantation extent and productivity varies widely among countries.

WATER QUALITY AND QUANTITY

Global data on current forest cover and historic loss in major watersheds have been compiled by World Resources Institute (WRI). Data on water runoff, soil erosion, and sedimentation in deforested watersheds are available mostly at regional or local levels. Evidence of the importance of forest cover in regulating water quality and quantity is based on experience in forests managed primarily for soil and water protection in the industrial countries and on studies that value forests according to the avoided costs of constructing water filtration plants. Forest degradation by air pollution in Europe is surveyed by the UN Economic Commission for Europe (UN-ECE).

BIODIVERSITY

Global data sets are few, and evidence is often anecdotal. Forests with high conservation value are identified by field observation and expert opinion. More quantitative information on threatened species is available globally for forest trees and regionally for some birds, butterflies, moths, and larger mammals. Good-quality data on restricted-range birds are available, as are data on threatened birds in the neotropics. Identification of global centers of plant diversity is based on field observation and expert opinion.

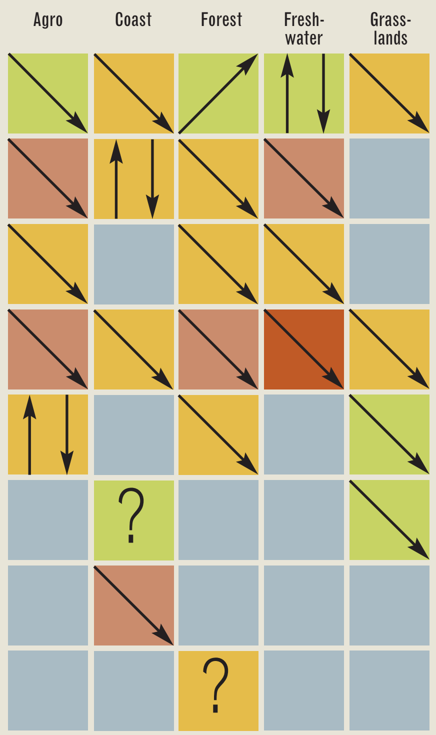
CARBON STORAGE

Methodologies for estimating the size of carbon stores in biomass and soils are developing rapidly. This study relied on the estimates of carbon stored in above- and below-ground live vegetation developed by Olson. This data set was modified by updating carbon storage estimates to accord with the land-cover map from the International Geosphere-Biosphere Programme (IGBP), delineated by global ecosystems. Estimates of soil carbon stores were based on the International Soil Reference and Information Centre—World Inventory of Soil Emission Potentials (ISRIC-WISE) Global Data Set of Derived Soil Properties.

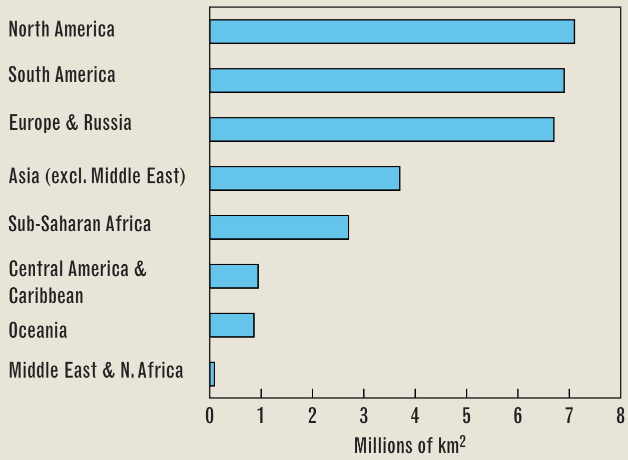
WOODFUEL PRODUCTION

The International Energy Agency (IEA) holds good recent data on wood energy production and consumption in industrial countries, where most wood energy is derived from industrial wood processing residues. Global time series data on woodfuel and charcoal production, available from FAO, are modeled or estimated from household surveys. Data on woodfuel plantations and nonforest sources of production (such as public lands) are patchy. Human dependence on woodfuel in developing countries is largely inferred from information on availability and price of other energy sources.

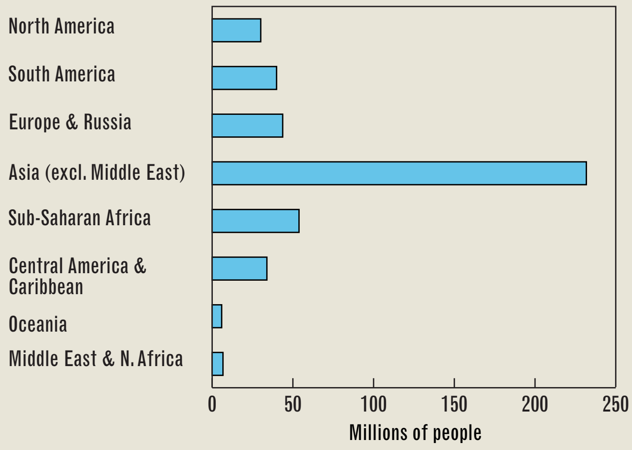
Scorecard



Area of Forest Ecosystems



Population of Forest Ecosystems



Forest Extent and Modification

More than 90 different definitions of "forest" are in use throughout the world, complicating the effort to measure and evaluate global forest ecosystems. PAGE researchers adopted the definition used by IGBP, which defines *forest ecosystems* as "the area dominated by trees forming a closed or partially closed canopy" (Box 2.18 The Changing Extent of Forests). Forest ecosystems include tropical, subtropical, temperate, and boreal forests as well as woodlands.

Using the IGBP definition, and using data from satellite imagery, the PAGE study calculated the total forest area in 1993 as 29 million km^2, approximately 22 percent of the world's land area (excluding Antarctica and Greenland). This estimate differs somewhat from that calculated by FAO, which is compiled from national forest inventories rather than satellite data and reflects a somewhat different definition. (FAO defines forests to be all areas having a minimum crown cover of 10 percent and minimum tree height of 5 m.) The FAO estimate puts global forest area in 1995 at 34.5 million km^2 (FAO 1997a:185), or 27 percent of the world's land area.

The area of transition between forest and other land cover is one of the most dynamic portions of forest ecosystems and makes up a significant percentage of forest ecosystems in many parts of the world. Nearly 4 million km^2 in Africa now qualifies as forest/cropland mosaics; cropland accounts for between 30 percent and 40 percent of the vegetation cover and forests account for some part of the remainder. Because these forest transition zones typically have at least 10 percent crown cover and still contain more than 30 percent agricultural land, PAGE researchers–as well as FAO and other researchers–included them in the analyses of both forest and agricultural ecosystems.

The change from closed forest to a forest-agriculture mosaic inevitably changes the goods and services that the "forest" provides. The transition zone could, in principle, be managed sustainably to provide timber, tree and fodder crops, and shelter for field crops, fuelwood, and habitat for wildlife. But without effective management, land-use change and ecosystem degradation in transition zones can proceed rapidly. Currently, neither national nor global forest inventories offer insight into how fast forest transition zones are expanding or how well they are functioning as ecosystems.

DEFORESTATION AND FOREST LOSS

Human actions have caused the world's forest cover to shrink significantly over the last several millennia, but it is difficult to specify exactly how much. Scientists can't precisely determine what the original extent of forest was prior to human impact. Forests are not static; their size and composition have evolved with changing climate. However, scientists can determine–by using knowledge of the soil, elevation, and climatic conditions required by forests–where forest could potentially exist if it were not for human actions. Comparing this "potential" forest area to today's actual forest cover gives a plausible estimate of historical forest loss.

Using this approach, Matthews (1983:474–487) estimated that as of the early 1980s, humans had reduced global forest cover about 16 percent. Updating this study with more recent deforestation data available from FAO brings the total loss of original forest cover to roughly 20 percent. Historical forest loss could be much higher, however. A 1997 study by WRI, which used a higher resolution map of potential forest than the Matthews study, estimates that original forest cover has been reduced by nearly 50 percent (Bryant et al. 1997:1).

Calculating current deforestation rates is every bit as challenging as estimating past forest loss. FAO estimates that forested area increased by 0.2 million km^2 (2.7 percent) in industrialized countries between 1980 and 1995 (Matthews et al. [PAGE] 2000; FAO 1997a:17), while it decreased by 2 million km^2 (10 percent) in developing countries (FAO 1997a:16–17). FAO also estimates that the rate of forest loss in developing countries decreased by 11 percent between 1980–90 and 1990–95, from 154,600 km^2 to 130,000 km^2 annually (FAO 1997a:18). However, the uncertainty in these estimates is high. Measuring deforestation on a global level is complicated by a scarcity of reliable direct measurements and the expense and difficulty of satellite measurements. As a result, estimates of the current deforestation rate vary widely, from about 50,000 km^2 to 170,000 km^2/year (Tucker and Townshend 2000:1461). Although the FAO estimate of 130,000 km^2/year is widely quoted, more recent studies–notably of Indonesia and Brazil–suggest that it underestimates actual forest loss.[4]

The underlying causes of forest loss have been the focus of many studies and reports over the past several decades. In its 1997 forest assessment, FAO attributes forest loss in Africa principally to the expansion of subsistence agriculture, under pressure from rural population growth (FAO 1997a:20). Forest loss in Latin America was due more to large-scale cattle ranching, clearance for government-planned settlement schemes, and hydroelectric reservoirs. FAO found forests in Asia to be subject about equally to pressure from subsistence agriculture and economic development schemes (FAO 1997a:20).

Historically, woodfuel collection was considered a leading factor in deforestation in some regions of the world; however, better information is undermining that conclusion. FAO does not consider woodfuel collecting to be an important cause of deforestation, although it can add to pressures that degrade forest quality and health. As much as two-thirds of woodfuel is obtained from nonforest sources such as woodlands, roadside verges, and wood industries (FAO 1997c:21).

FOREST FRAGMENTATION

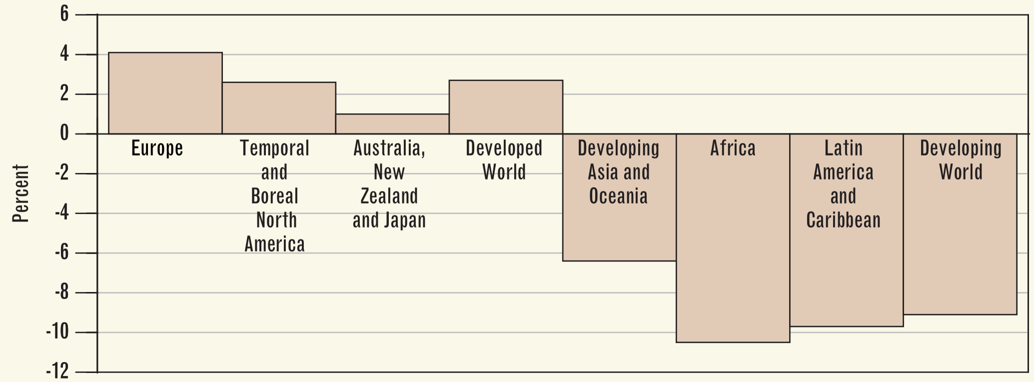
Although change in actual extent clearly has an impact on the various goods and services that forests provide, fragmentation of forests can have just as great an impact. As part of the

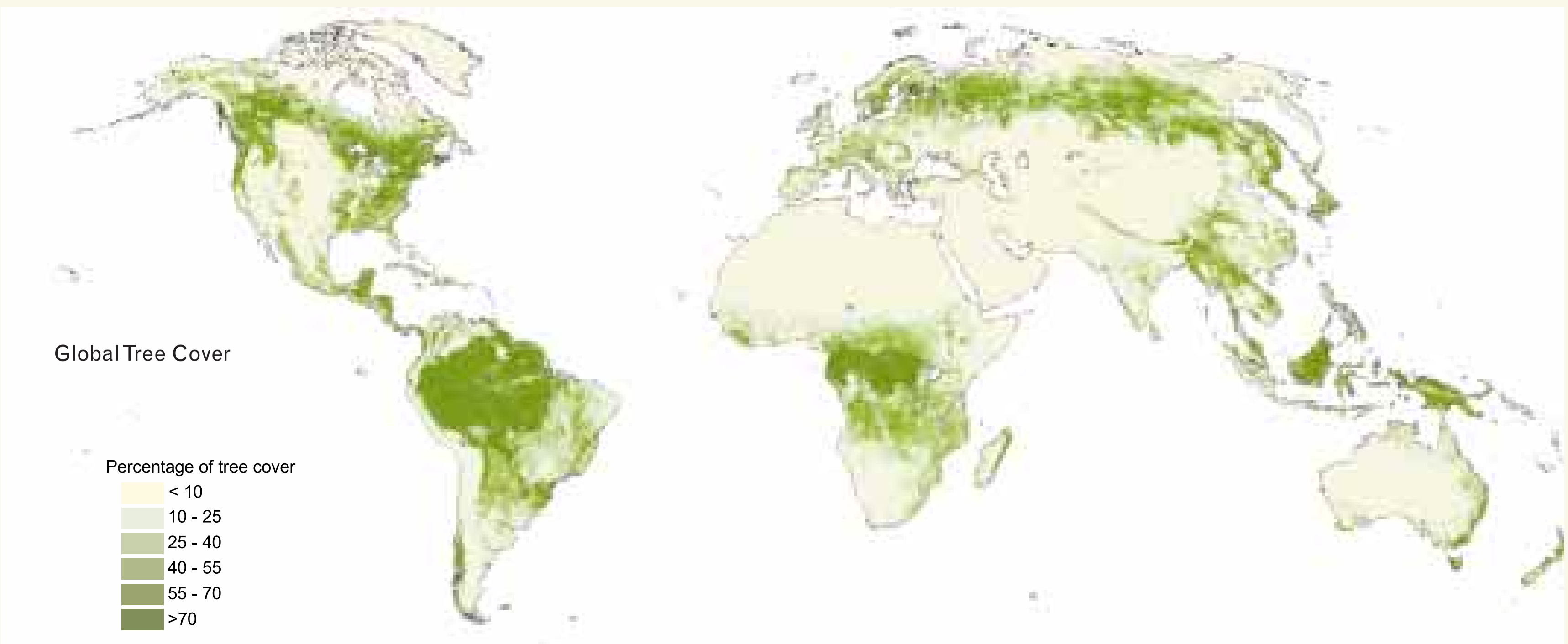
Box 2.18 The Changing Extent of Forests

Since the 16th century, the forests of the northern temperate zone have suffered the most extensive losses as a result of human activity. In recent years, they have begun to recover. However, these gains have been more than offset by rapid decreases in the more extensive and species-rich forests of the developing world.

Many of the world's trees grow within areas that are only partially forested. These lands provide many of the goods associated with forests, especially woodfuel, species habitat, and soil protection. Such areas are particularly vulnerable to clearance, however, since they are often more accessible and less likely to be legally protected than forest areas with higher tree cover.

Change in Forest Area from 1980 to 1995





Sources: Matthews et al. [PAGE] 2000. Map is based on Defries et al. (2000). Figure is based on FAO (1997a).

characterization of the extent and change of forests, PAGE researchers developed an indicator of forest fragmentation based on the world's growing road network. Roads provide development benefits, but they also fragment otherwise continuous stretches of forest.

The impact of fragmentation is twofold. First, fragmentation directly affects species biodiversity by diminishing the amount of natural habitat available, blocking migration routes, providing avenues for invasion by nonnative species, and changing the microclimate along the remaining habitat edge. Second, roads provide access for hunting, timber harvest, land clearing, and other human disturbances that further change the characteristics of the local ecosystem.

Forests are naturally fragmented to some extent by such features as rivers, mountain ranges, natural fires, and storm damage. Road networks, however, provide a relatively unambiguous and globally applicable indicator of human-caused fragmentation, albeit a conservative indicator since human actions fragment forests in other ways as well. To demonstrate the potential use of such a fragmentation indicator, the PAGE study included a pilot analysis of forest fragmentation in Central Africa in which researchers documented the effect of road building in breaking up large forest blocks (Box 2.19 Fragmentation of Forests in Africa). In the absence of roads, large continuous blocks of habitat–more than 10,000 km^2–would naturally make up 83 percent of the forest area in Central Africa. However, in the presence of the existing road network, large forest blocks account for just 49 percent of the forest area (Matthews et al. [PAGE] 2000).

FOREST FIRES

In addition to outright conversion and fragmentation of forests, a third human-caused pressure is the frequency and intensity of fires. Wildfires are a natural and necessary phenomenon in many forest ecosystems, helping to shape landscape structure, improve the availability of soil nutrients, and initiate natural cycles of plant succession. In fact, some plant species can't reproduce without periodic fire.

The number of human-caused fires, however, greatly exceeds naturally occurring fires. Fires are set intentionally for timber harvesting, land conversion, or shifting agriculture, and also in the course of disputes over property and land rights. Tropical forest fires were unusually severe in 1997–98, following less-than-average rainfalls due to El Niño. The number of fires in Brazil increased dramatically between 1995 and 1998, spreading from agricultural areas into moist forest that traditionally had not burned (Elvidge et al. 1999). Brazilian fires increased 50 percent between 1996 and 1997, and another 86 percent between 1997 and 1998 (FAO 1999:3)(Box 2.20 Forest Fires).

Globally, humans initiate as much as 90 percent of total biomass burning (including savannas) (Levine et al. 1999:iv). Human-caused fires are thus already reshaping forest ecosystems and their impact could grow substantially. Recent studies indicate that fires in tropical moist forests create feedback loops that increase the forest's susceptibility to subsequent fires. The first fire serves to open up the canopy, allowing sun and air movement to increase drying of the forest. Previously fire-killed trees increase fuel availability, and invading grasses and weeds add combustible live fuels. Second and third fires are faster-moving, more intense, and of longer duration. Initial fires have been demonstrated to kill no more than 45 percent of trees more than 20 cm in diameter, whereas in recurrent fires, up to 98 percent of trees are liable to be killed (Cochrane et al. 1999:1832–1835). This enhanced fire cycle raises the risk that large areas of tropical forest could be transformed into savanna or scrub.

The social and economic costs of forest fires are also significant. An estimated 20 million people were at risk of respiratory problems from the recent fires in Southeast Asia (Levine et al. 1999:12), with economic damages (excluding health impacts) conservatively estimated at $4.4 billion (Economy and Environment Programme for Southeast Asia 1999, cited in Levine et al. 1999:14).

Despite the advent of satellite imagery and the growing significance of fires to the condition of global forests, no reliable global statistics are available for the total forest area burned annually. Within boreal forests, detailed records for the United States and Canada reveal that the annual area burned has more than doubled in the past 30 years (Kasischke et al. 1999:141, 147). Information about tropical forests is more uncertain. For example, estimates of the total area burned in Indonesia during 1997–98 range from 6,000 km^2 (official Indonesian estimates) to more than 45,000 km^2 (unofficial estimate based on analysis of satellite images) (Levine et al. 1999:8–10).

Assessing Goods and Services

FIBER

Commercial timber production is a major global industry. In 1998, global production of industrial roundwood–which includes all wood not used as fuel–was 1.5 billion m^3 (FAO 2000). In the early 1990s, production and manufacture of industrial wood products contributed about US$400 billion to the global economy, or about 2 percent of global GDP (Solberg et al. 1996:48). North America and Europe dominate production, but the timber industry is of greater economic importance to developing countries such as Cambodia, Solomon Islands, and Myanmar, where wood exports can account for more than 30 percent of international trade (FAO 1997a:36).

The three main sources of industrial roundwood are primary forests, secondary-growth forests, and plantations. Secondary-growth forests have replaced virtually all of the primary or original forests of eastern North America, Europe, and large parts of South America and Asia. Estimates of plantation area vary, partly because of differences in how plantations are defined. Plantations are generally defined as forests that have considerable human intervention in their establishment and management, but no clear line divides a "plantation" from an intensively managed "secondary forest."

FAO estimates that industrial roundwood plantations account for approximately 3 percent of total forest area, or about 1 million km^2. However, they provide about 22 percent of the world's industrial roundwood supply (Brown 1999:7, 41). Plantation forest area is highly concentrated. Five countries–China, Russia, United States, India, and Japan–account for 65 percent of global plantation forests (Brown 1999:15).

Assessing a forest's capacity to produce timber is difficult in part because the cycle of harvest and regrowth stretches over many decades. One clear indicator that a forest's capacity to produce timber is being degraded would be evidence of harvest rates greater than the rate of tree growth. According to preliminary data (FAO 1998), it appears that many countries are cutting more timber than grows each year.

In most European countries and the United States, the volume of wood felled is less than the volume of yearly growth (FAO 1998:Technical Annex 1). However, in some countries, like the United States, even though net removal is less than net growth, the rate of growth has diminished in recent years (Haynes et al. 1995:43). This imbalance suggests that current timber production may not be sustainable in the long term (Johnson and Ditz 1997:226). Moreover, information about the diameter of trees in the United States indicates a long-term trend toward smaller, younger trees, and a simplified forest structure, with less diversity of sizes and ages of trees. This could, in turn, reduce the diversity of plant and animal species the forest supports.

For most developing nations, there is a lack of reliable data on net annual forest growth and removal rates and the age of trees–information that is needed to accurately assess the long-term condition of forests. Even so, there is considerable evidence that in some regions, harvest rates greatly exceed regrowth. Typically, in such regions, once forest is cleared, the land is eventually converted to other uses. In other regions, overall harvest may be less than annual growth, but not for certain highly valued species such as mahogany, which are harvested at rates far in excess of their growth rate, which will lead to eventual depletion.

The Bottom Line for Fiber Production. Increasing demand for wood fiber has increased production and, in particular, increased the extent of plantations, which now provide 22 percent of the world's industrial wood. This has not reduced pressure on natural forests. Although forests that have been in timber production for decades show no distinct signs that their capacity to maintain that production is in doubt, some indicators give cause for concern. In developing countries, evidence exists of degradation of timber production capacity, and in these regions, after forests are harvested, the land is often converted to other uses.

WOODFUELS

Fuelwood, charcoal, and other wood-derived fuels (collectively known as woodfuels) are the most important form of nonfossil energy. Biomass energy, which includes woodfuels, agricultural residues, and animal wastes, provides nearly 30 percent of the total primary energy supply in developing countries. Rough estimates indicate that more than 2 billion people depend directly on biomass fuels as their primary or sole source of energy. Woodfuels are the dominant form of biomass energy for many countries, although the data are too sparse to know whether this is true for all countries (IEA 1996:II.289–308, III.31–187).

Available data show woodfuels account for more than half of biomass energy consumed in developing countries and, if China is excluded (where agricultural residues are a particularly important fuel), they account for about two-thirds (IEA 1996:II.289–308, III.31–187)(Box 2.21 Global Use of Woodfuels). Woodfuels are also significant sources of energy in some developed countries. Wood energy supplies nearly 17 percent of total energy consumption in Sweden and 3 percent in the United States (FAO 1997b:7, 11). Economic growth in developing countries has reduced the proportion of energy provided by woodfuel, but overall biomass energy consumption has continued to rise.

Will there be enough woodfuel in the future? Already, in some regions, particularly near urban centers, woodfuel availability has decreased significantly in recent decades. In some cases, production has been maintained even in the face of growing demand by tree planting programs and community woodlots. By 2010, an estimated 2.3–2.4 billion m^3 of fuelwood and charcoal will be available (Nilsson 1996), approximately 30 percent more than in 2000. However, woodfuel demand by 2010 is forecast to be 2.4–4.3 billion m^3 (Matthews et al. [PAGE] 2000). Whether a regional or even global woodfuel crisis will develop depends on a variety of factors such as the affordability of alternative fuels. Nevertheless, there is little doubt that growing woodfuel scarcity will increase the economic burden on the poor in some regions.

Perhaps the most striking feature of this information about woodfuels is how limited and imprecise the information actually is. Woodfuel is a critical energy source for a large percentage of the world's population but, despite the efforts of international institutions such as FAO and the International Energy Agency, the information needed to determine whether ecosystems will be able to meet the growing demand is largely unavailable.

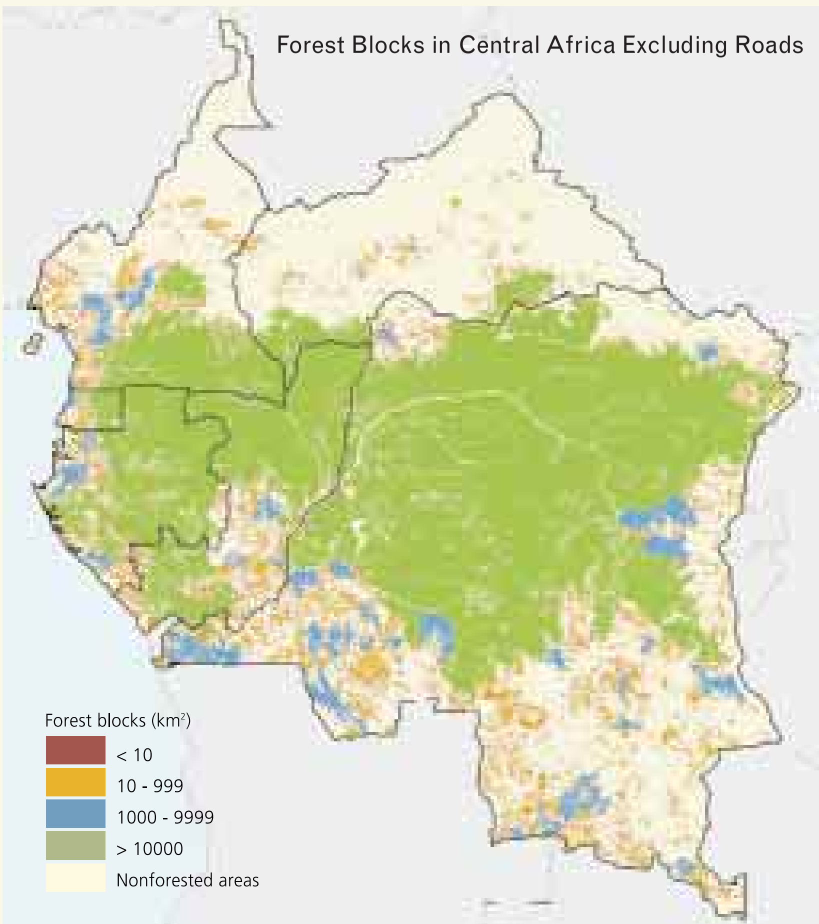
(continues on p. 99)

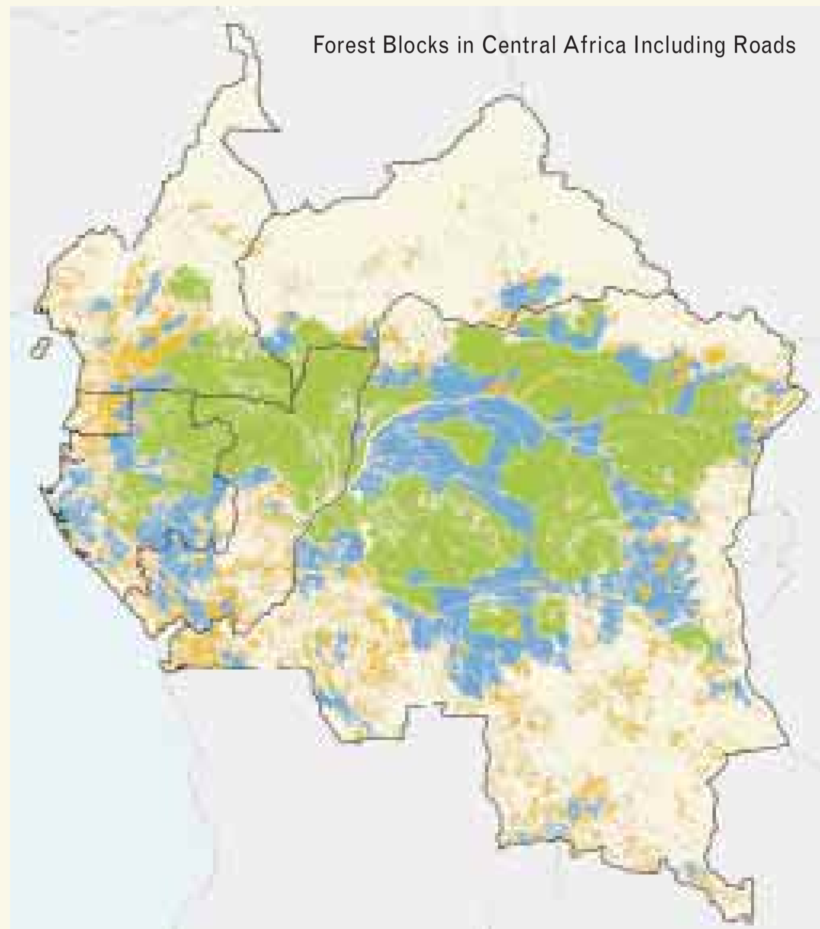
Box 2.19 Fragmentation of Forests in Africa

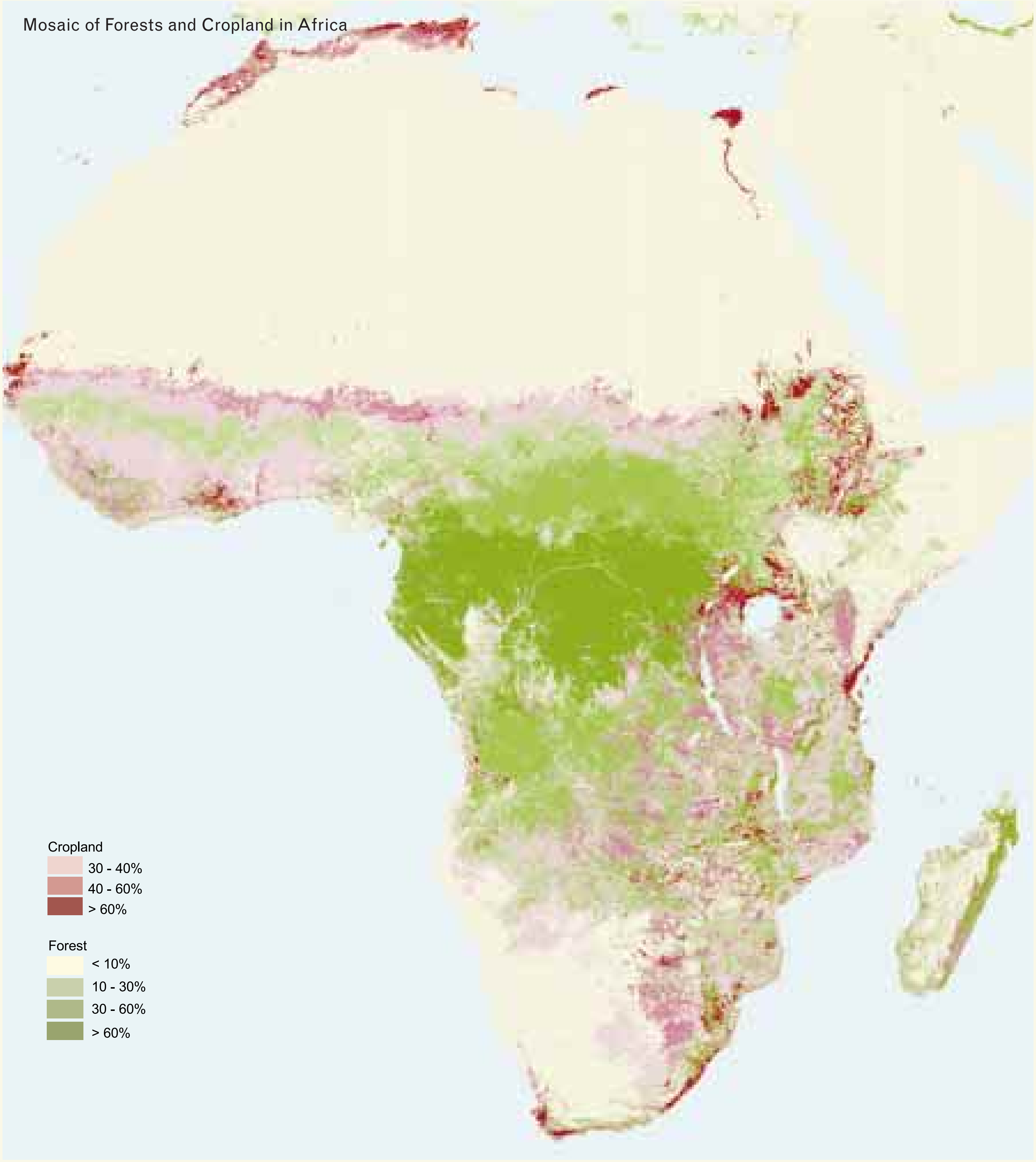
Fragmentation can affect forest ecosystems as profoundly as changes in the total tree cover. In Africa and many other parts of the world, the effect of human encroachment on closed canopy forests has been to create forest "transition zones," in which forested land is interspersed with cropland to form an intricate mosaic, as shown on the facing page.

Road networks provide an unambiguous and easily measured, if conservative, indicator of the extent of human-induced fragmentation. When a road is built through a forest, it breaks up species habitats, sometimes into parcels too small to support viable breeding populations. It also provides avenues for invasion by nonnative species and alters the microclimate along the remaining habitat edge. Roads open up previously inaccessible areas of forest to hunting, timber cutting, and clearing for cultivation.

The maps below show the distribution of various sized blocks of forest in central Africa with and without roads. Without roads, continuous blocks of habitat of more than 10,000 km^2 make up 83 percent of the forested area's total extent. When roads are taken into account, this proportion drops to only 49 percent of the total.





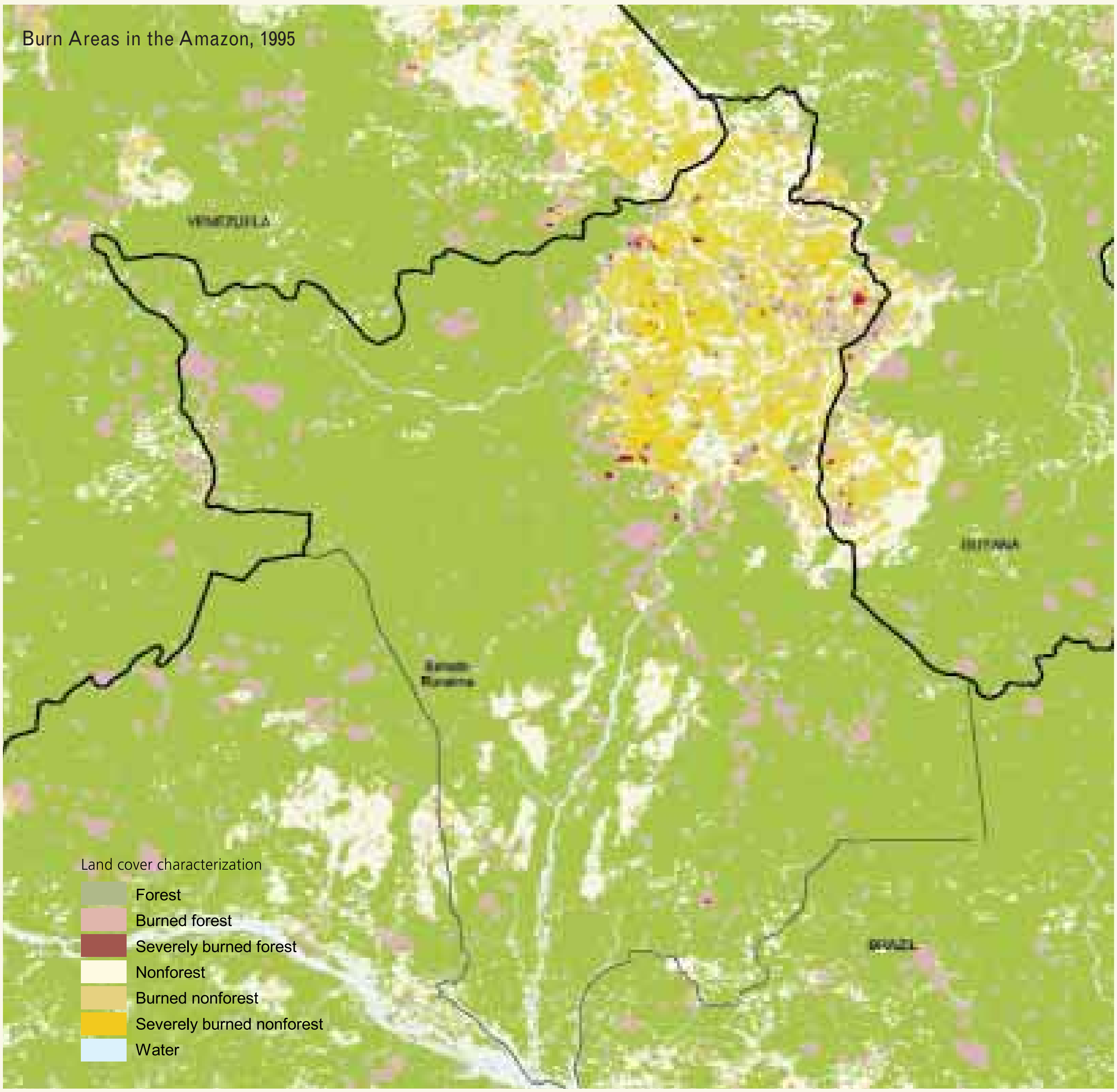


Sources: Matthews et al. [PAGE] 2000. The road fragmentation maps on the previous page are based on CARPE (1998) and Global Land Cover Characteristics Database Version 1.2 (Loveland et al. [2000]). The map above is based on Defries et al. (2000) and Global Land Cover Characteristics Database Version 1.2 (Loveland et al. [2000]).

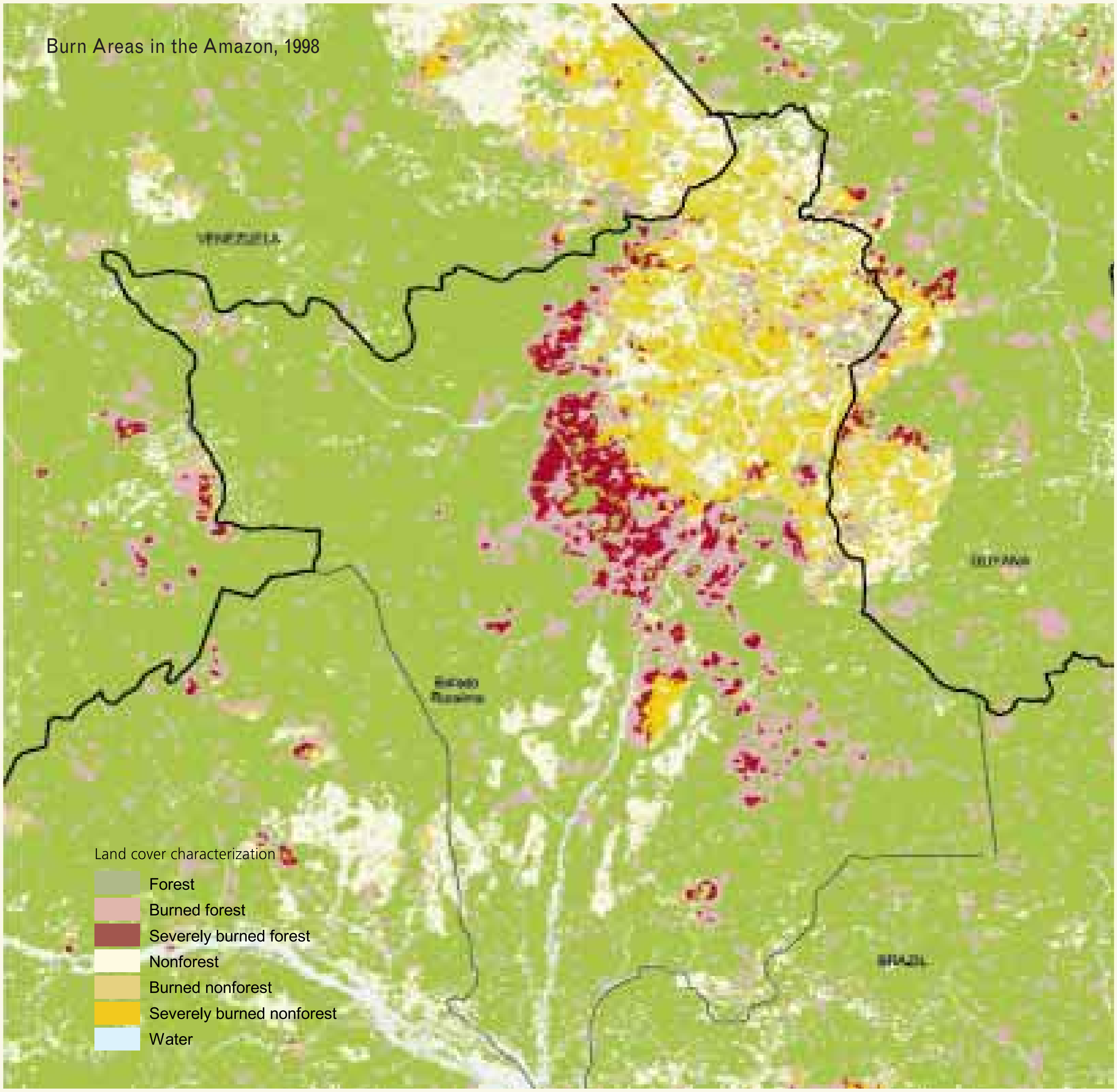
Box 2.20 Forest Fires

Wildfires are a natural phenomenon in many forest ecosystems. They structure the landscape, improve the availability of soil nutrients, and initiate natural cycles of plant succession. Human-induced fires can have pervasive impact on the condition of forests and their capacity to produce goods and services.

Worldwide, forest fires were especially severe in 1997–98, when millions of hectares of tropical forest in Indonesia, Central America, and the Amazon went up in smoke. Tropical forests, which are normally too wet to sustain extensive fires, were especially susceptible then because of the dry conditions created by El Niño. Evidence suggests, however, that people opportunistically used the dry conditions to set fires to clear land for further development. The burn areas shown for the Amazon in 1998 are adjacent to areas burned to clear land in 1995. This suggests that routine burning of unusually dry fields or pastures may have gotten out of hand. Similar patterns were found in Indonesian forests (Barber 2000).



Burn Areas in the Amazon, 1995



Sources: Matthews et al. [PAGE] 2000. The maps are based on Elvidge et al. (1999) and Global Land Cover Characteristics Database Version 1.2 (Loveland et al. [2000]). Fire data were collected between January and March 1995 and between the same months in 1998. Land-cover data were collected in 1992–93. Nonforested areas include grasslands, croplands, and some seasonal wetlands.

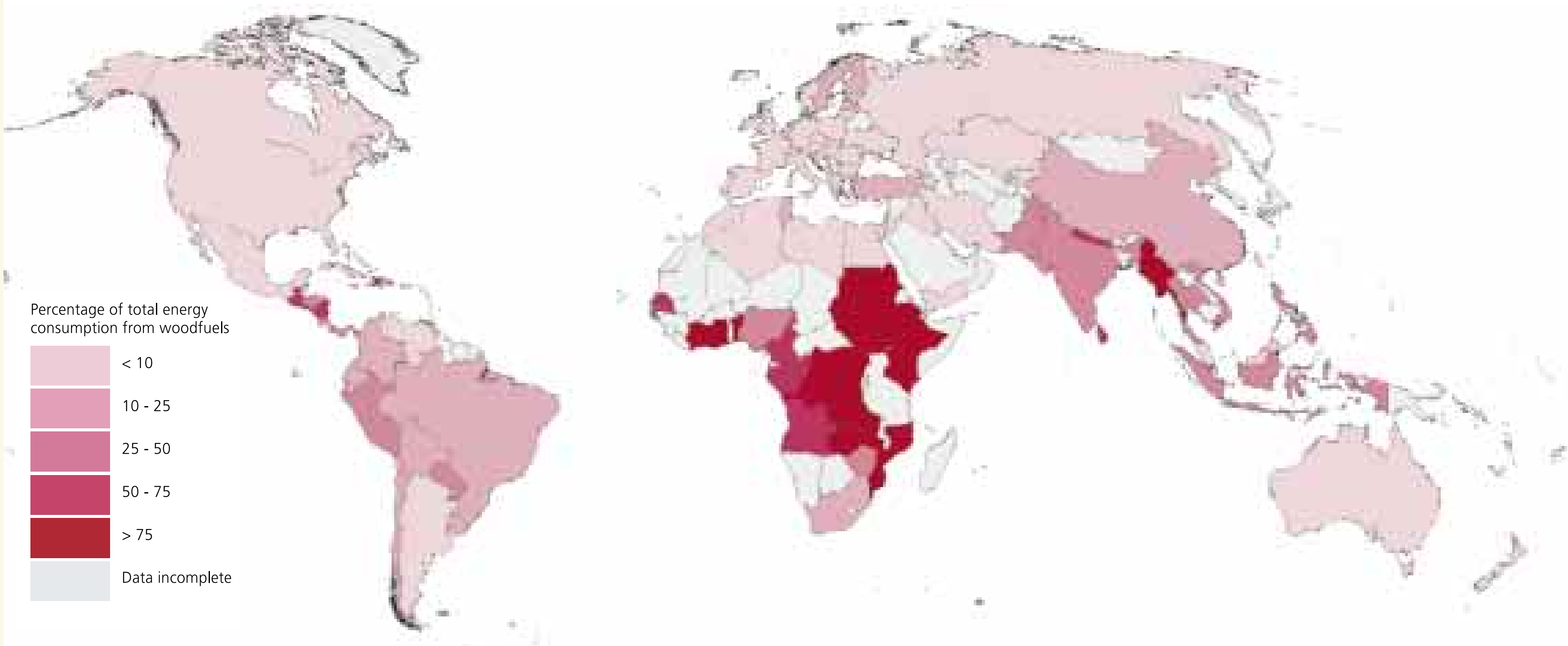
Box 2.21 Global Use of Woodfuels

Woodfuels are the most important source of nonfossil energy. Wood-derived fuels, including fuelwood and charcoal, account for approximately half the biomass energy used in developing countries (IEA 1996), while in some African countries, such as Tanzania, Uganda and Rwanda, woodfuel is the source of 80 percent of total energy consumed.

Although woodfuel collection was assumed to be a major cause of deforestation, recent studies show that up to two-thirds of all woodfuel is collected from nonforest sources such as dispersed woodland and roadside verges (FAO 1997c).

At present, data are insufficient to assess the global sustainability of woodfuel use. It is clear, however, that much of the world's population will continue to rely on wood energy for the foreseeable future and that total demand will increase significantly in coming decades. There is also evidence that in many densely populated areas of the developing world, such as the cities of Côte d'Ivoire, acquiring sufficient wood to meet energy needs is becoming increasingly arduous and costly as populations increase (Garnier 1997).

Share of Woodfuels in National Energy Consumption



Sources: Matthews et al. [PAGE] 2000. The map is based on IEA (1996).

The Bottom Line for Woodfuel. Woodfuels are the primary source of energy for approximately 2 billion people and by far the most important of the biomass fuels. But we have inadequate information about actual consumption at the household level or the capacity of ecosystems to continue to provide this good. Woodfuels will remain of prime importance in the developing world for the foreseeable future. It is essential to put wood energy data collection and planning on an equal footing with commercial energy sources like oil, coal, natural gas, and hydroelectricity.

BIODIVERSITY

Forest biodiversity is a good in its own right. Diverse species found only in forest habitats are sources of new pharmaceuticals, genetic resources, and nontimber forest products such as resins, fruits, vines, mushrooms, and livestock fodder. Even more important, all other forest goods and services depend to some extent on the diversity of forest species. The condition of biodiversity is thus a useful indicator of the aggregate condition of the forest ecosystem.

Forests are particularly important ecosystems for biodiversity conservation. Two-thirds of 136 ecologically distinct terrestrial regions identified as outstanding examples of biodiversity are located in forested regions, according to WWF (Olson and Dinerstein 1998:509). Similarly, BirdLife International identified 218 areas containing two or more species of birds with restricted ranges. BLI reasoned that these "narrowly endemic" species were likely to be most susceptible to extinction. Eighty-three percent of these 218 areas occur in forests, mostly tropical lowland forests (32 percent) and montane moist forest (24 percent) (Stattersfield et al. 1998:31). Finally, of 234 centers of plant diversity worldwide identified by IUCN and WWF, more than 70 percent are found in forests (Davis et al. 1994, 1995:12–36).

The condition of forest biodiversity can be most directly measured by changes in the number of species found in the forest, including loss or extinction of native species or introductions of nonnative species. Any change in the number or relative abundance of different species represents ecosystem degradation from the standpoint of biodiversity. Because most species have not yet even been identified, it is possible to monitor threats to only the best-known species groups: in practice, this means birds and trees. Of an estimated 100,000 species of trees, WCMC reports that more than 8,700 (Oldfield et al. 1998) are now threatened globally (Box 2.22 Endangered Trees).

Similar global data for forest-dwelling birds have not been compiled, but BLI has mapped the locations of 290 threatened birds in the Neotropics (excluding the Caribbean), allowing comparison among different ecosystems to determine where threats are greatest. Of 596 key areas harboring threatened species, more than 70 percent were in forests (Wege and Long 1995:15–16).

Another direct measure of biodiversity condition is the extent to which invasive species have colonized an ecosystem. Invasions by nonnative species are now ranked by many ecologists as second only to habitat conversion as a threat to global biodiversity. Comprehensive global data on invasives is not yet available, but information compiled by WWF shows how invasive plants have changed the condition of biodiversity in North American forests. In northeastern coastal forests of the United States, up to 32 percent of total vascular plant species are nonnative, although it is not known how many of these species are harmful (Ricketts et al. 1997:82).

Although these direct measures of change in the number of species in forests are the best way to assess the condition of forest biodiversity, data are unavailable for much of the world. Consequently, most of what is known about the condition of forest species is only inferred from various measures of the pressures on forest biodiversity. Three such pressures–habitat fragmentation, logging, and loss of habitat area–are known to change the numbers and types of species found in forest regions. Areas with high levels of fragmentation or logging, or regions that have experienced significant loss of forest habitat, will not contain as many of the native species previously found in the region.

The relationship between habitat area and species diversity is well enough established that it is possible to estimate how many native species might ultimately be lost from a particular habitat as its area is reduced. The Global Biodiversity Assessment conducted in 1995 under the auspices of UNEP found that if recent rates of tropical forest loss continue for the next 25 years, the number of species in forests would be reduced by approximately 4–8 percent (Heywood 1995:235).

The Bottom Line for Biodiversity. Forests have the highest species diversity and endemism of any ecosystem. Pressure on this diversity is immense, as judged from forest loss and fragmentation, but direct information about condition is more limited. What evidence exists suggests that the number of threatened forest species is significant and growing, and species introductions are very high in certain regions. Not only is forest area shrinking, but the capacity of remaining forests to maintain biodiversity appears to be significantly diminished.

CARBON STORAGE

Forests play a central role in the global carbon cycle. Trees capture carbon from the atmosphere as they grow and store it in their tissues. Because of their great biomass, global forests comprise one of the largest terrestrial reservoirs or "sinks" of carbon. Forests store 39 percent (471–929 GtC) of the 1,213–2,433 GtC that PAGE researchers calculated are stored in all terrestrial ecosystems. By way of comparison, grass-

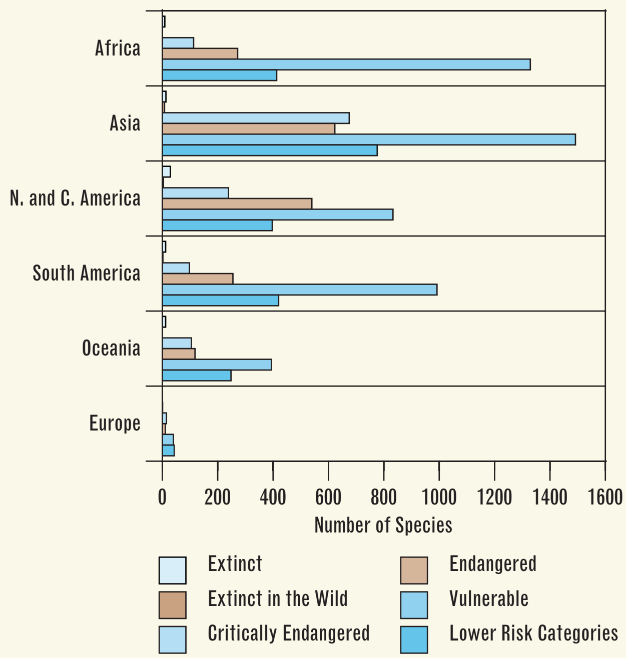
Box 2.22 Endangered Trees

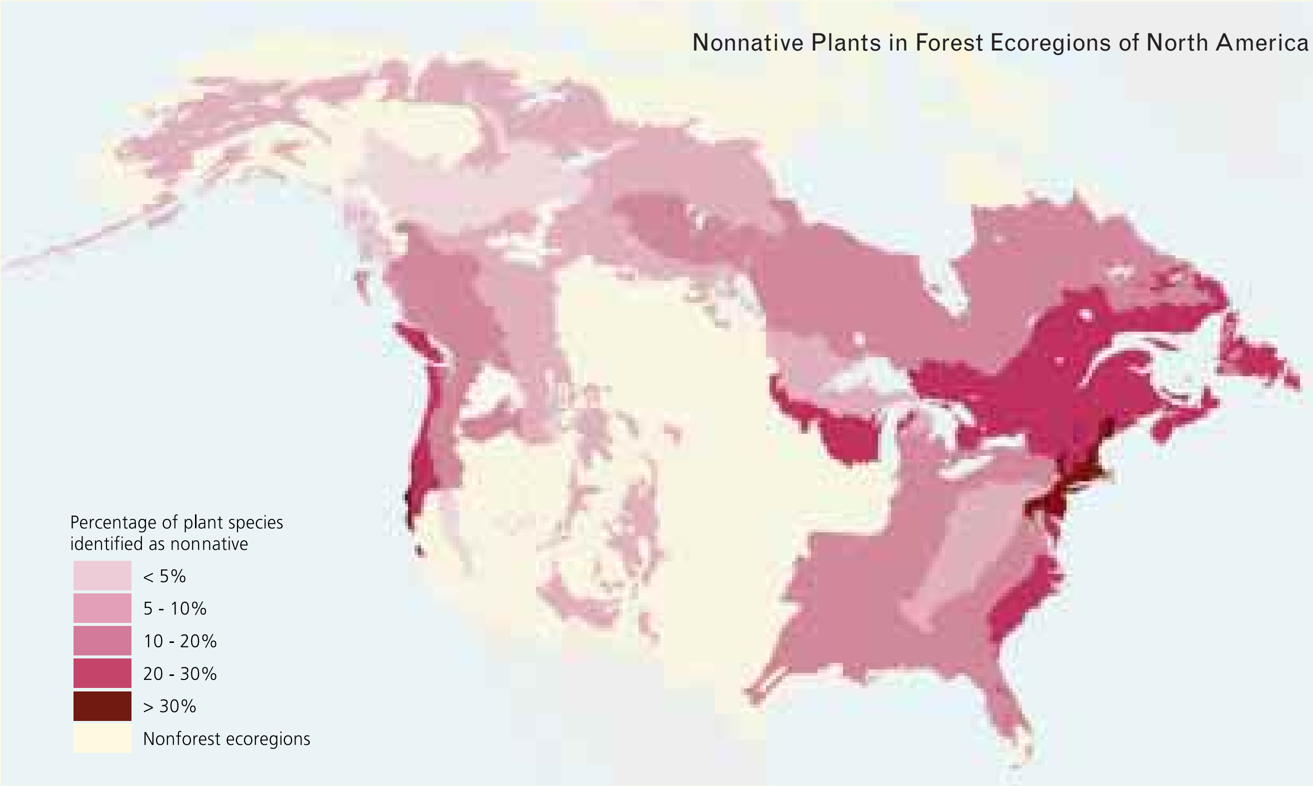
Survival of the world's estimated 100,000 tree species is threatened by conversion of forest land to other uses, timber harvesting, fire, pest attack, and ecosystem simplification resulting from forest management. WCMC has compiled a list of threatened species, assessed according to the 1994 IUCN categories of threat. Altogether, more than 8,700 tree species, almost 9 percent of the world total, are at risk.

A major threat is posed by the deliberate or accidental introduction by humans of nonnative plants and animals to forest habitats. These can threaten the survival of native species by attacking them, competing with them for food and space, or altering local ecosystems to the point that they can no longer support indigenous tree populations. The number of nonnative species are, thus, an indicator of the degree of potential "assault" on native flora.

In North America, the highest concentrations of nonnative species are found around ports, along major transportation routes, and in fertile agricultural regions that have proved favorable to both introduced crops and their pests. Densely forested taiga regions away from major human settlements appear to be little affected, and the conifer forests of the Southeast have proved relatively resistant to invasive species.

Risk Categories for the World's Trees





Sources: Matthews et al. [PAGE] 2000. The map is from Ricketts et al. (1997). The figure is based on Oldfield et al. (1998).

lands store about 33 percent of terrestrial carbon, yet cover nearly twice as much area as forested regions.

Land-use change is thought to release an average of 1.6 GtC to the atmosphere each year, or roughly 20 percent of all carbon emissions caused by human action (IPCC 2000:5). By far the most significant component of global land-use change is deforestation in the tropics (Houghton 1999:305, 310). Clearing forests and burning the debris releases large amounts of carbon stored in the vegetation back into the atmosphere. On the other hand, restoring degraded forests or changing their management can increase their carbon storing ability and thus increase the total carbon stored in world forests.

Loss of carbon storage in forests does not always take the form of large-scale clearance or outright deforestation. Logging and clearing small areas for agriculture can also degrade forests and significantly reduce their carbon-storing capacity. One recent study in tropical Asia reported that deforestation accounted for two-thirds of carbon loss in Asian forests, whereas one-third was due to degradation from logging and shifting cultivation (Houghton and Hackler 1999:486). Another study, in Africa, found that outright loss of forest accounted for 43 percent of carbon loss, while degradation of the forest was responsible for 57 percent (Gaston et al. 1998:110).

The Bottom Line for Carbon Storage. Forests store more carbon than any other terrestrial ecosystem—nearly 40 percent of total carbon stored. Deforestation and forest degradation are responsible for approximately 20 percent of annual carbon emissions. The condition of forest ecosystems from the standpoint of carbon storage is clearly declining, but with appropriate economic incentives, this trend could potentially be reversed. However, there are trade-offs to be borne in mind: more carbon is sequestered by young, fast-growing trees than by mature trees. Simply managing forests to store maximum carbon might encourage replacement of many existing old-growth forests with plantations, which would clearly jeopardize biodiversity, tourism, and other services that natural forests provide.

WATER QUALITY AND QUANTITY

Forests provide several valuable services in relation to watershed protection. They physically stabilize the upper reaches of watersheds. Tree roots "pump" water out of the soil to be used by the plant, thereby reducing soil moisture and the likelihood of mud slides; root structures increase the shear strength of soil and help prevent landslides. Forests also tend to moderate the rate of runoff from precipitation, reducing flows during flooding and increasing flows during drier times.

Forest cover also helps to maintain drinking water supplies. Within the United States, more than 60 million people in 3,400 communities rely on National Forest lands for their drinking water, a service estimated to be worth $3.7 billion per year (Dombeck 1999). Finally, forest cover affects the total amount of water available in a watershed. In many regions, forest loss will increase net water discharge because less water is transpired to the atmosphere. In other regions, however, forest loss can decrease net discharge. In cloud forests, for example, forests play a role in directly condensing or "stripping" water from moisture-laden air and making it available for discharge. In other regions, precipitation is dependent in part on the transpiration of water-laden air from the local forest. For example, climate researchers have estimated that temperatures are about 1°C higher and precipitation is 30 percent lower in large deforested patches in the Amazon (Couzin 1999:317).

Overall, forest loss has certainly impaired the world's watersheds to a significant degree. A 1998 analysis by WRI found that nearly 30 percent of the world's major watersheds have lost more than three-fourths of their original forest cover, and 10 percent have lost more than 95 percent of their original forest cover (Revenga et al. 1998:I-13) (Box 2.23 The Deforestation of Watersheds).

Perhaps a more revealing measure of the condition of forests for watershed protection today is the status of montane forests. These forests play an especially important role in the hydrological processes of watersheds by controlling soil erosion in steeply sloping mountains and sometimes "capturing" water in cloud forests.

In temperate regions, the extent of montane forest has increased in recent years, except in the mature old-growth coniferous forests of the Pacific Northwest of North America, Chile, Tasmania, and southern New Zealand. Highly prized for producing lumber, these forests may have been reduced to less than half their original extent by logging (Denniston 1995:32). In the tropics, montane forests are under even greater pressure. According to FAO, tropical montane forests were disappearing at a rate of 1.1 percent/year in the 1980s, which exceeded the rate of loss for all other tropical forest types (FAO 1993:28).

The Bottom Line for Water Quality and Quantity. Forests retain water in soil, regulate flow, influence precipitation, and filter drinking water. The water purification service alone has high economic value in certain regions. Forest loss in general has eroded the capacity of the world's forests to protect watersheds and provide water-related services, and this decline will likely continue as pressures on forests mount. Nearly 30 percent of the world's major watersheds have lost more than three-quarters of their original forest. Montane forests, which are particularly important in protecting watersheds, have suffered extensively. In spite of the importance of forests for vital water services, these services are rarely factored into land-management decisions.

Box 2.23 The Deforestation of Watersheds

Deforestation is a useful indicator of watershed degradation, because forests are often crucial for maintaining water quality and moderating water flow. The loss of original forest cover is estimated from the extent of forests that are believed to have existed 8,000 years ago assuming current climate conditions. Almost a third of all watersheds have lost more than 75 percent of their original forest cover, and seventeen have lost more than 90 percent. Most of these basins are relatively small. Large basins, such as the Congo and the Amazon, still have extensive original forest cover and have lost a relatively small percentage of their original forest. Nonetheless, the total area of original forest lost is large: nine large basins have lost more than 500,000 km^2 (Revenga et al. 1998:I-13).

Watersheds Losing the Greatest Share of Original Forest Cover

Region and Watershed	Percentage of Original Forest Lost
Africa	
Lake Chad	100
Limpopo	99
Mangoky	97
Mania	98
Niger	96
Nile	91
Orange	100
Senegal	100
Volta	97
Asia and Oceania	
Amu Darya	99
Indus	90
Europe	
Guadalquivir	96
Seine	93
Tigris & Euphrates	100
South America	
Rio Colorado	100
Lake Titicaca	100
Uruguay	92

Watersheds Losing the Greatest Area of Original Forest Cover

Region and Watershed	Area of Original Forest Lost (km^2)
Africa	
Congo	>1,000,000
Asia and Oceania	
Ganges	500,000–1,000,000
Mekong	500,000–1,000,000
Ob	500,000–1,000,000
Yangtze	>1,000,000
Europe	
Volga	500,000–1,000,000
North America	
Mississippi	500,000–1,000,000
South America	
Amazon	500,000–1,000,000
Paraná	500,000–1,000,000

Source: Revenga (personal communication, 2000) updating Revenga et al. (1998).

FRESHWATER SYSTEMS

Freshwater ecosystems in rivers, lakes, and wetlands contain just a fraction–one one-hundredth of one percent–of Earth's water and occupy less than 1 percent of Earth's surface (Watson et al. 1996:329; McAllister et al. 1997:18). Yet these vital systems render services of enormous global value–on the order of several trillion U.S. dollars, according to some estimates (Postel and Carpenter 1997:210).

The most important services revolve around water supply: providing a sufficient quantity of water for domestic consumption and agriculture, maintaining high water quality, and recharging aquifers that feed groundwater supplies. But freshwater ecosystems provide many other crucial goods and services as well: habitats for fish (for food and sport), mitigation of floods, maintenance of biodiversity, assimilation and dilution of wastes, recreational opportunities, and a transportation route for goods. Harnessed by dams, these systems also produce hydropower, one of the world's most important renewable energy sources.

Prior to the 20th century, global demand for these goods and services was small compared to what freshwater systems could provide. But with population growth, industrialization, and the expansion of irrigated agriculture, demand for all water-related goods and services increased dramatically, straining the capacity of freshwater ecosystems. Many policy makers are aware of the growing problems of water scarcity, but scarcity is only one of many ways in which these ecosystems are stressed today.

Extent and Modification

Freshwater systems have been altered since historical times; however, the pace of change accelerated markedly in the early 20th century. Rivers and lakes have been modified by altering waterways, draining wetlands, constructing dams and irrigation channels, and establishing connections between water basins, such as canals and pipelines, to transfer water. Although these changes have brought increased farm output, flood control, and hydropower, they have also radically changed the natural hydrological cycle in most of the world's water basins (Box 2.24 Taking Stock of Freshwater Systems).

RIVERS

Modification of rivers has greatly altered the way rivers flow, flood, and act on the landscape. In many instances, rivers have become disconnected from their floodplains and wet-

(continues on p. 106)

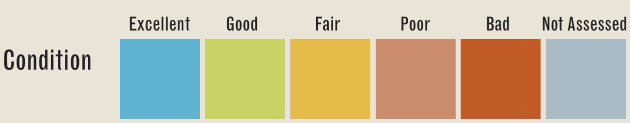
Box 2.24 Taking Stock of Freshwater Systems

Highlights

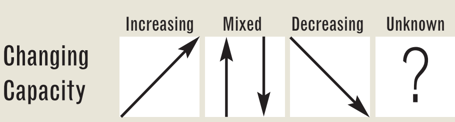
- Although rivers, lakes, and wetlands contain only 0.01 percent of the world's freshwater and occupy only 1 percent of the Earth's surface, the global value of freshwater services is estimated in the trillions of U.S. dollars.
- Dams have had the greatest impact on freshwater ecosystems. Large dams have increased sevenfold since the 1950s and now impound 14 percent of the world's runoff.
- Almost 60 percent of the world's largest 227 rivers are strongly or moderately fragmented by dams, diversions, or canals.
- In 1997, 7.7 million metric tons of fish were caught from lakes, rivers, and wetlands, a production level estimated to be at or above maximum sustainable yield for these systems.
- Freshwater aquaculture contributed 17 million metric tons of fish in 1997. Since 1990, freshwater aquaculture has more than doubled its yield and now accounts for 60 percent of global aquaculture production.
- Half the world's wetlands are estimated to have been lost in the 20th century, as land was converted to agriculture and urban areas, or filled to combat diseases such as malaria.
- At least 1.5 billion people depend on groundwater as their sole source of drinking water. Overexploitation and pollution in many regions of the world are threatening groundwater supplies, but comprehensive data on the quality and quantity of this resource are not available at the global level.

Key

Condition assesses the current output and quality of the ecosystem good or service compared with output and quality of 20–30 years ago.



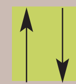
Changing Capacity assesses the underlying biological ability of the ecosystem to continue to provide the good or service.



Scores are expert judgments about each ecosystem good or service over time, without regard to changes in other ecosystems. Scores estimate the predominant global condition or capacity by balancing the relative strength and reliability of the various indicators. When regional findings diverge, in the absence of global data weight is given to better-quality data, larger geographic coverage, and longer time series. Pronounced differences in global trends are scored as "mixed" if a net value cannot be determined. Serious inadequacy of current data is scored as "unknown."

Conditions and Changing Capacity

FOOD PRODUCTION



At the global level, inland fisheries landings have been increasing since 1984. Most of this increase has occurred in Asia, Africa, and Latin America. In North America, Europe, and the former Soviet Union, landings have declined, while in Australia and Oceania they have remained stable. The increase in landings has been maintained in many regions by stocking and by introducing nonnative fish. The greatest threat for the long-term sustainability of inland fisheries is the loss of fish habitat and the degradation of the aquatic environment.

WATER QUALITY

Even though surface water quality has improved in the United States and Western Europe in the past 20 years (at least with respect to phosphorus concentrations), worldwide conditions appear to have degraded in almost all regions with intensive agriculture and large urban or industrial areas. Algal blooms and eutrophication are being documented more frequently in most inland water systems, and waterborne diseases from fecal contamination of surface waters continue to be a major cause of mortality and morbidity in the developing world.

WATER QUANTITY

The construction of dams has helped provide drinking water for much of the world's population, increased agricultural output through irrigation, eased transport, and provided flood control and hydropower. People now withdraw about half of the readily available water in rivers. Between 1900 and 1995, withdrawals increased sixfold, more than twice the rate of population growth. Many regions of the world have ample water supplies, but currently almost 40 percent of the world's population experience serious water shortages. With growing populations, water scarcity is projected to grow dramatically in the next decades. On almost every continent, river modification has affected the natural flow of rivers to a point where many no longer reach the ocean during the dry season. This is the case for the Colorado, Huang-He (Yellow), Ganges, Nile, Syr Darya, and Amu Darya rivers.

BIODIVERSITY

The biodiversity of freshwater ecosystems is much more threatened than that of terrestrial ecosystems. About 20 percent of the world's freshwater fish species have become extinct, threatened, or endangered in recent decades. Physical alteration, habitat loss and degradation, water withdrawal, overexploitation, pollution, and the introduction of nonnative species all contribute to declines in freshwater species. Amphibians, fish, and wetland-dependent birds are at high risk in many regions of the world.

Data Quality

FOOD PRODUCTION

Data on inland fisheries landings are poor, especially in developing countries. Much of the catch is not reported at the species level, and much of the fish consumed locally is never reported. No data are systematically collected on the contribution to inland fisheries of fish stocking, fish introduction programs, and other enhancement programs. Historical trends in fisheries statistics are only available for a few well-studied rivers.

WATER QUALITY

Data on water quality at a global level are scarce; there are few sustained programs to monitor water quality worldwide. Information is usually limited to industrial countries or small, localized areas. Water monitoring is almost exclusively limited to chemical pollution, rather than biological monitoring, which would provide a better understanding of the systems' condition and capacity. For regions such as Europe, where some monitoring is taking place, differences in measures and approaches make the data hard to compare.

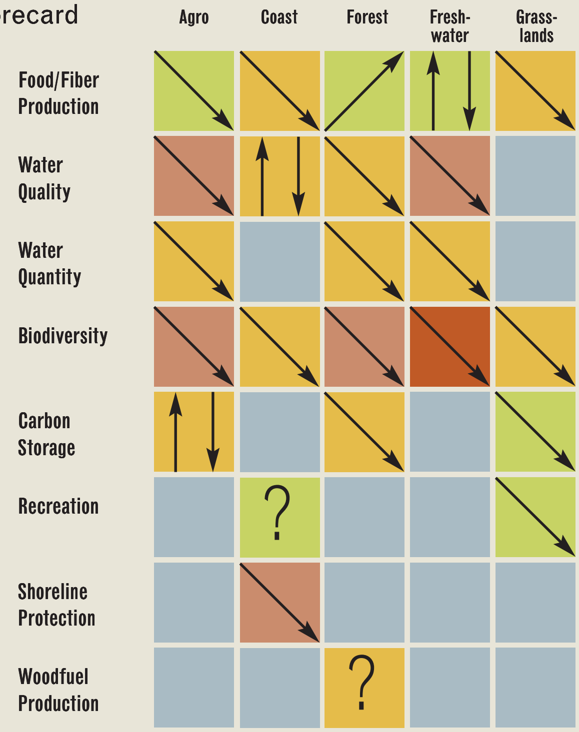
WATER QUANTITY

Statistics are poor on water use, water availability, and irrigated area on a global scale. Estimates are frequently based on a combination of modeled and observed data. National figures, which are usually reported, vary from estimates used in this study, which are done at the watershed or river catchment level.

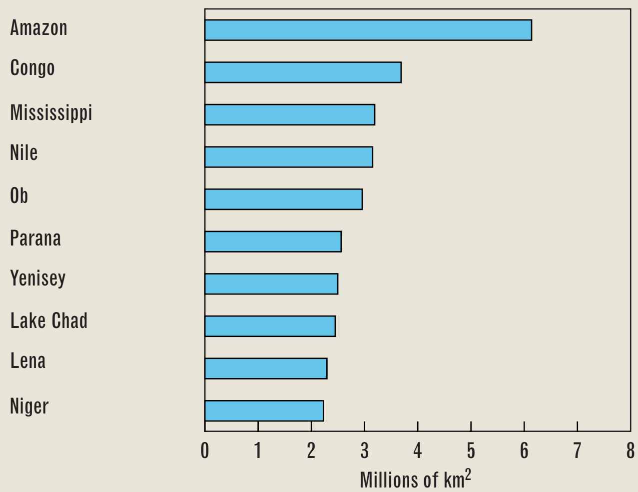
BIODIVERSITY

Direct measurements of the condition of biodiversity in freshwater systems are sparse worldwide. Basic information is lacking on freshwater species for many developing countries, as well as threat analyses for most freshwater species worldwide. This makes analyzing population trends impossible or limited to a few well-known species. Information on nonnative species is frequently anecdotal and often limited to records of the existence of a particular species, without documentation of the effects on the native flora and fauna. Spatial data on invasive species are available for a few species, mostly in North America.

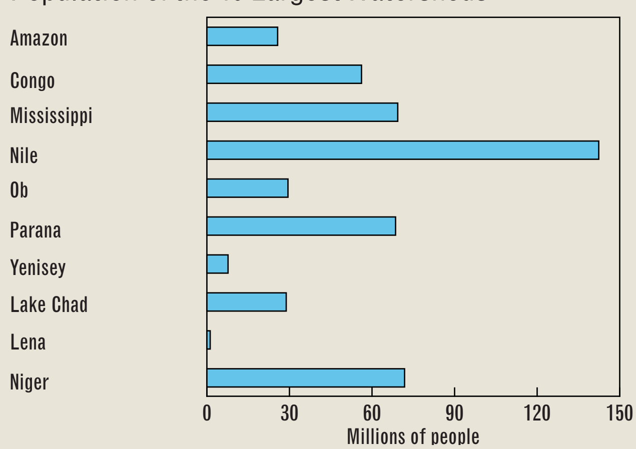
Scorecard



Area of the 10 Largest Watersheds



Population of the 10 Largest Watersheds



lands. Dams, the most significant physical impact on freshwater systems, have slowed water velocity in river systems, converting many of them to chains of connected reservoirs. This fragmentation of freshwater ecosystems has changed patterns of sediment and nutrient transport, affected migratory patterns of fish species, altered the composition of riparian habitat, created migratory paths for exotic species, and contributed to changes in coastal ecosystems.

Damming the World's Rivers

The number of large dams (more than 15 m high) has increased nearly sevenfold since 1950, from about 5,750 to more than 41,000 (ICOLD 1998:7, 13), impounding 14 percent of the world's annual runoff (L'vovich and White 1990:239). Even though dam construction has greatly slowed in most developed countries, demand and untapped potential for dams is still high in the developing world, particularly in Asia. As of 1998, there were 349 dams more than 60 m high under construction around the world (IJHD 1998:12–14). The regions with the greatest number of dams under construction are Turkey, China, Japan, Iraq, Iran, Greece, Romania, Spain, and the Paraná basin in South America. The river basins with the most large dams under construction are the Yangtze basin in China, with 38 dams under construction; the Tigris and Euphrates basin with 19; and the Danube with 11.

PAGE researchers assessed most of the world's large rivers (average annual discharge of at least 350 m^3/second) to quantify the extent to which dams and canals have fragmented river basins and to determine how water withdrawals have altered river flows. The PAGE analysis shows that, of the 227 major river basins assessed, 37 percent are strongly affected by fragmentation and altered flows, 23 percent are moderately affected, and 40 percent are unaffected (Dynesius and Nilsson 1994:753–762; Revenga et al. [PAGE] 2000) (Box 2.25 Fragmentation and Flow). "Strongly affected" systems include those with less than one-quarter of their main channel left without dams, as well as rivers whose annual discharge has decreased substantially. "Unaffected rivers" are those without dams in the main channel of the river and, if tributaries have been dammed, river discharge has declined no more than 2 percent.

In all, strongly or moderately fragmented systems account for nearly 90 percent of the total water volume flowing through the rivers in the analysis. The only remaining large free-flowing rivers in the world are found in the tundra regions of North America and Russia, and in smaller basins in Africa and Latin America.

Slowing the Flow

Clearly, water diversions and extractions have profoundly affected river flow on a global basis. On almost every continent, the natural flow of one or more major rivers has decreased so much that it no longer reaches the sea during the dry season; the Colorado, Huang He (Yellow), Ganges, Nile, Syr Darya, and Amu Darya, all run dry at the river mouth during the dry season (Postel 1995:10). The Amu Darya and Syr Darya used to contribute 55 billion m^3 of water annually to the Aral Sea prior to 1960, but diversions for irrigation reduced this volume to an annual average of 7 billion m^3–6 percent of the previous annual flow–during 1981–90 (Postel 1995:14–15).

By slowing the movement of water, dams also prevent large amounts of sediment from being carried downstream–as they normally would be–to deltas, estuaries, flooded forests, wetlands, and inland seas. This retention can rob these areas of the sediments and nutrients they depend on, affecting their species composition and productivity. Sediment retention also interferes with dam operations and shortens their useful life. In the United States, about 2 km^3 of reservoir storage capacity is lost to sediment retention each year, at a cost of $819 million annually (Vörösmarty et al. 1997:217). And retention eliminates or reduces spring runoff or flood pulses that often play a critical role in maintaining downstream riparian and wetland communities (Abramovitz 1996:11).

Water and sediment retention also affect water quality and the waste processing capacity of rivers–their ability to break down organic pollutants. The slower moving water in reservoirs is not well-mixed, but rather is stratified into layers, with the bottom layers often depleted of oxygen. These oxygen-starved waters can produce a toxic hydrogen sulfide gas that degrades water quality. In addition, oxygen-depleted waters released from dams have a reduced capacity to process waste for as far as 100 km downstream, because the waste-processing ability of river water depends directly on its level of dissolved oxygen.

An indicator of the extent to which dams have affected water storage and sediment retention at the global level is the change in "residence time" of otherwise free-flowing water–in other words, the increase in time that it takes an average drop of water entering a river to reach the sea. Vörösmarty et al. (1997:210–219) calculated the changes in this residence time, or "aging" of river water, at the mouth of each of 236 drainage basins (see also Revenga et al. [PAGE] 2000). Worldwide, the average age of river water has tripled to well over 1 month. Among the basins most affected are the Colorado River and Rio Grande in North America, the Nile and the Volta Rivers in Africa, and the Rio Negro in Argentina.

WETLANDS

Wetlands include a variety of highly productive habitat types from flooded forests and floodplains to shallow lakes and marshes. They are a key component of freshwater ecosystems, providing flood control, carbon storage, water purification, and goods such as fish, shellfish, timber, and fiber. Although wetlands are a significant feature of many regions, a recent review by the Ramsar Convention on Wetlands concluded that available data are too incomplete to yield a reliable estimate of the global extent of wetlands (Finlayson and Davidson 1999:3).

Because wetlands are valued as potential agricultural land or feared for harboring disease, they have undergone massive conversion around the world, sometimes at considerable ecological and socioeconomic costs. Without accurate global information on the original extent of wetlands, scientists can't say precisely how much wetland area has been lost; but based on a variety of historical records and sources, Myers (1997:129) estimated that half of the wetlands of the world have been lost this century. More detailed studies have tracked freshwater wetland loss in specific regions and countries. For example, experts estimate 53 percent of all wetlands in the lower 48 states of the United States was lost from the 1780s to the 1980s (Dahl 1990:5). In Europe, wetland loss is even more severe; draining and conversion to agriculture alone has reduced wetlands area by some 60 percent (EEA 1999:291).

Assessing Goods and Services

WATER QUANTITY

Water, for domestic use as well as use in agriculture and industry, is clearly the most important good provided by freshwater systems. Humans withdraw about 4,000 km^3 of water a year– about 20 percent of the normal flow of the world's rivers (their nonflood or "base flow") (Shiklomanov 1997:14, 69). Between 1900 and 1995, withdrawals increased more than sixfold, which is more than twice the rate of population growth (WMO 1997:9).

Scientists estimate the average amount of runoff worldwide to be between 39,500 km^3 and 42,700 km^3 per year (Fekete et al. 1999:31; Shiklomanov 1997:13). However, most of this occurs in flood events or is otherwise not accessible for human use. In fact, only about 9,000 km^3 is readily accessible to humans, and an additional 3,500 km^3 is stored by reservoirs (WMO 1997:7).

Given a limited supply of freshwater and a growing population, the amount of water available per person has been decreasing. Between 1950 and 2000, annual water availability per person decreased from 16,800 m^3 to 6,800 m^3 per year, calculated on a global basis (Shiklomanov 1997:73). However, such global averages don't portray the world water situation well. Water supplies are distributed unevenly around the world, with some areas containing abundant water and others a much more limited supply. For example, the arid and semiarid zones of the world receive only 2 percent of the world's runoff, even though they occupy roughly 40 percent of the terrestrial area (WMO 1997:7).

High Demand, Low Runoff

In river basins with high water demand relative to the available runoff, water scarcity is a growing problem. In fact, water experts frequently warn that water availability will be one of the major challenges facing human society in the 21st century and the lack of water will be one of the key factors limiting development (WMO 1997:1, 19). A 1997 analysis estimated that roughly one-third of the world's people live in countries experiencing moderate to high water stress–a number that will undoubtedly rise as population and per capita water demand grow (WMO 1997:1).

To get a better understanding of the balance of water demand and supply, and to better estimate the dimensions of the global water problem, PAGE researchers undertook a new analysis of water scarcity using a somewhat different method than the 1997 study. PAGE researchers calculated water availability and population for individual river basins, rather than on a national or state level,[5] with the object of identifying those areas where annual water availability per person was less than 1,700 m^3. Water experts define areas where per capita water availability drops below 1,700 m^3/year as experiencing "water stress"–a situation where disruptive water shortages can frequently occur. In areas where annual water supplies drop below 1,000 m^3 per person, the consequences are usually more severe: problems with food production, sanitation, health, economic development, and loss of ecosystems occur, except where the region is wealthy enough to use new technologies for water conservation or reuse (Hinrichsen et al. 1998:4).

According to the PAGE analysis, 41 percent of the world's population, or 2.3 billion people, live in river basins under water stress, where per capita water availability is less than 1,700 m^3/year (Revenga et al. [PAGE] 2000) (Box 2.26 The Quantity and Quality of Freshwater). Of these, 1.7 billion people reside in highly stressed river basins where annual water availability is less than 1,000 m^3/person. Assuming current consumption patterns continue, by 2025, PAGE researchers project that at least 3.5 billion people–or 48 percent of the world's population–will live in water-stressed river basins. Of these, 2.4 billion will live under high water stress conditions.

Even some regions that normally have water availability above scarcity levels may in fact face significant water shortages during dry seasons. The PAGE study identified a number of such river basins, particularly in northeast Brazil, southern Africa, central India, eastern Turkey, northwest Iran, and mainland Southeast Asia.

Groundwater Sources

Global concerns about water scarcity include not only surface water sources but groundwater sources as well. Some 1.5 billion people rely on groundwater sources, withdrawing approximately 600–700 km^3/year–about 20 percent of global water withdrawals (Shiklomanov 1997:53–54). Some of this water–fossil water–comes from deep sources isolated from the normal runoff cycle, but much groundwater comes from shallower aquifers that draw from the same global runoff that feeds freshwater systems. Indeed, overdrafting of ground-

(continues on p. 112)

Box 2.25 Fragmentation and Flow

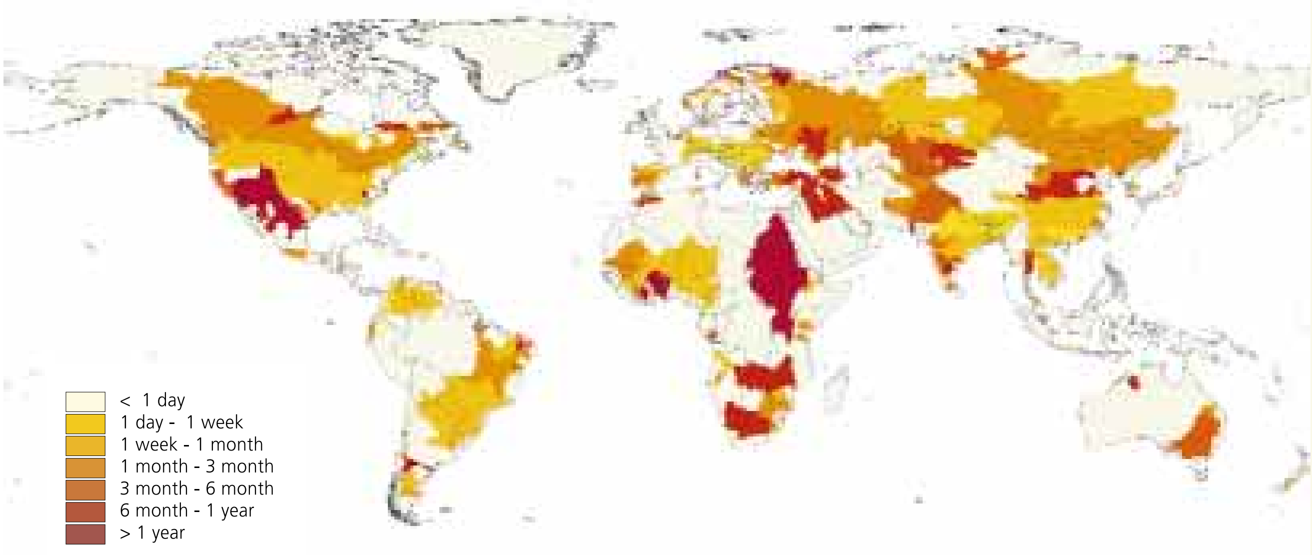
For centuries, in all parts of the world, rivers and lakes have been modified to improve navigation, wetlands drained to make way for settlement, and dams and channels built to control the flow of water for human purposes. These changes have raised agricultural output by making more land and irrigation water available, easing transport, and providing flood control and hydropower.

But human modifications have also had far-reaching effects on hydrological cycles and the species that depend on those cycles. Rivers have been disconnected from their floodplains and wetlands, and water velocity has been reduced as river systems are converted into chains of connected reservoirs. These changes have altered fish migrations, created access routes for nonnative species, and narrowed or transformed riparian habitats. The result has been species loss and an overall reduction in the level of ecosystem services freshwater environments are able to provide.

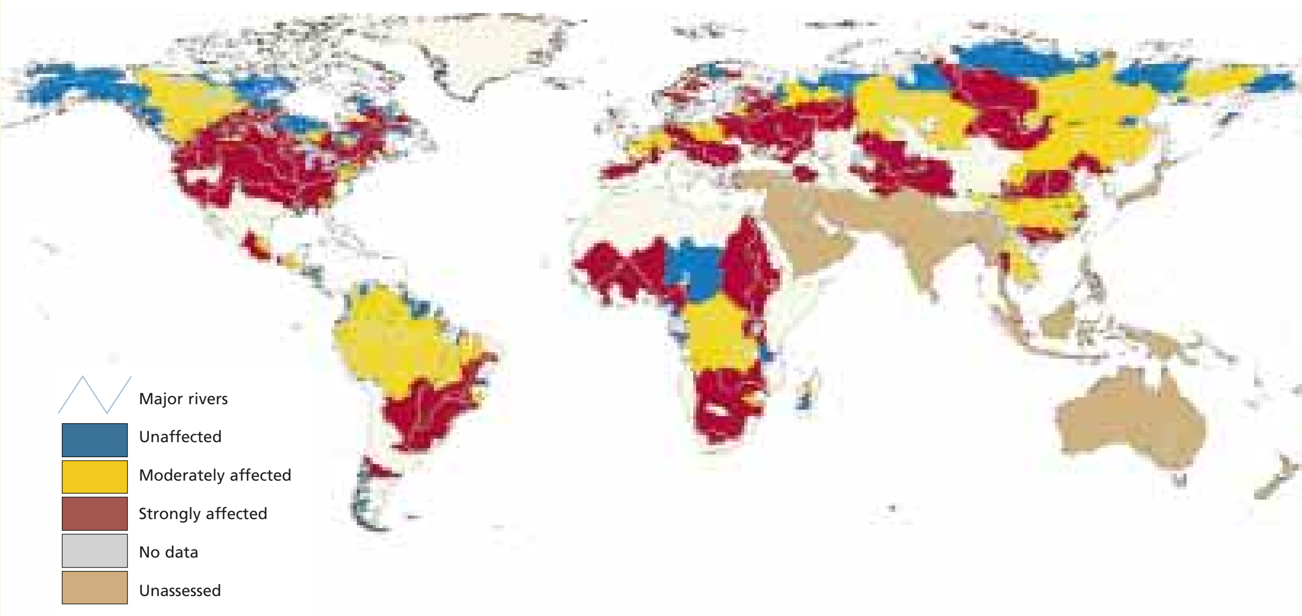
The construction of dams has had an impact on most of the world's major river systems. There are more than 41,000 large dams in the world—a sevenfold increase in storage capacity since 1950 (ICOLD 1998, Vörösmarty et al 1997). The map at the top of the facing page shows the extent of fragmentation, or interruption of natural flow, caused by human intervention in 227 large river systems (Dynesius and Nilsson 1994; Nilson et al. 1999; Revenga et al. [PAGE] 2000). Almost all large river systems in temperate and arid regions are classified as highly or moderately affected, while all but a handful of the unaffected systems in which water still flows freely are located in Arctic or boreal regions. This trend will continue as new large dams are built throughout Asia, the Middle East, and Eastern Europe.

Dams slow the rate of natural flow, thereby increasing sedimentation and lowering levels of dissolved oxygen. The most affected river systems, in which length of water retention has risen by more than a year, include the Colorado River and Rio Grande in North America, the Nile and Volta Rivers in Africa, and the Rio Negro in Argentina.

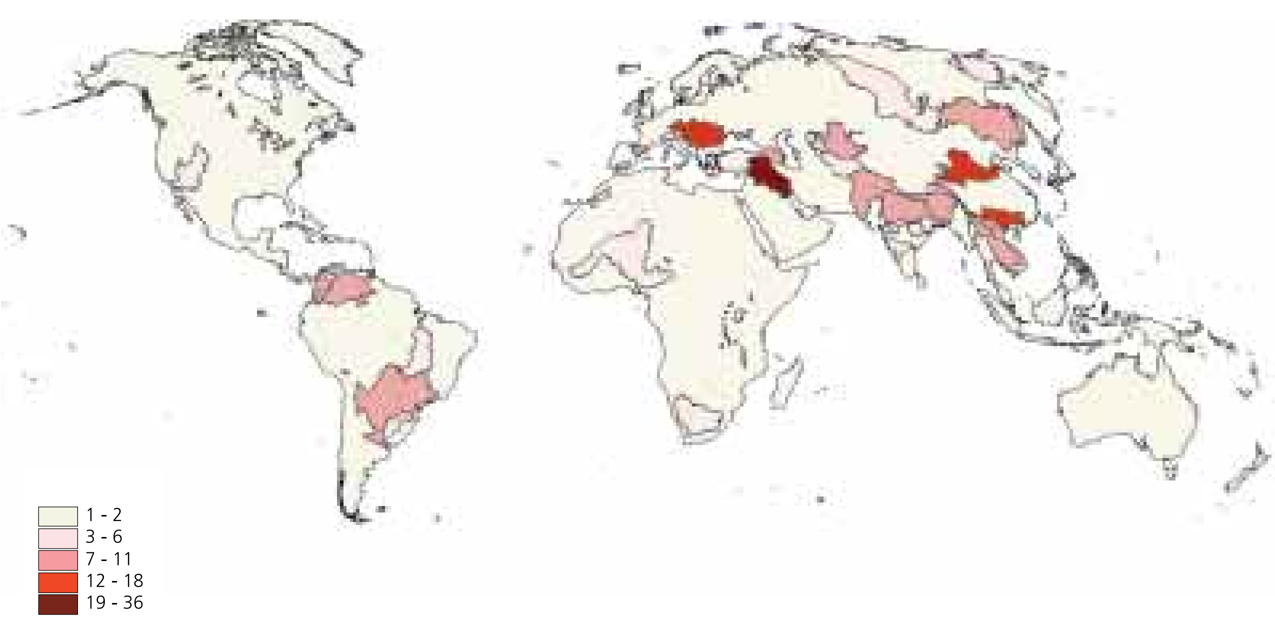
Aging of Continental Runoff in Major Reservoir Systems



River Channel Fragmentation and Flow Regulation



New Dams under Construction by Basin, 1998



Sources: Revenga et al. [PAGE] 2000. The continental runoff map on the preceding page is from Vörösmarty et al. (1997.) The fragmentation map above is based on Revenga et al. (1998), Dynesius and Nilsson (1994), and Nilsson et al. (1999). The map showing dams under construction are based on data from IJHD(1998)

Box 2.26 The Quantity and Quality of Freshwater

Freshwater systems provide the single most essential good: water—for drinking, cooking, washing, rinsing, mixing, growing, processing, and countless other human uses. Increases in population, industrial production, and agricultural demand have caused the global rate of water consumption to grow twice as fast as the population rate (WMO 1997:9).

The quantity and quality of water available from freshwater systems is greatly influenced by land use within the watershed from which the water is drawn. The mix of cities, roads, agroecosystems, and natural areas affects transpiration, drainage, and runoff and often dictates the amount of pollution carried in the water. Natural waters have low concentrations of nitrates and phosphorous, but these levels increase in rivers fed by runoff from agroecosystems (especially in Europe and North America, where synthetic fertilizers are widely used) and urban areas. The excess nutrients stimulate plant growth, which can choke out local freshwater species, clog distribution systems, and endanger human health.

Just as clean water is often a victim of development, development, too, can be a victim of the lack of clean water. Many experts predict that the lack of clean water is likely to be one of the key factors limiting economic growth in the 21st century. As of 1995, more than 40 percent of the world's population lived in conditions of water stress (less than 1,700 m^3 of water available/person/year) or water scarcity (less than 1,000 m^3 of water available/person/year). This percentage will increase to almost half the world's population by 2025. River basins with more than 10 million people by 2025 that will move into situations of water stress are the Volta, Farah, Nile, Tigris and Euphrates, Narmada, and Colorado (Brunner et al. 2000).

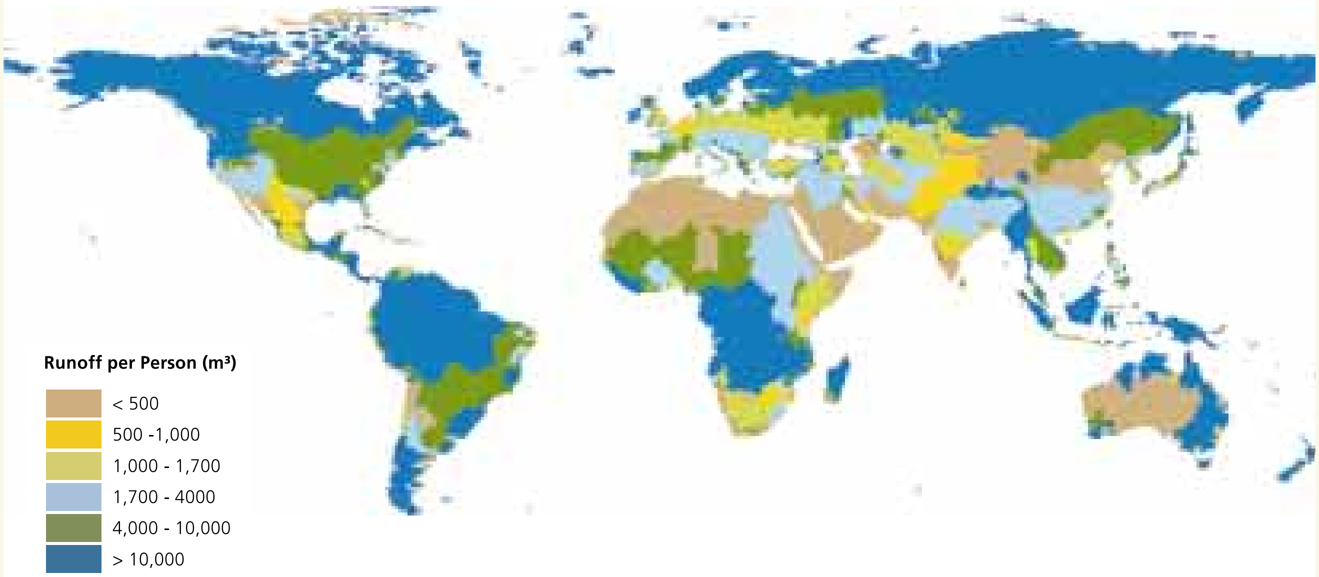
Nutrient Pollution in Selected Rivers, 1994

Region	River	Area (millions of km^2)	Concentration (mg/l) Nitrates	Phosphates
Africa	Zaire	3.69	n.a.	n.a.
	Nile	2.96	0.80	0.03
Asia	Huang He	0.77	0.17	0.02
	Brahmaputra	0.58	0.82	0.06
Europe	Volga	1.35	0.62	0.02
	Seine	0.06	4.30	0.40
N. America	Mississippi	3.27	1.06	0.20
	St. Lawrence	1.02	0.22	0.02
Oceania	Murray Darling	1.14	0.03	0.10
	Waikato	0.01	0.30	0.10
S. America	Amazon	6.11	0.17	0.02
	Orinoco	1.10	0.08	0.01

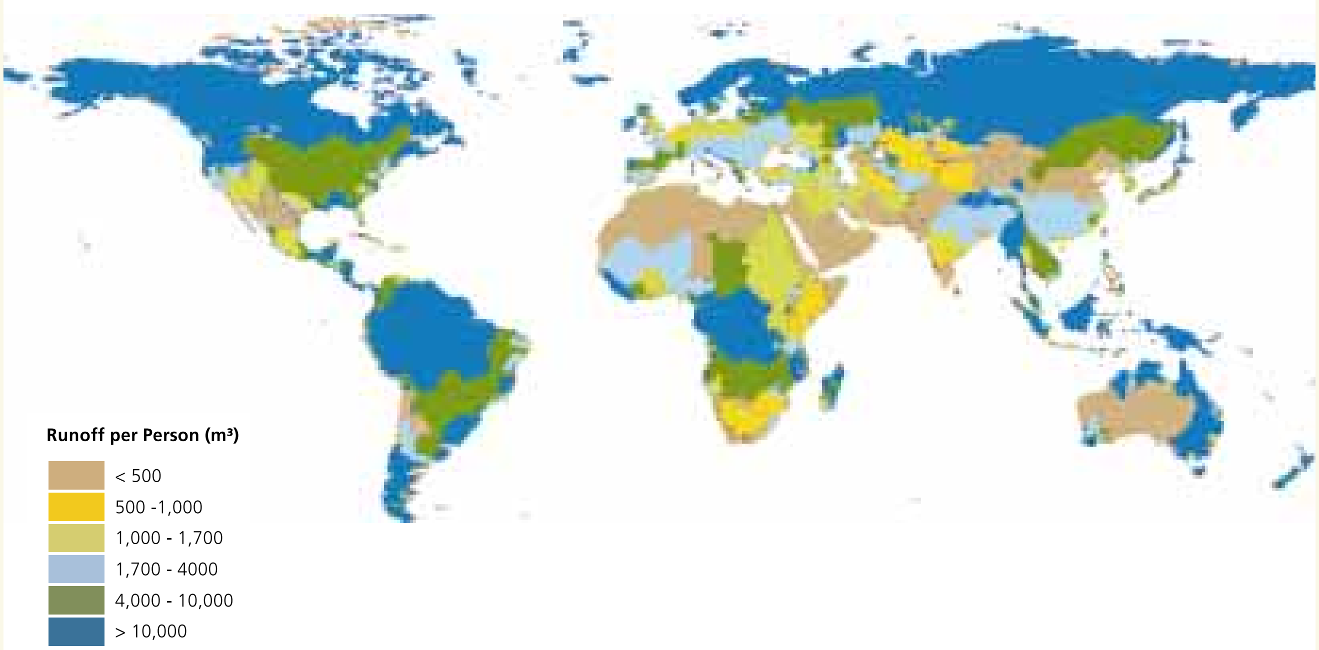
Global Water Availability, 1995 and 2025

Status	Water supply (m^3/person)	1995 Population (millions)	1995 Percentage of Total	2025 Population (millions)	2025 Percentage of Total
Scarcity	<500	1,077	19	1,783	25
	500–1,000	587	10	624	9
Stress	1,000–1,700	669	12	1,077	15
Adequacy	>1,700	3,091	55	3,494	48
Unallocated		241	4	296	4
Total		5,665	100	7,274	100

Annual Water Availability per Person by River Basin 1995



Annual Water Availability per Person by River Basin 2025



Sources: Nutrient pollution table is based on UNEP-GEMS (1995). The water availability table and maps are from Revenga et al. [PAGE] 2000, based on Brunner et al. (2000), Fekete et al. (1999), and CIESIN (2000). Water scarcity projections are based on the UN's low-growth projection of population growth or decline; they do not take into account effects of pollution and climate change.

water sources can rob streams and rivers of a significant percentage of their flow. In the same way, polluting aquifers with nitrates, pesticides, and industrial chemicals often affects water quality in adjacent freshwater ecosystems. Although overdrafting from and polluting groundwater aquifers are known to be widespread and growing problems (UNEP 1996:4–5), comprehensive data on groundwater resources and pollution trends are not available on a global level.

The Bottom Line for Water Quantity. Humans now withdraw annually about one-fifth of the normal (nonflood) flow of the world's rivers, but in river basins in arid or populous regions the proportion can be much higher. This has implications for all species living in or dependent on these systems, as well as for future human water supplies. Currently, more than 40 percent of the world's population lives in water-scarce river basins. With growing populations, water scarcity is projected to increase significantly in the next decades, affecting half of the world's people by 2025. Widespread depletion and pollution of groundwater sources, which account for about 20 percent of global water withdrawals, is also a growing problem for freshwater ecosystems, since groundwater aquifers are often linked to surface water sources.

WATER QUALITY

Freshwater systems, particularly wetlands, play an essential role in maintaining water quality by removing contaminants and helping to break down and disperse organic wastes. But the filtering capacity of wetlands and other habitats is limited and can be overwhelmed by an excess of human waste, agricultural runoff, or industrial contaminants. Indeed, water quality is routinely degraded by a vast array of pollutants including sewage, food processing and papermaking wastes, fertilizers, heavy metals, microbial agents, industrial solvents, toxic compounds such as oil and pesticides, salts from irrigation, acid precipitation, and silt.

Information about water quality on a global level is poor and difficult to obtain for a number of reasons. Water-quality problems are often local and can be highly variable depending on the location, season, or even time of day. In addition, monitoring for water quality is by no means universal, and water-quality standards often vary significantly from country to country.

Nonetheless, existing information makes it clear that there are many consistent trends in the contamination of water supplies worldwide. One hundred years ago, the main contamination problems were fecal and organic pollution from untreated human waste and the by-products of early industries. These pollution sources have been greatly reduced in most industrialized countries, with consequent improvements in water quality. However, a new suite of contaminants from intensive agriculture and development activities in watersheds has kept the clean-up from being complete. Meanwhile, in most developing countries, the problems of traditional pollution sources and new pollutants like pesticides have combined to heavily degrade water quality, particularly near urban industrial centers and intensive agriculture areas (Shiklomanov 1997:28; UNEP/GEMS 1995:6).

Increased use of manure and manufactured fertilizers–a major source of nutrients such as nitrates and phosphorous–has been a significant cause of pollution in freshwater systems. Nitrate and phosphorus concentrations are low in natural systems but increase with runoff from agroecosystems and urban and industrial wastewater. As a consequence, algal blooms and eutrophication are being documented more frequently in most inland water systems. The highest nitrate concentrations occur in Europe, but high levels are also found in watersheds that have been intensively used and modified by human activity in China, South Africa, and the Nile and Mississippi basins (UNEP/GEMS 1995:33–36). These high nitrate levels, in turn, are associated with extreme eutrophication caused by agricultural runoff in at least two areas: the Mediterranean Sea and the northern Gulf of Mexico at the mouth of the Mississippi River. Water pollution caused by agricultural runoff remains an intractable problem because of its extremely diffuse nature, which makes it hard to control even in industrialized countries.

Although water quality measurements that focus on levels of contaminants are useful, they do not directly tell us how water pollution affects freshwater ecosystems. To determine this, the aquatic community itself must be monitored. The Index of Biotic Integrity (IBI), which includes information about fish or insect species richness, composition, and condition, is one of the most widely used approaches for assessing the health of the aquatic community in a given water body or stretch of river (Karr and Chu 1999). A number of states in the United States now use various IBI approaches and it has been applied in France and Mexico; as yet its use is too limited to give an idea of global aquatic conditions (Oberdorff and Hughes 1992; Lyons et al. 1995).

The Bottom Line for Water Quality. Surface water quality has improved in the United States and Western Europe during the past 20 years, but nitrate and pesticide contamination remain persistent problems. Data on water quality in other regions of the world are sparse, but water quality appears to be degraded in almost all regions with intensive agriculture and rapid urbanization. Unfortunately, little information is available to evaluate the extent to which chemical contamination has impaired freshwater biological functions. However, incidents of algal blooms and eutrophication are widespread in freshwater ecosystems the world over—an indicator that these systems are profoundly affected by water pollution. In addition, the massive loss of wetlands on a global level has left the capacity of freshwater ecosystems to filter and purify water much impaired.

FOOD: INLAND FISHERIES

Fish are a major source of protein and micronutrients for a large percentage of the world's population, particularly the poor (Bräutigam 1999:5). Inland fisheries–stocks of fish and shellfish from rivers, lakes, and wetlands–are an important component of this protein source. The population of Cambodia, for example, gets roughly 60 percent of its total animal protein from the fishery resources of Tonle Sap, a large freshwater lake (MRC 1997:19). In Malawi, the freshwater catch provides about 70–75 percent of the animal protein for both urban and rural low-income families (FAO 1996).

Inland Fish Catch. Worldwide, the inland fisheries harvest totaled 7.7 million metric tons in 1997. Not counting the fish raised in aquaculture, this represents nearly 12 percent of all fish–freshwater and ocean-caught–that humans directly consume (FAO 1999a:7–10). The inland fisheries catch consists largely of freshwater fish, although mollusks, crustaceans, and some aquatic reptiles are also caught and are of regional and local importance (FAO 1999a:9) (Box 2.27 Changes in Inland Fisheries).

The inland fisheries harvest is believed to be greatly underreported–by a factor of two or three (FAO 1999b:4). Asia and Africa lead the world's regions in inland fish production. According to FAO, most inland capture fisheries (all fish except those raised in aquaculture) are exploited at or above their maximum sustainable yields. Globally, inland fisheries production (including aquaculture) increased at 2 percent per year from 1984 to 1997, although in Asia the rate has been much higher–7 percent per year since 1992. This growth in part results from deliberate fisheries enhancements such as artificial stocking or introduction of new species. Such enhancements are particularly important in Asia, which produces 64 percent of the world's inland fish catch (FAO 1999b:6). Another factor in increased production may, ironically, be the eutrophication of inland waters, which, in mild forms, can raise the production of some fish species by providing more food at the base of the food chain (FAO 1999b:7).

Aquaculture. As important as the inland fish catch is, production from freshwater aquaculture has now eclipsed it in size, value, and nutritional importance. Freshwater aquaculture production reached 17.7 million tons in 1997 (FAO 1999b:6). Marine and freshwater aquaculture together provided 30 percent of the fish consumed directly by humans in 1997, and more than 60 percent of this production is freshwater fish or fish that migrate between fresh and saltwater (FAO 1999a:7; FAO 1998). Asia, and China in particular, dominate aquaculture production (FAO 1999b:7).

Recreational Fishing. In Europe and North America, freshwater fish consumption has declined in recent decades and much of the fishing effort now is devoted to recreation. Recreational fishing contributes significantly to some economies. For instance, Canadian anglers spend $2.9 billion Canadian dollars per year on products and services directly related to fishing (McAllister et al. 1997:12). In the United States, anglers spent US$447 million on fishing licenses alone in 1996 (FAO 1999b:42). Recreational fisheries also contribute to the food supply since anglers usually consume what they catch, although recently there is a trend toward releasing fish after they are caught (Kapetsky 1999). The recreational catch is currently estimated to be around 2 million tons per year (FAO 1999b:42).

Condition of Inland Fisheries. The principal factor threatening inland capture fisheries is the loss of fish habitat and environmental degradation (FAO 1999b:19). In certain areas like the Mekong River basin in Asia, overfishing and destructive fishing practices also contribute to the threat (FAO 1999b:19). In addition, nonnative species introduced into lakes, rivers, and reservoirs–either accidentally or for food or recreational fishing–affect the composition of the native aquatic communities, sometimes increasing levels of production and sometimes decreasing them. Introduced species can be predators or competitors or can introduce new diseases to the native fauna, sometimes with severe consequences. (See Box 1.9 Trade-Offs: Lake Victoria's Ecosystem Balance Sheet, p. 21).

Assessing the actual condition of inland fisheries is complicated by the difficulty of collecting reliable and comprehensive data on fish landings. Much of the catch comes from subsistence and recreational fisheries and these are particularly hard to monitor, since these harvests are not brought back to centralized markets or entered into commerce (FAO 1999b:4).

Nevertheless, harvest and trend information exist for certain well-studied fisheries. Harvest information includes changes in landings of important commercial species and in the species composition of well-studied rivers. Without exception, each of the major fisheries examined has experienced dramatic declines during this century.

A somewhat different picture of the condition of inland fisheries is provided by data from FAO. By analyzing catch statistics over 1984–97, FAO found positive trends in inland capture fish harvests in South and Southeast Asia, Central America, and parts of Africa and South America. Harvest trends were negative in the United States, Canada, parts of Africa, Eastern Europe, Spain, Australia, and the former Soviet Union (FAO 1999b:9–18, 51–53).

(continues on p. 116)

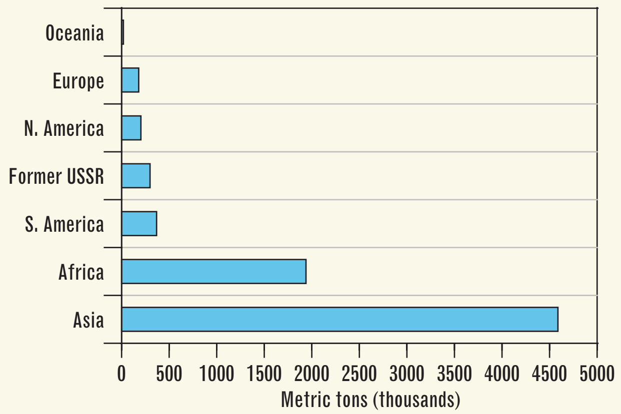
Box 2.27 Changes in Inland Fisheries

Catches from inland fisheries account for nearly 12 percent of the total fish consumed by humans (FAO 1999a). In many landlocked countries, such as Malawi, freshwater fish make up a high proportion of total protein intake, particularly among the poor (FAO 1999b).

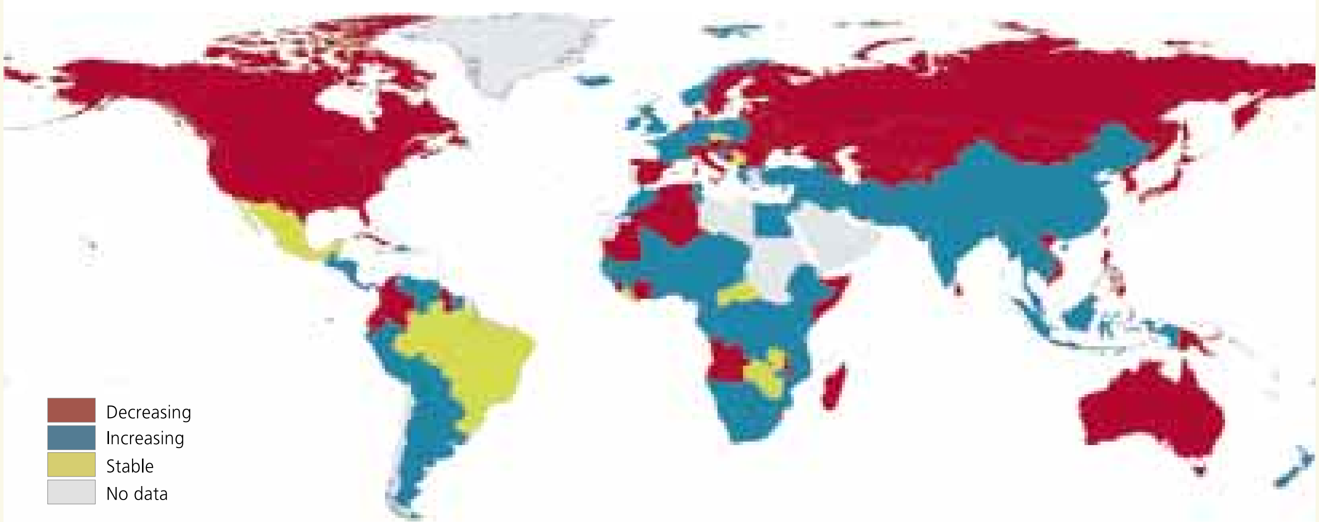
Globally, landings from inland capture fisheries (wildfish caught by line, net, or trap) have increased by an average of 2 percent per year from 1984 to 1996. Regional trends, however have diverged widely, with declines in Australia, North America, and the former Soviet Union and increases in much of Africa and Asia. Since 1987, aquaculture has outstripped capture fisheries as the major source of freshwater fish, with production dominated by Asian countries (FAO 1999a).

According to FAO, most inland capture fisheries are being exploited at above-sustainable levels. The effects of overharvesting are exacerbated by the loss or degradation of freshwater habitat caused by factors like dam building and pollution. The growth in total catch has been achieved only through reliance on restocking and the introduction of more productive species in major producing countries such as China.

Inland Capture Fisheries Landings, 1997



Inland Capture Fisheries Trends, 1984–97



Source: FAO, 1999.

Sources: Revenga et al. [PAGE] 2000. The map is based on (FAO 1999b). The figure is based on FAO (1998). Table is derived from Carlson and Muth (1989), Bacalbasa-Dobrovici (1989), Postel (1995), Abramovitz (1996, citing Missouri River Coalition 1995), Hughes and Noss (1992), Sparks (1992), Kauffman (1992), and Liao et al. (1989).

Changes in Fish Species Composition and Fisheries for Selected Rivers

River	Change in Fish Species and Fishery	Major Causes of Decline	Main Goods and Services Lost
Colorado River, USA	Historically native fish included 36 species, 20 genera, and 9 families; 64 percent of these were endemic. Current status of species under the Endangered Species Act: 2 extinct, 15 threatened or endangered, 18 proposed for listing or under review	Dams, river diversions, canals, and loss of riparian habitat.	Loss of fisheries and biodiversity.
Danube River	Since the early 1900s, Danube sturgeon fishery has almost disappeared. Current fisheries are maintained through aquaculture and introduction of nonnative species.	Dams, creation of channels, pollution, loss of floodplain areas, water pumping, sand and gravel extraction, and nonnative species introductions.	Loss of fisheries, loss of biodiversity, and change in species composition.
Aral Sea	Of 24 fish species, 20 have disappeared. The commercial fishery that used to have a catch of 40,000 tons and support 60,000 jobs is now gone.	Water diversion for irrigation, pollution from fertilizers and pesticides.	Loss of important fishery and biodiversity. Associated health effects caused by toxic salts from the exposed lakebed.
Rhine River	Forty-four species became rare or disappeared between 1890 and 1975. Salmon and sturgeon fisheries are gone, and yields from eel fisheries have declined even though it is maintained by stocking.	Dams, creation of channels, heavy pollution, and nonnative species introductions.	Loss of important fishery, loss of biodiversity.
Missouri River	Commercial fisheries declined by 83 percent since 1947.	Dams, creation of channels and pollution from agriculture runoff.	Loss of fishery and biodiversity.
Great Lakes	Change in species composition, loss of native salmonid fishery. Four of the native fish have become extinct and seven others are threatened.	Pollution from agriculture and industry, non-native species introductions.	Loss of fishery, biodiversity, and recreation.
Illinois River	Commercial fisheries decreased by 98 percent in the 1950s.	Siltation from soil erosion, pollution, and eutriphication.	Loss of fishery and biodiversity.
Lake Victoria	Mass extinction of native cichlid fishes. Changes in species composition and disappearance of the small-scale subsistence fishery that many local communities depended on.	Eutrophication, siltation from deforestation, overfishing, and introduction of nonnative species.	Loss of biodiversity and local artisanal fishery.
Pearl River (Xi Jiang)	In the 1980s, yield levels in commercial fisheries dropped to 37 percent of 1950s levels.	Overfishing, destructive fishing practices, pollution, and dams.	Loss of fishery.

Depending on the region, the growth in harvests that FAO documented could stem from a variety of reasons: the exploitation of a formerly underfished resource, overexploitation of a fishery that will soon collapse, or enhancement of fisheries by stocking or introducing more productive species. FAO found that in every region, the major threat to fisheries was environmental degradation of freshwater habitat (FAO 1999b:19).

The Bottom Line for Food Production. Freshwater fish play an extremely important role in human nutrition as well as in local economies. Harvests have increased significantly in recent decades, reaching their current 7.7-million ton level for captured fish and 17.7 million tons for aquaculture-raised fish. Data are inadequate to determine sustainable yields for most wild populations, but where data exist, they show that the capacity of freshwater ecosystems to support wild fish stocks has declined significantly because of habitat degradation and overharvest. Production of freshwater aquaculture, however, has been increasing rapidly and is expected to continue to do so. The yield of some inland capture fisheries focused on introduced species has also increased, but sometimes to the detriment of native fish species.

BIODIVERSITY

Freshwater systems, like other major ecosystems, harbor a diverse and impressive array of species. Twelve percent of all animal species live in freshwater ecosystems (Abramovitz 1996:7) and many more species are closely associated with these ecosystems. In Europe, for example, 25 percent of birds and 11 percent of mammals use freshwater wetlands as their main breeding and feeding areas (EEA 1994:90).

Although freshwater ecosystems have fewer species than marine and terrestrial habitats, species richness is high, given the limited extent of aquatic and riparian areas. According to estimates from Reaka-Kudla (1997:90), there are 44,000 described aquatic species, representing 2.4 percent of all known species; yet freshwater systems occupy only 0.8 percent of Earth's surface (McAllister et al. 1997:5).

Some regions are particularly important because they contain large numbers of species or many endemic species (those that are found nowhere else) (Box 2.28 Biodiversity in Freshwater Systems). Many of the most diverse fish faunas are found in the tropics, particularly Central Africa, mainland Southeast Asia, and South America, but high diversity is also found in central North America and in several basins in China and India.

Physical alteration, habitat loss and degradation, water withdrawal, overexploitation, pollution, and the introduction of nonnative species all contribute directly or indirectly to declines in freshwater species. These varied stresses affecting aquatic systems occur all over the world, although their particular effects differ from watershed to watershed.

Threats and Extinctions

Perhaps the best measure of the actual condition of freshwater biodiversity is the extent to which species are threatened with extinction. Globally, scientists estimate that more than 20 percent of the world's freshwater fish species–of which some 10,000 have been described–have become extinct, are threatened, or endangered in recent decades (Moyle and Leidy 1992:127, cited in McAllister et al. 1997:38; Bräutigam 1999:5). According to the 1996 IUCN Red List of Threatened Animals, 734 species of fish are classified as threatened; of those, 84 percent are freshwater species (IUCN 1996:37 Introduction; McAllister et al. 1997:38). In Australia, 33 percent of freshwater fish are threatened, and in Europe, the number rises to 42 percent (Bräutigam 1999:4).

In the United States, one of the countries for which good data on freshwater species exist, 37 percent of freshwater fish species, 67 percent of mussels, 51 percent of crayfish, and 40 percent of amphibians are threatened or have become extinct (Master et al. 1998:6). In western North America, data from 1997 show that more than 10 percent of fish species are imperiled in most ecoregions (distinct ecological regions), with more than 25 percent imperiled in eleven ecoregions (Abell et al. 2000:75). Similar patterns are found for endangered frogs and salamanders. Based on recent extinction rates, an estimated 4 percent of freshwater species will be lost in North America each decade, a rate nearly five times that of terrestrial species (Ricciardi and Rasmussen 1999:1220).

It is not surprising that wetland species are often most threatened in arid areas, where there isn't enough water to meet the competing needs of humans and the environment. For example, of 391 "important bird areas" in the Middle East identified by BirdLife International, half are wetlands (Evans 1994:31). Moreover, these wetland sites were also judged to be the most threatened (Evans 1994:35).

Amphibian Declines

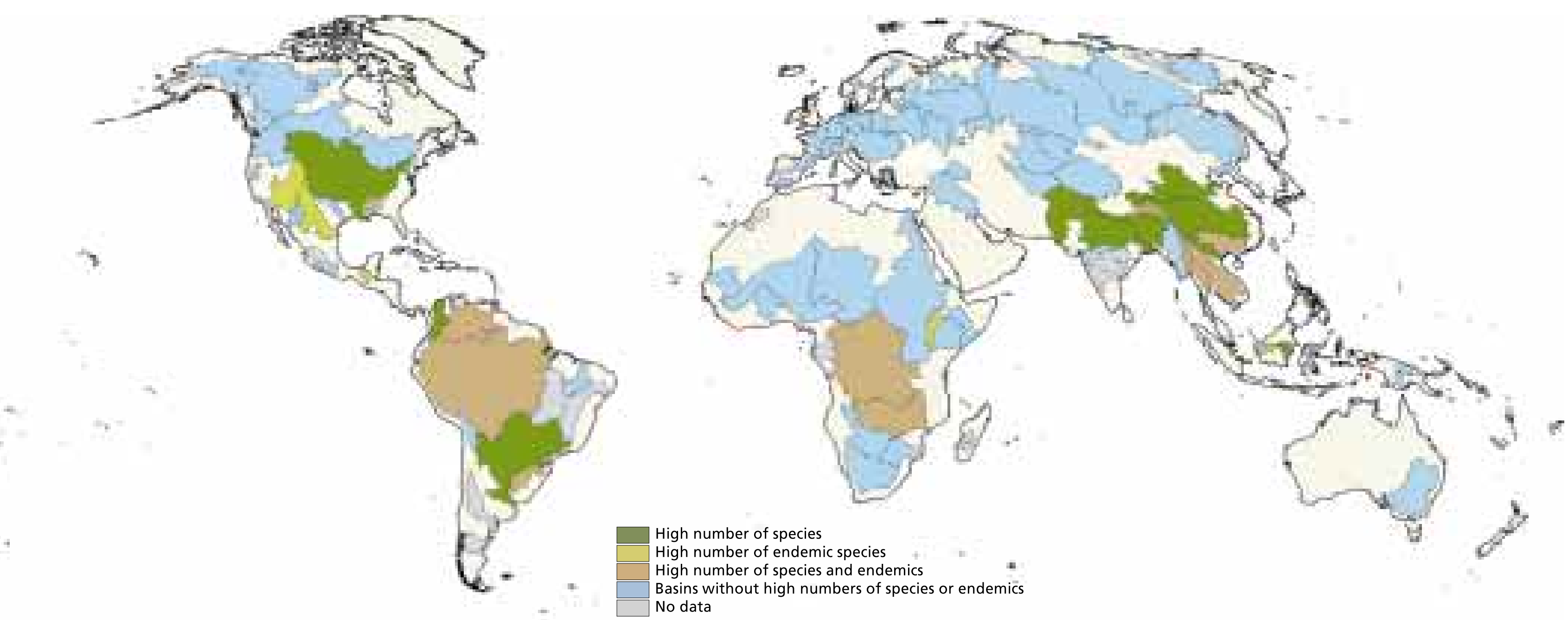
Population trends are one of the best ways to measure the condition of individual species and groups of species. Continental- or global-level data on population trends for extended time periods are not readily available for many freshwater-dependent species. But the availability of global population data for one taxonomic group–amphibians–has grown dramatically over the past 15 years as scientists have sought to ascertain the causes of an apparent world-wide decline of frogs and other amphibians (Pelley 1998). These data show significant declines in all world regions over several decades. For example, of nearly 600 amphibian populations studied in Western Europe, 53 percent declined beginning in the 1950s (Houlahan et al. 2000:754). In North America, 54 percent of the populations studied declined, while in South America, 60

Box 2.28 Biodiversity in Freshwater Systems

Despite their small area, compared with other ecosystems, freshwater systems are relatively rich in the number of species they support. Although 12 percent of all animal species live in freshwater systems (Abramovitz 1996:7), many more depend on them for survival. Physical alterations, habitat loss and degradation, water withdrawal, overexploitation, and introduction of nonnative species all contribute to declines in freshwater species. Globally, more than 20 percent of the world's freshwater fish species have become extinct, threatened, or endangered in recent decades (Moyle and Leidy 1992:127).

Freshwater biodiversity is not uniformly distributed around the world; some regions are particularly important because they contain large numbers of species or many endemic species (species occurring only in a restricted area). Endemism tends to correlate with overall species richness. Most of the highest concentrations of both endemism and species diversity are found in the tropics, particularly the Amazon, Congo, and Mekong watersheds.

Fish Species Richness and Endemism, by Watershed



Sources: Revenga et al. [PAGE] 2000. The map is based on Revenga et al. (1998). Because there is a correlation between number of species and total area sampled, large watersheds tend to have more fish species than smaller ones (Oberdorff 1995). To reduce bias in size differences, basins were categorized as large (more than 1.5 million km^2), medium (400,000 to 1.5 million km^2), and small (less than 400,000 km^2). The map shows large basins with more than 230 fish species, medium basins with more than 143 species, and small basins with more than 112 species. For endemics, the map shows large basins with more than 166 species, medium basins with more than 29 species, and small basins with more than 15 species. Cut-off points for each category were determined by selecting the upper two-thirds within each range.

percent declined. In Australia and New Zealand, as much as 70 percent of studied populations declined, although far fewer populations were monitored. The mechanisms thought to be responsible for declines include increased exposure to ultraviolet-B rays, resulting from the thinning of the stratospheric ozone layer; chemical pollution from pesticides, fertilizers, and herbicides; acid rain; pathogens; introduction of predators; and global climate change (Lips 1998; Pelley 1998; DAPTF 1999).

Invasive Species

The number and abundance of nonnative species is another important indicator of the condition of freshwater biodiversity. Introduced species are a major cause of extinction in freshwater systems, affecting native fauna through predation, competition, disruption of food webs, and the introduction of diseases. Species introductions have been particularly successful in freshwater ecosystems. For example, two-thirds of the freshwater species introduced into the tropics have subsequently become established (Beveridge et al. 1994:500).

Nonnative fish introductions are common and increasing in most parts of the world. Fish are often deliberately introduced to increase food production or to establish or expand recreational fisheries or aquaculture. For example, introduced fish account for 97 percent of fish production in South America and 85 percent in Oceania (Garibaldi and Bartley 1998). However, nonnative fish introductions often have significant ecological costs. A 1991 survey of fish introductions in Europe, North America, Australia, and New Zealand found that 77 percent of the time, native fish populations decreased or were eliminated following the introduction of nonnative fish (Ross 1991:359). In North America, introduced species have played a large role in the extinction of 68 percent of the fish that have become extinct in the past 100 years (Miller et al. 1989:22).

The economic costs of accidental introductions can also be high. For example, the introduction of the sea lamprey (*Petromyzon marinus*) in the Great Lakes of North America was a factor in the crash of the lake trout fishery in the 1940s and 1950s. In 1991, efforts to control sea lampreys through chemical and mechanical means cost Canada and the United States $8 million, with an additional $12 million spent on lake trout restoration (Fuller et al. 1999:21). Similarly, between 1989 and 1995, the costs of zebra mussel (*Dreissena polymorpha*) eradication in the United States and Canada totaled well over $69 million, with some estimates as high as $300–$400 million (O'Neill 1996:2; O'Neill 1999). On the ecological front, zebra mussel infestation has dramatically reduced populations of native clams at 17 different sampling stations, leading to the near-extinction of many species.

Some of the most dramatic trade-offs between economic benefits and ecological costs involve introductions of species of tilapia (*Oreochromis niloticus* and *O. mossambicus*) and the common carp (*Cyprinus carpio*). These important aquaculture species have now been introduced around the world. In 1996, 1.99 million tons of common carp and 600,000 tons of Nile tilapia were produced through aquaculture (FAO 1999a:14). But in lakes and rivers where these species have been introduced, native species have suffered. By feeding at the bottom of lakes and rivers, carp increase siltation and turbidity, decreasing water clarity and harming native species (Fuller et al. 1999:69). They have been associated with the disappearance of native fishes in Argentina, Venezuela, Mexico, Kenya, India, and elsewhere (Welcomme 1988:101–109).

Water hyacinth (*Eichhornia crassipes*) is another example of a widespread invasive species that is causing considerable economic and ecological damage in many parts of the world. This plant, thought to be indigenous to the upper reaches of the Amazon basin, was spread widely across the planet for use as an ornamental plant beginning in the mid-19th century and is now distributed throughout the tropics (Gopal 1987:1). Water hyacinth poses practical problems for fishing and navigation, and is a threat to biological diversity, affecting fish, plants and other freshwater life. The plant spreads quickly to new rivers and lakes in the tropics, clogging waterways and causing serious disruption to the livelihood of local communities that depend on goods and services derived from these freshwater ecosystems (Hill et al. 1997). In addition, hyacinth and other aquatic plants act as vectors in the life cycles of insects that transmit diseases such as malaria, schistosomiasis, and lymphatic filariasis (Bos 1997).

The Bottom Line for Biodiversity. Physical alteration, water withdrawals, overharvesting, and the introduction of nonnative species have all taken a heavy toll on freshwater biodiversity. Indeed, of all the ecosystems examined in this report, freshwater systems by far are in the worst condition from the standpoint of their ability to support biological diversity—on a global level. More than 20 percent of the world's 10,000 freshwater fish species have become extinct, threatened, or endangered in recent decades. In the United States, where data are more complete, 37 percent of freshwater fish species, 67 percent of mussels, 51 percent of crayfish, and 40 percent of amphibians are known to be threatened or extinct. Increased global demands for food and water will increase the already considerable pressures on freshwater systems.

GRASSLAND ECOSYSTEMS

The goods and services provided by the world's grasslands have received far less attention than those supplied by, for example, tropical forests and coral reefs, although grasslands are arguably more important to a larger percentage of people. Grasslands are home to 938 million people–about 17 percent of the world's population (White et al. [PAGE] 2000). They are found throughout the world, in humid as well as arid zones, but grasslands are particularly important features of the world's drylands. Approximately half of the people living in grassland regions live in the world's arid, semiarid, and dry subhumid zones (White et al. [PAGE] 2000). Scant rains make these drylands particularly susceptible to damage from human management and slower to recover from degradation such as overgrazing or improper cultivation practices.

Grassland ecosystems have historically been crucial to the human food supply. The ancestors of nearly all the major cereal crops originally developed in grasslands, including wheat, rice, rye, barley, sorghum, and millet. Agroecosystems have replaced many grasslands, but grasslands still provide genetic resources for improving food crops and are a potential source of pharmaceuticals and industrial products.

Grasslands are important habitats for many species, including breeding, migratory, and wintering birds, and support many wild and domestic grazing animals. Grassland vegetation and soils also store a considerable quantity of carbon. Other grassland ecosystem goods and services include meat and milk; wool and leather products; energy from fuelwood and wind generated from windfarms; cultural and recreational services such as tourism, hunting, and aesthetic and spiritual gratification; and water regulation and purification. PAGE researchers examined four of these goods and services: food production, biodiversity maintenance, carbon storage, and tourism (Box 2.29 Taking Stock of Grassland Ecosystems).

Extent and Modification

PAGE researchers defined *grassland ecosystems* as "areas dominated by grassy vegetation and maintained by fire, grazing, and drought or freezing temperatures." Using this broad definition, grasslands encompass nonwoody grasslands, savannas, woodlands, shrublands, and tundra. Grassland ecosystems are found on every continent. Among the most extensive are the savannas

(continues on p. 122)

Box 2.29 Taking Stock of Grassland Ecosystems

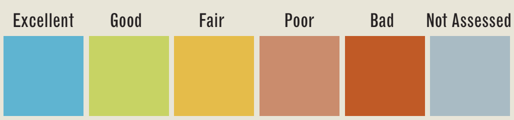
Highlights

- Grasslands, which cover 40 percent of the Earth's surface, are home to almost a billion people, half of them living on susceptible drylands.
- Agriculture and urbanization are transforming grasslands. For some North American prairies, conversion is already nearly 100 percent. Road-building and human-induced fires also are changing the extent, composition, and structure of grasslands.
- All of the major foodgrains—corn, wheat, oats, rice, barley, millet, rye, and sorghum—originate in grasslands. Wild strains of grasses can provide genetic material to improve food crops and to help keep cultivated varieties resistant to disease.
- Grasslands attract tourists willing to travel long distances and pay safari fees to hunt and view grassland fauna. Grasslands boast some of the world's greatest natural phenomena: major migratory treks of large herds of wildebeest in Africa, caribou in North America, and Tibetan antelope in Asia.
- As habitat for biologically important flora and fauna, grasslands make up 19 percent of the Centers of Plant Diversity, 11 percent of Endemic Bird Areas, and 29 percent of ecoregions considered outstanding for biological distinctiveness.

Key

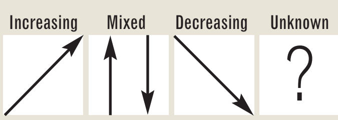
Condition assesses the current output and quality of the ecosystem good or service compared with output and quality of 20–30 years ago.

Condition



Changing Capacity assesses the underlying biological ability of the ecosystem to continue to provide the good or service.

Changing Capacity



Scores are expert judgments about each ecosystem good or service over time, without regard to changes in other ecosystems. Scores estimate the predominant global condition or capacity by balancing the relative strength and reliability of the various indicators. When regional findings diverge, in the absence of global data weight is given to better-quality data, larger geographic coverage, and longer time series. Pronounced differences in global trends are scored as "mixed" if a net value cannot be determined. Serious inadequacy of current data is scored as "unknown."

Conditions and Changing Capacity

FOOD PRODUCTION

Many grasslands today support high livestock densities and substantial meat production, but soil degradation is a mounting problem. Soil data show that 20 percent of the world's susceptible drylands, where many grasslands are located, are degraded. Overall, the ability of grasslands to support livestock production over the long term appears to be declining. Areas of greatest concern are in Africa, where livestock densities are high, and some countries already show decreases in meat production.

BIODIVERSITY

Regional data for North America document marked declines in grassland bird species and classify 10–20 percent of grassland plant species in some areas as nonnative. In other areas, such as the Serengeti in Africa, In other areas, such as the Serengeti in Africa, population levels of large grassland herbivores have not changed significantly n the past 2 decades.

CARBON STORAGE

Grasslands store about one-third of the global stock of carbon in terrestrial ecosystems. That amount is less than the carbon stored in forests, even though grasslands occupy twice as much area. Unlike forests, where vegetation is the primary source of carbon storage, most of the grassland carbon stocks are in the soil. Thus, the future capacity of grasslands to store carbon may decline if soils are degraded by erosion, pollution, overgrazing, or static rather than mobile grazing.

RECREATION

People worldwide rely on grasslands for hiking, hunting, fishing, and religious or cultural activities. The economic value of recreation and tourism can be high in some grasslands, especially from safari tours and hunting. Some 667 protected areas worldwide include at least 50 percent grasslands. Nonetheless, as they are modified by agriculture, unbanization, and human-induced fires, grasslands are likely to lose some capacity to sustain recreation services.

Data Quality

FOOD PRODUCTION

Soil degradation can be determined globally, but assessment often relies on expert opinion, and the scale of the data is too coarse to apply to national policies. Data on livestock density in grasslands include global and some regional coverage, but only for domestic animals. We still lack corresponding studies of vegetation, soil condition, management practices, and long-term resilience. Data on meat production are available globally, but meat produced from livestock raised in feedlots cannot be separated from meat produced from range-fed livestock.

BIODIVERSITY

Long-term trends in grassland bird populations can be assessed from comprehensive regional data for the United States and Canada. Some long-term regional data within Africa show steady levels of major herbivore populations, but geographic coverage is limited. Other regional, national, and local data for grassland species lack long-term trends. Regional and local coverage of invasive species are more descriptive than quantitative.

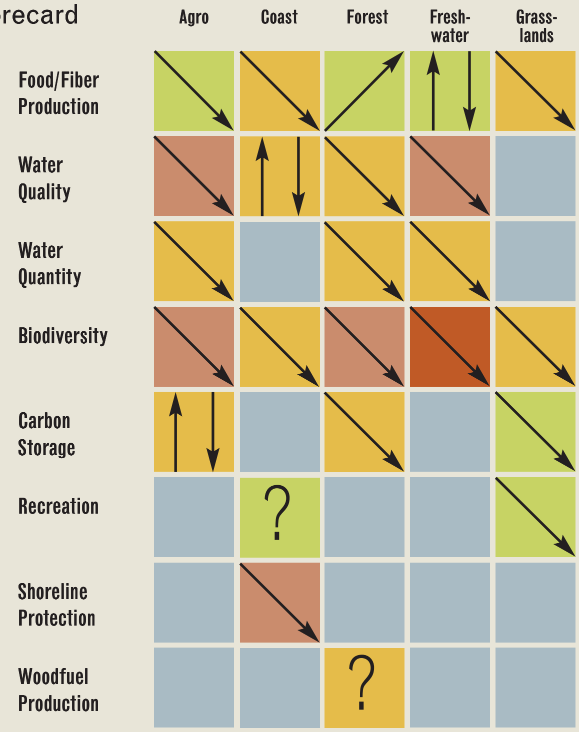
CARBON STORAGE

Methods for estimating the size of carbon stores in biomass and soils continue to evolve. This study relied on previous global estimates for above- and below-ground live vegetation, updated to fit the current land cover map by the International Geosphere-Biosphere Programme, with the addition of soil carbon storage estimates. Models are needed to incorporate carbon storage modifications based on different management practices.

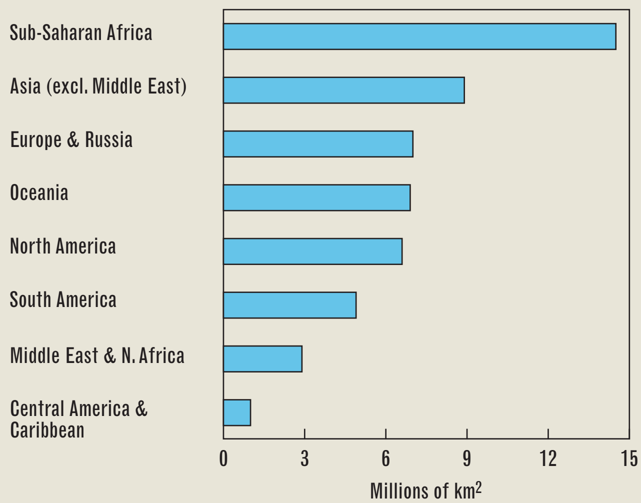
RECREATION

Regional information evaluates the exploitation of grassland wildlife but summaries are based primarily on expert opinion. Global country-level expenditures on international tourism provide estimates for all types of tourism but cannot be related specifically to grasslands. Regional data for tourism and safari hunting are good for some areas but rarely report long-term trends.

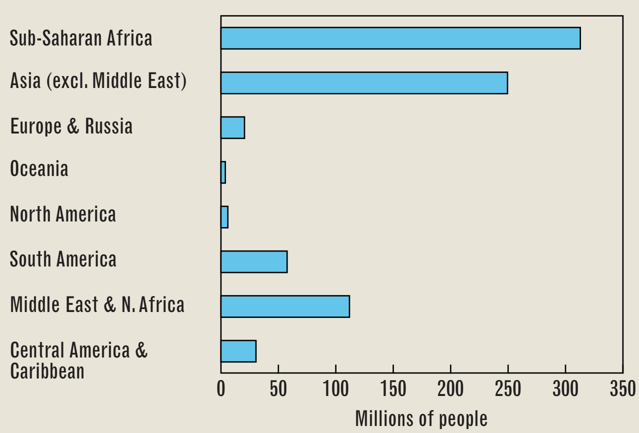
Scorecard



Area of Grassland Ecosystems



Population of Grassland Ecosystems



of Africa, the steppes of Central Asia, the cerrado and campo of South America, the prairies of North America, and the grasslands of Australia.

Extent

Estimates of the extent of the world's grassland ecosystems range from approximately 41 million km^2 to 56 million km^2, covering 31–43 percent of Earth's surface (Whittaker and Likens 1975:306, Table 15-1; Atjay et al. 1979:132–133; Olson et al. 1983:20–21). The differences among estimates are due, in part, to different definitions of grasslands; for instance, different researchers include more (or less) tundra or shrubland.

Using land-cover maps generated from recent satellite data, PAGE researchers produced a new map of the extent of the world's grasslands (Box 2.30 Global Extent of Grasslands). Some of the grasslands in this map are actually mosaics of grasslands and other land uses such as agriculture but are considered to be grasslands when those "other" land uses cover 40 percent or less of the area. Mapped this way, grassland ecosystems cover 52.5 million km^2–about 41 percent of the world's land area (excluding Antarctica and Greenland)–much more than forests or agroecosystems. Indeed, on a national basis, grasslands are one of the most common and extensive types of land cover. In 40 countries, grasslands cover more than 50 percent of the land area, and in 20 of these countries–most of them in Africa–grasslands make up more than 70 percent of the land area.

Grasslands are a significant ecosystem in many of the world's important watersheds as well. For example, grasslands comprise more than 50 percent of the land area in these watersheds: the Yellow River in China; the Nile, Zambezi, Orange, and Niger Rivers in Africa; the Rio Colorado in South America; and the Colorado and Rio Grande in North America (White et al. [PAGE] 2000). The extent of grasslands in these watersheds underscores the importance of managing grasslands so that they retain their watershed functions of absorbing rainfall to recharge aquifers, stabilizing soils, and moderating runoff. These essential watershed services are an often underappreciated aspect of grasslands.

Modifications

Like forests, the world's grasslands have lost much of their original extent through human actions–mostly conversion to agriculture. Scientists have no easy way to determine the extent of global grasslands prior to human disturbance, and thus no easy way to determine the exact amount of grasslands lost over time. However, PAGE researchers obtained a good rough estimate of historical loss by comparing current grasslands extent to "potential" grassland areas–those areas where grasslands would be expected to exist today (based on soil, elevation, and climate conditions) if humans had not intervened.

Using this approach, PAGE researchers examined in depth five regions for which the potential vegetation would likely be 100 percent grassland in the absence of humans disturbance. Among these regions, the Tallgrass Prairie in North America shows the greatest change. Croplands cover 71 percent of this region and urban areas cover 19 percent. In contrast, the grassland regions in Asia, Africa, and Australia each retain at least 60 percent of their area in grasslands with less than 20 percent in cropland and less than 2 percent in urban or built-up areas.

FIRE

Fire is a natural occurrence in most grassland ecosystems and has been one of the primary tools humans have used to manage grasslands. Fire prevents bushes from encroaching, removes dry vegetation, and recycles nutrients. Without fire the tree density in many of the world's grasslands would increase, eventually converting them to forests. In addition, fire helps hunters stalk grassland species and helps farmers control pests (Menaut et al. 1991:134).

Natural fires–typically caused by lightening–are thought to occur about every 1–3 years in humid areas (Frost 1985:232) and every 1–20 years in dry areas (Walker 1985:85). But today, the number of natural fires is insignificant compared to the number of fires started by humans (Levine et al. 1999:1). Humans have set fires in the savannas for at least 1.5–2 million years and continue to use fire as a low-cost and effective means to manage grasslands (Andreae 1991:4). Today, for example, in many African countries people use burning to maintain good forage conditions for grazing herds of livestock and to clear away dead debris (Box 2.31 Grassland Fires). Some 500 Mha of tropical and subtropical savannas, woodlands, and open forests now burn each year (Goldammer 1995, cited in Levine et al. 1999:4).

Although fire can benefit grasslands, it can be harmful too–particularly when fires become much more frequent than is natural. If too frequent, fire can remove plant cover and increase soil erosion (Ehrlich et al. 1997:201). Fires also release atmospheric pollutants. Because much of the biomass that is burned each year is from savannas, and because two-thirds of Earth's savannas are in Africa, UNEP reports that Africa is now recognized as the "burn center" of the planet (Levine et al. 1999:2). Burning of savannas is responsible for more than 40 percent of the carbon emissions from global biomass burning each year (Andreae et al. 1991:5).

FRAGMENTATION

Globally, grasslands have been heavily modified by human activities. Few large unaltered expanses remain (Box 2.32 Fragmentation of American Grasslands). Even many smaller grassland areas are extensively fragmented (Risser 1996:265). Fragmentation can affect the condition of grasslands in many ways, increasing fire frequency, degrading habitat, and damaging the capacity of the grassland to maintain biological diversity. Agriculture, urbanization, and road building are the biggest sources of grassland fragmentation, but livestock

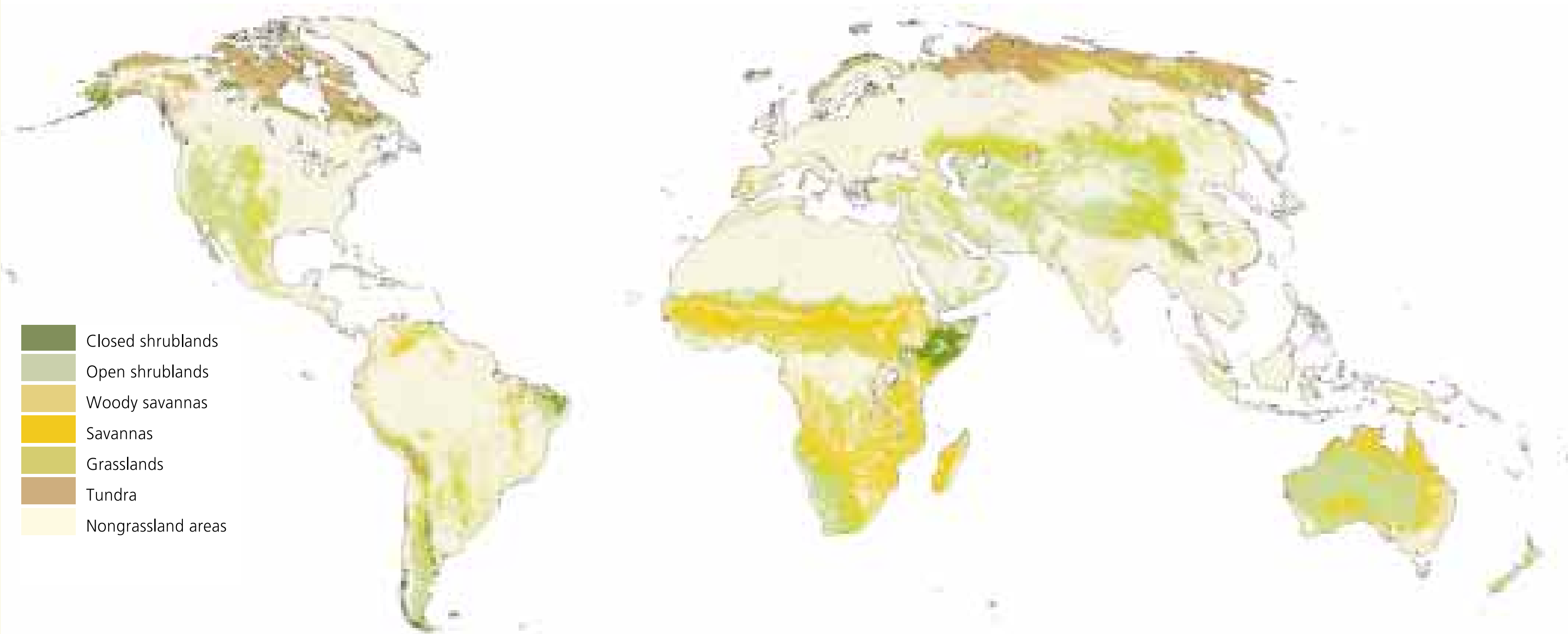
Box 2.30 Global Extent of Grasslands

Grasslands are found on every continent and cover approximately 41 percent of Earth's land area (excluding Greenland and Antarctica). To gauge the impact of human activity on the extent of grasslands, PAGE researchers looked at five regions that could be expected to be entirely grasslands, based on current climate and geographic conditions. Of these the Tallgrass Prairie in North America shows the greatest change, with grasslands now accounting for only 9.4 percent of the total area. Only 21 percent of grasslands remains in South America. By contrast, more than 50 percent of the regions selected in Asia, Africa, and Australia remain as grasslands.

Estimated Grassland, Remaining and Converted (percent)

Continent and Region	Remaining in Grasslands	Converted to Croplands	Converted to Urban Areas	Total Converted
N. America Tallgrass Prairie in the United States	9.4	71.2	18.7	89.9
S. America Cerrado Woodland and Savanna in Brazil, Paraguay, and Bolivia	21.0	71.0	5.0	76.0
Asia Daurian Steppe in Mongolia, Russia, and China	71.7	19.9	1.5	21.4
Africa Central and eastern Mopane and Miombo Woodlands in Tanzania, Rwanda, Burundi, Dem. Rep. Congo, Zambia, Botswana, Zimbabwe, and Mozambique	73.3	19.1	0.4	19.5
Oceania Southwest Australian shrublands and woodlands	56.7	37.2	1.8	39.0

The Global Extent of Grasslands



Sources: White et al. [PAGE] 2000. Map is based on the Global Land Cover Characteristics Database Version 1.2 (Loveland et al. 2000). The map shows all lands where grassland made up at least 60 percent of each 1 km^2 satellite mapping unit. Tundra areas are estimated using the Olson Global Ecosystem classification; all other areas are estimtaed from the International Geosphere-Biosphere Programme classification. Table is based on data from WWF and this map.

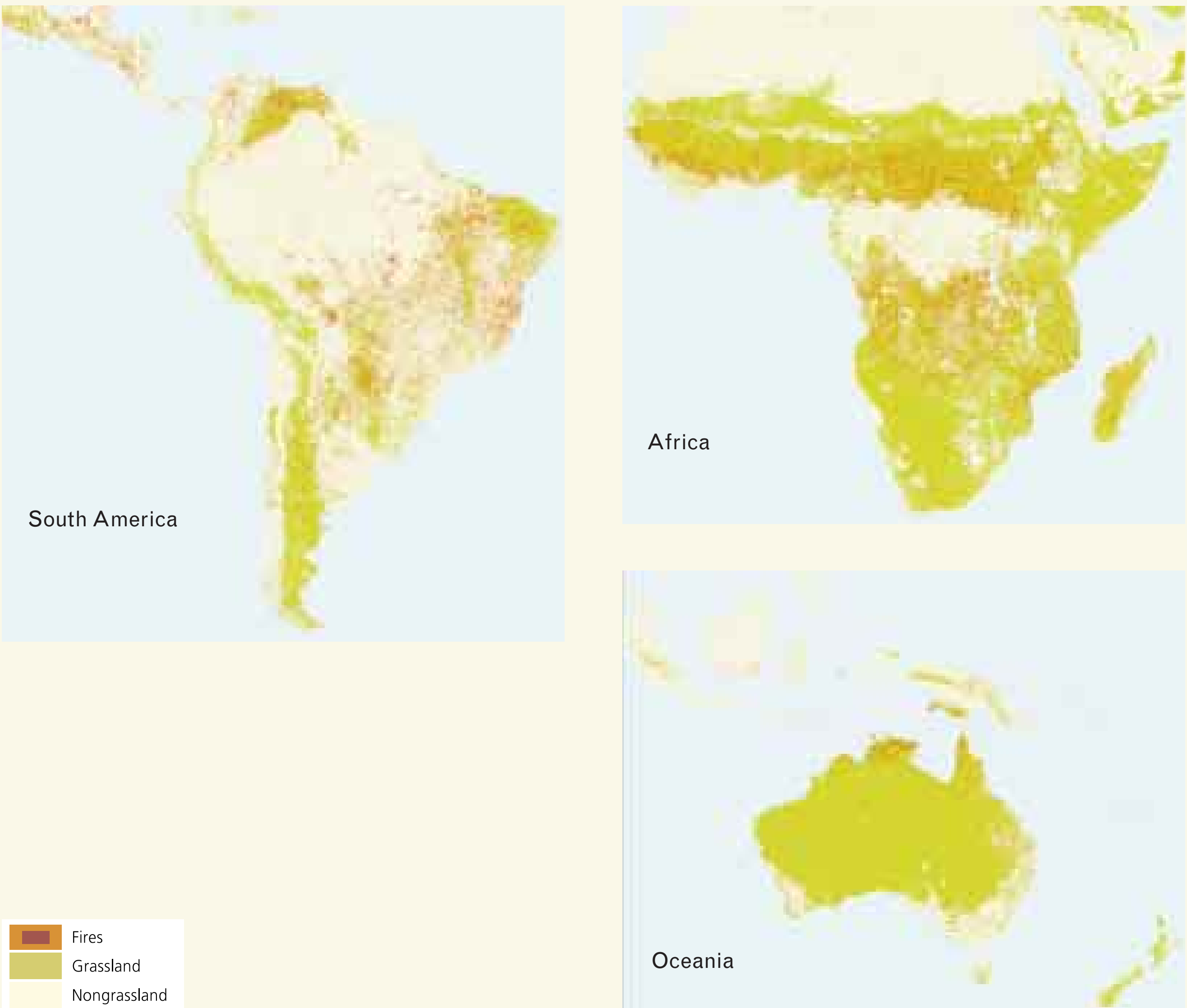
Box 2.31 Grassland Fires

Fire plays a vital role in determining the character and extent of the world's grasslands. Fires clear dry vegetation, prevent bush encroachment, and recycle nutrients. Without them, much of the world's grasslands would eventually become forested.

Today, the number of natural fires, typically caused by lightning, is insignificant compared with the number set by humans, who have used fire for millennia to hunt, clear land for cultivation and grazing, remove dead debris, and kill pests. Deliberate burning of grasslands is widely practiced in many African countries, with 25–50 percent of total land surface in the arid Sudan Zone and 60–80 percent in the humid Guinea Zone burned annually (Menaut et al. 1991:137).

Fires can be beneficial for grassland ecosystems, but if they become too frequent, they can remove vegetation cover and increase soil erosion (Ehrlich et al. 1997:201). In addition, fires are a significant source of atmospheric pollutants and carbon emissions, with savanna fires, mostly in Africa, accounting for a large proportion of the carbon released into the atmosphere as a result of biomass burning.

Fires Detected by Remote Sensing in Africa, South America, and Oceania, 1993



Source: White et al. [PAGE] 2000. Map is based on Arino and Melinotte (1998) and Global Land Cover Characteristics Database Version 1.2 (Loveland et al. 2000).

fencing and the spread of woody vegetation into grasslands also cause significant fragmentation and harm to native species.

One way to evaluate fragmentation is visually–using habitat maps and expert opinion to gauge the size of habitat blocks and the degree of fragmentation in an area. Using this approach, an analysis of 90 grassland regions in North and Latin America showed that the most heavily fragmented grasslands were in temperate and subtropical zones of North America, where there has been extensive agricultural development (Dinerstein et al. 1995:78–83; Ricketts et al. 1997:33, 147–150).

Another way to assess the pressure of fragmentation is to measure the extent to which road networks have contributed to the breakup of larger blocks of grasslands. PAGE researchers used this approach to measure fragmentation in two pilot regions: Botswana and the Great Plains in the United States. In Botswana, if the impact of roads is not considered, 98 percent of the grassland area is found in patches of at least 10,000 km^2. What little fragmentation researchers did observe is caused mainly by agricultural development or natural factors like rivers. When fragmentation by the road network is included, fragmentation increases somewhat, but 58 percent of the area still remains in 10,000 km^2 patches. In contrast, in the Great Plains of the United States, road fragmentation is pervasive. If the effect of roads is ignored, 90 percent of the grassland area is in patches of 10,000 km^2 or greater. But when roads are factored in, 70 percent of the area is in patches less than 1,000 km^2 and none larger than 10,000 km^2.

LIVESTOCK GRAZING

Grasslands and grazing animals have coexisted for millions of years. Large migratory herbivores–like the bison of North America, the wildebeest and zebra of Africa, and the Tibetan antelope of Asia–are integral to the functioning of grassland ecosystems. Through grazing, these animals stimulate regrowth of grasses and remove older, less productive plant tissue. Thinning of older plant tissues allows increased light to reach younger tissues, which promotes growth, increased soil moisture, and improved water-use efficiency of grass plants (Frank et al. 1998:518).

Grazing by domestic livestock can replicate many of these beneficial effects, but the herding and grazing regimes used to manage livestock can also harm grasslands by concentrating their impacts. Given the advantages of veterinary care, predator control, and water and feed supplements, livestock are often present in greater numbers than wild herbivores and can put higher demands on the ecosystem. In addition, herds of domestic cattle, sheep, and goats do not replicate the grazing patterns of herds of wild grazers. Use of water pumps and barbed wire fences has lead to more sedentary and often more intense use of grasslands by domestic animals (Frank et al. 1998:519, citing McNaughten 1993). Grazing animals in high densities can destroy vegetation, change the balance of plant species, reduce biodiversity, compact soil and accelerate soil erosion, and impede water retention, depending on the number and breed of livestock and their grazing pattern (Evans 1998:263).

Assessing Goods and Services

FOOD PRODUCTION

Grasslands are central to world food production. Historically, grasslands have been the ecosystem most extensively transformed to agriculture; they are the original source of many food crops and a continuing source of genetic material to improve modern crops. But grasslands are also major suppliers of food and income in the form of meat production from livestock. This is particularly important for rural populations. For example, in Africa, where rural populations are substantial, grasslands often support high livestock densities (the number of livestock raised per hectare) and are responsible for most of the continent's beef production (Box 2.33 Rangelands in Africa).

How much meat do grasslands currently produce? Global data on livestock production show more than 5 percent growth in world beef output in the last decade, to 54 million tons in 1998. Mutton and goat output increased even more–up 26 percent over the last decade to nearly 11 million tons. But such data do not provide a direct indicator of rangeland condition or its ability to support livestock. Meat production depends not only on grassland condition, but also on a range of other factors such as the availability of watering holes, dietary supplements, veterinary care, and the economic resources to acquire these things. In addition, some of the growth in meat production has come from the rapid rise in the use of feedlots (confined systems where animals cannot graze and are fattened on grain-based feeds to maximize weight gain). The popularity of intensive feedlot production is growing not only in developed countries where it is already common, but also in developing counties (Sere and Steinfeld 1996:40–41). It is not clear what implications the growing use of intensive livestock systems will have on grassland conditions, worldwide. Feedlots accounted for 12 percent of world beef and mutton production in 1996 (De Haan et al. 1997:53).

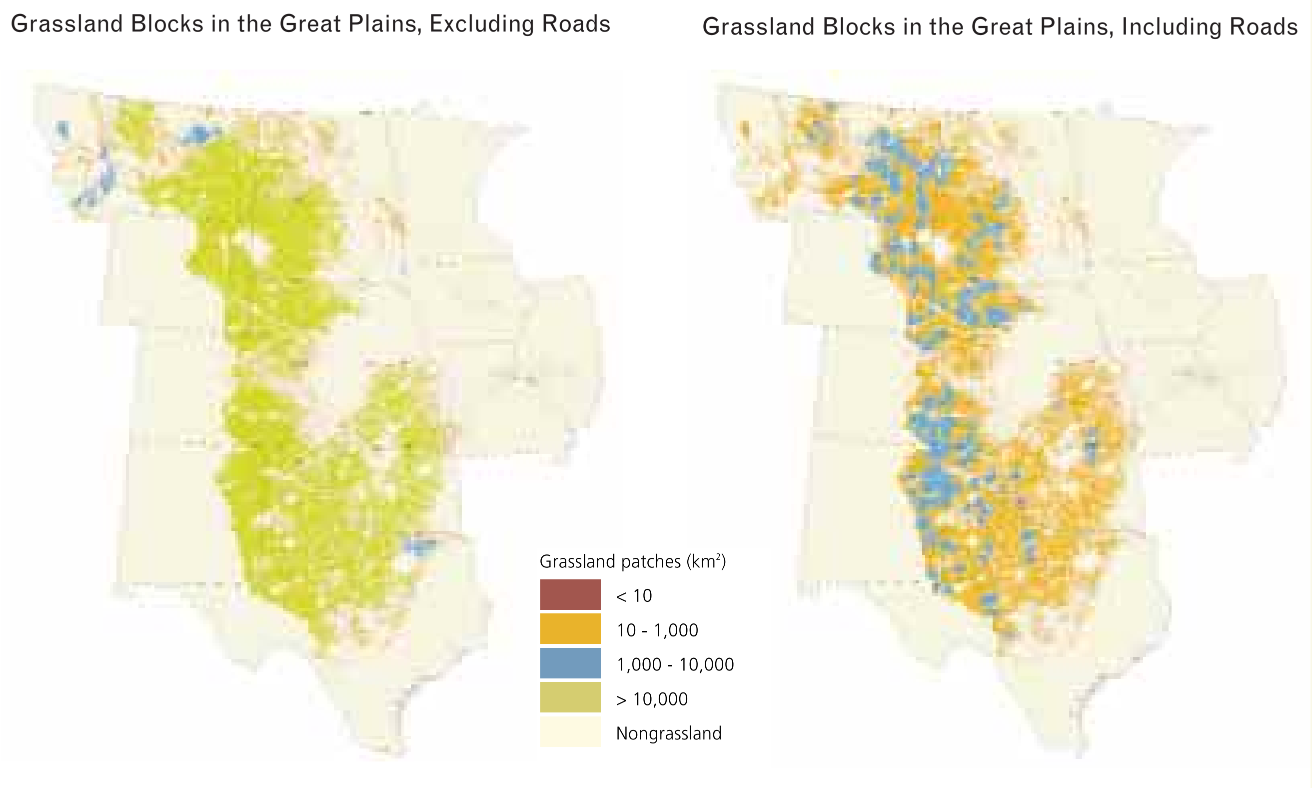
Information about livestock density is available for much of the world's grasslands and can provide a window on the grazing pressure grasslands face. However, like meat production, livestock density alone does not provide an accurate measure of the condition of the grassland system. Again, it is important to know how the livestock are managed–in particular, whether they are maintained in stable grazing systems, where livestock continuously graze a given parcel, or mobile grazing systems, where livestock are rotated over many different grazing lands. High livestock densities may indicate a highly productive system–one that effectively rotates cattle among grazing lands

(continues on p. 129)

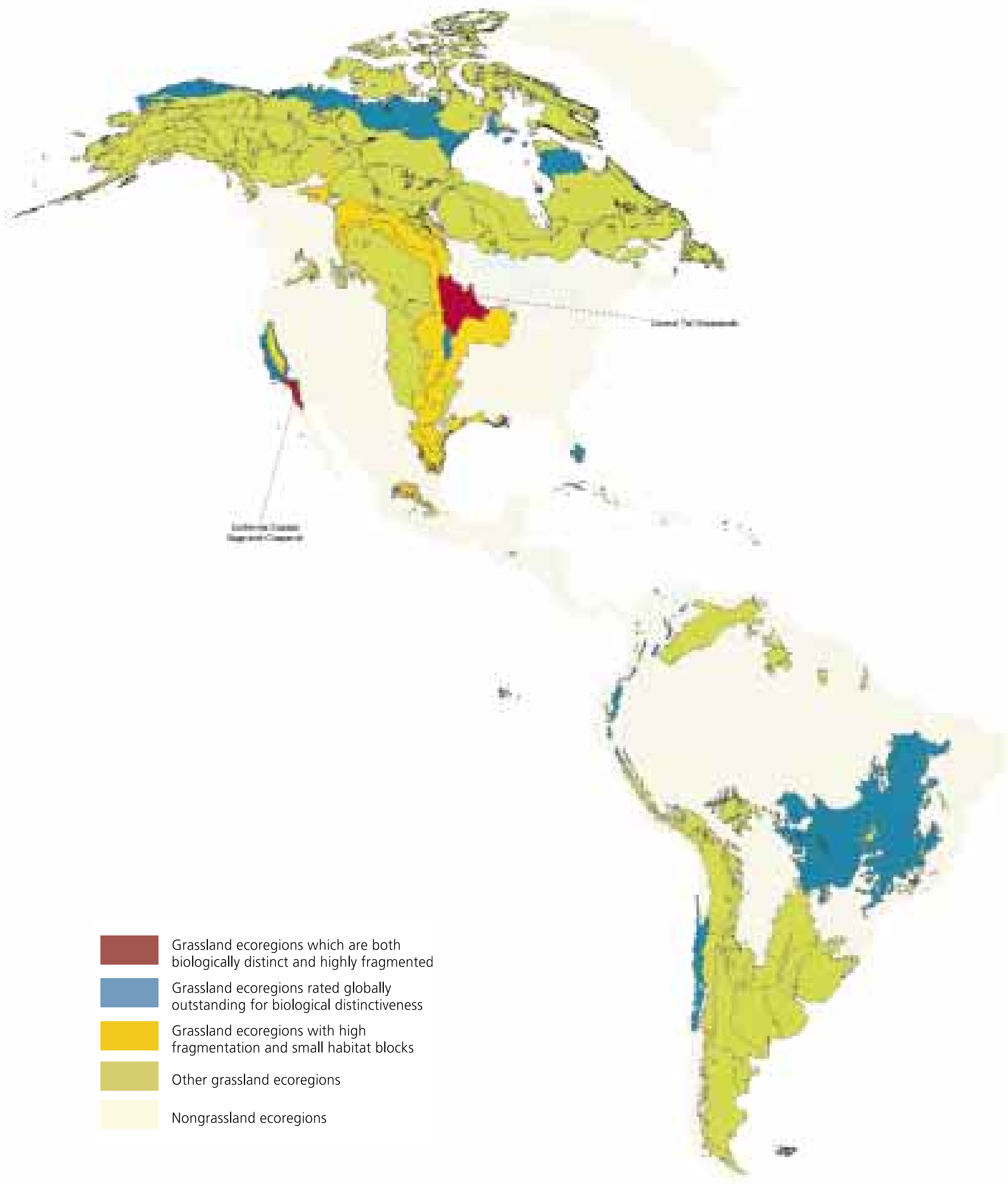
Box 2.32 Fragmentation of American Grasslands

Fragmentation of grassland ecosystems can compromise their ability to provide goods and services and jeopardize their biodiversity. Agriculture, urbanization, and road building are the primary human-caused sources of grassland fragmentation, but fencing and encroachment by woody vegetation can also have significant impacts.

In the Western Hemisphere, the most fragmented grassland ecoregions are the intensively farmed areas of temperate and subtropical North America. The degree of fragmentation of the grasslands of the Great Plains region in the United States has been exacerbated by extensive road construction. If the road network is not taken into account, 90 percent of grassland area is composed of blocks 10,000 km^2 or more in extent. With roads factored in, however, no continuous blocks of this size remain, and 70 percent of the total area is made up of patches less than 1,000 km^2.



Fragmented Grassland Ecoregions of the Americas

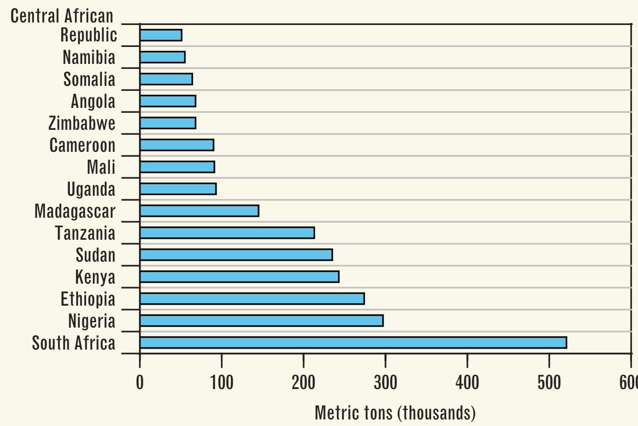


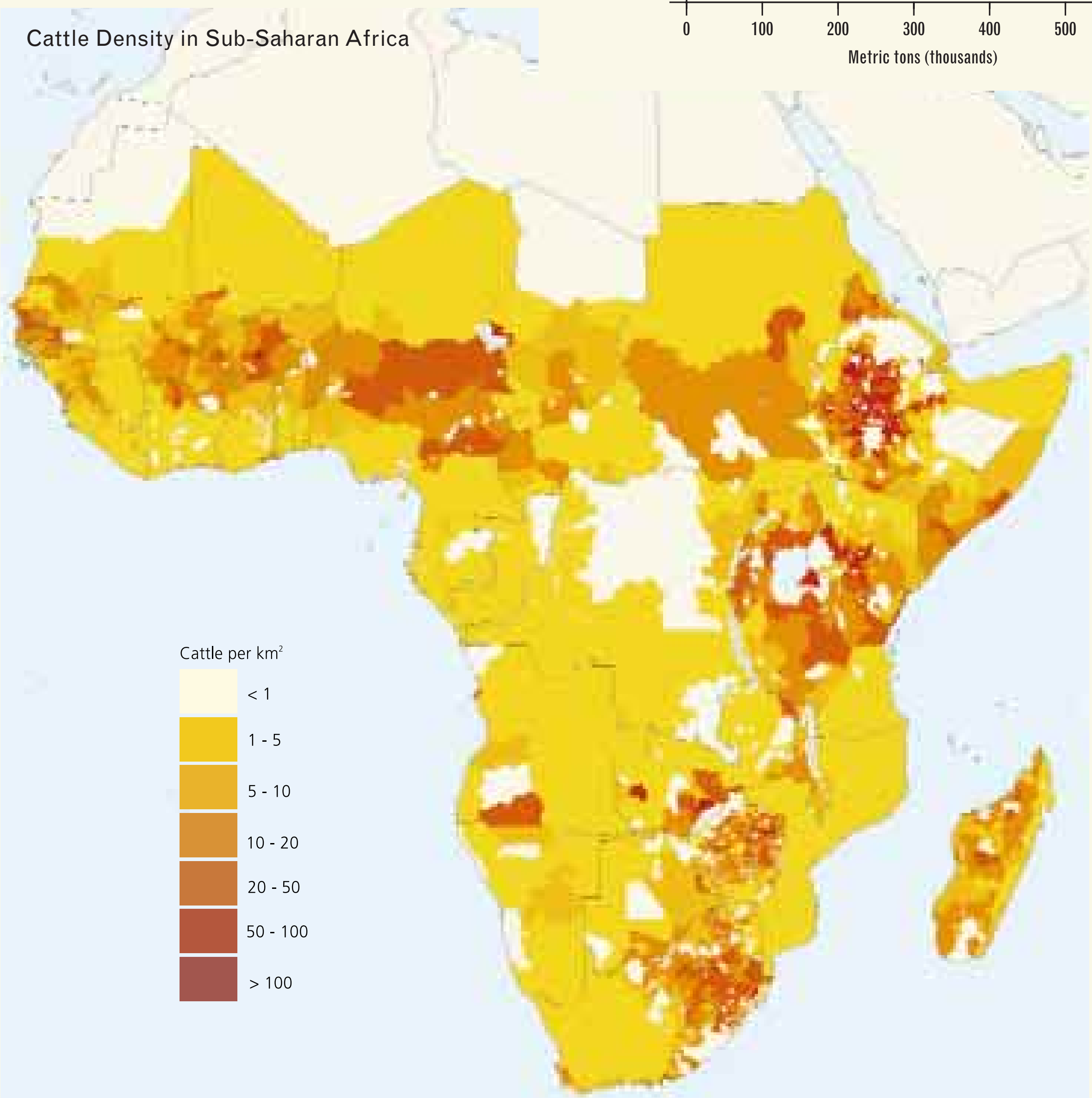
Sources: White et al. [PAGE] 2000. Maps of the Great Plains are based on Global Land Cover Characteristics Database Version 1.2 (Loveland et al. 2000). Map of the Americas is based on the WWF Conservation Assessment for North America, Latin America, and the Caribbean.

Box 2.33 Rangelands in Africa

Grasslands support some of the highest concentrations of cattle in Africa, where many rural populations depend on livestock for sustenance. High densities of livestock may indicate productive, well-managed systems or overstocked, poorly managed ones. Evidence of soil degradation often signals poor management because overstocking of herds diminishes vegetative cover and contributes to erosion. In Africa, a quarter of the susceptible drylands are now degraded, and much of that 320-Mha area is considered to be strongly or extremely degraded. The capacity of African grasslands to continue to support livestock production appears to be poor.

Beef and Veal Production in Sub-Saharan Africa, 1998





Source: White et al. [PAGE] 2000. Map is based on International Livestock Research Institute (1998). Table is based on FAOSTAT (1999).

and spreads the grazing pressure so that overgrazing does not occur. But high livestock densities could just as easily indicate an overstocked grassland, prone to overgrazing, and with production likely to decrease in subsequent years.

The importance of the livestock management system–mobile or static–is clear from a study of six grassland-rich regions of Mongolia, Russia, and China. In many parts of the study area, more recent sedentary methods of raising livestock using enclosed pastures have replaced older grazing systems more characterized by mobility, rotating livestock over multiple, sometimes widely separated, grazing sites. Comparisons among the regions indicate that the highest levels of grassland degradation are found where livestock mobility is lowest and static production systems have become the norm (Sneath 1998:1148) (see also Chapter 3 Sustaining the Steppe: The Future of Mongolia's Grasslands).

One of the most visible and useful indicators of degradation of grazing lands is soil erosion. High densities of livestock or poor management of herds diminish vegetative cover and contribute to erosion. This eventually will reduce the productivity of the grassland, although some areas with deep soils can withstand high rates of erosion for considerable time. Accordingly, information about soil condition provides a good indicator of the capacity of grassland ecosystems to sustain food production over the long term.

GLASOD provides the only source of comprehensive global information about soil loss for regions with extensive grasslands (Oldeman et al. 1991). The GLASOD study did not explicitly report on grassland areas as defined in the PAGE study; however, it did report data on the world's drylands, where grasslands are a major presence. Drylands in the arid, semiarid, and dry subhumid zones are considered particularly susceptible to soil degradation, and these susceptible drylands constitute 55 percent of grasslands as defined in PAGE. GLASOD found that slightly more than 1 Bha, or 20 percent, of all susceptible drylands globally have been degraded by human activity (Middleton and Thomas 1997:19). Water erosion is responsible for 45 percent of this damage and wind erosion 42 percent (White et al. [PAGE] 2000; Middleton and Thomas 1997:24).

Regionally, Asia has the largest area of degraded drylands: 370 Mha, or 22 percent of susceptible drylands. However, a larger fraction of Africa's susceptible drylands are degraded (25 percent, or 320 Mha) and–perhaps more critical–a higher proportion of these degraded areas are classified as "strongly degraded" and "extremely degraded"–GLASOD's severest degradation categories (Middleton and Thomas 1997:19). Elsewhere in the world, although the absolute area of degraded drylands is small, the proportionate area is sometimes large. In Europe, 99.4 Mha, or 32 percent, of the dryland area is degraded to some extent. North America, Australia, and South America have 11, 15, and 13 percent of susceptible dryland soils degraded, respectively (Middleton and Thomas 1997:19).

The Bottom Line for Food Production. Worldwide production of beef, mutton, and goat meat has never been higher. However, this reflects more the intensification of meat production into feedlots than an increase in grasslands' ability to support livestock. In fact, data on soil degradation in the world's susceptible drylands suggest that the capacity of grasslands to continue to support livestock production over the long term appears to be declining in many areas, with 20 percent of the world's susceptible drylands being degraded.

BIODIVERSITY

As in other ecosystems, grassland biodiversity supplies direct goods–game species, medicinal plants, tourism, and genetic material for breeding purposes, to name a few–and is also a critical factor underlying the capacity of grasslands to provide other goods and services. Many grasslands contain a rich assemblage of species–often species found in no other ecosystems. For example, PAGE researchers found that 19 percent of the world's recognized Centers of Plant Diversity (regions that contain large numbers of species, especially species found in only limited areas) are located in grasslands (White et al. [PAGE] 2000). Similarly, grassland areas contain 11 percent of the world's endemic bird areas (areas encompassing the ranges of two or more species that have relatively small breeding ranges).

The importance of grasslands for biological diversity is also evident from the biological distinctiveness index developed by WWF. This index considers species richness, species endemism, rarity of habitat type, and ecological phenomena, among other criteria. For North America, 10 of 32 regions rated as "globally outstanding" for biological distinctiveness are in grassland ecosystems. In Latin America, 9 of 34 of these regions are in grasslands (Dinerstein et al. 1995:21; Ricketts et al. 1997:33).

Information about the actual condition of grassland biodiversity is far less common than information about pressures threatening biodiversity, such as habitat loss and fragmentation. For this reason, the PAGE study does not include globally comprehensive measures of grassland biodiversity condition. However, PAGE researchers did draw on more restricted regional studies that can provide insight into grassland biodiversity trends.

For grasslands in North America, the North American Breeding Bird Survey provides 30-year population trends for a wide range of bird species. Survey data from 1966 to 1995 for bird species that breed in grasslands show declines throughout most of the United States and Canada. In contrast, a recent study of the Serengeti region of East Africa concluded that significant changes have not occurred in resident herbivore densities in the last 20 years. In areas close to protected area boundaries but less accessible to vehicle patrols, wildlife populations that were already low experienced declines (Campbell and Borner 1995:141).

The number and abundance of introduced species is also an indicator of biodiversity condition. Information about introduced species has never been assembled globally, but studies in North America are illustrative of nonnative species invasions in the grasslands there. The United States Congressional Office of Technology Assessment estimated that at least 4,500 nonnative species have been introduced into the United States, with approximately 15 percent causing severe harm (USCOTA 1993:3–5). A WWF study of the distribution of nonnative plant species in North America shows that at least 10 percent of the species in all ecoregions (ecologically distinct regions) within the Great Plains are nonnative, and more than 20 percent are nonnative in the California Central Valley Grasslands (Ricketts et al. 1997:83).

In the face of significant pressures on biodiversity and declining condition at a regional level, protected areas can play a pivotal role in maintaining at least samples of the natural diversity of species and habitats in grasslands. However, PAGE researchers determined that less than 15 percent of the world's protected areas consist of at least 50 percent grassland. Protected grasslands total 2.1 million km^2–about 4 percent of global grassland area (White et al. [PAGE] 2000).

The Bottom Line for Biodiversity. Direct measurements of biodiversity condition in grasslands are sparse. However, where information is available it shows that serious problems of species introductions are common and that populations of many native species are dropping. This suggests that, at least regionally, the capacity of grasslands to support biodiversity is decreasing. Indeed, the extensive conversion of grasslands to agriculture and urban areas and the growing degree of fragmentation suggest that many grassland ecosystems may already be unable to provide goods and services related to biodiversity. And, of the many areas that have been identified as still containing outstanding grassland biodiversity, few are monitored or protected by legislation or maintenance programs.

CARBON STORAGE

How the world's grasslands are managed will have a significant influence on atmospheric carbon concentrations. PAGE researchers calculated that the soil and vegetation in grasslands worldwide currently store 405–806 GtC–about 33 percent of the total carbon stored in terrestrial ecosystems. The amount of carbon stored in grasslands is about half the amount stored in forest ecosystems, even though the total area of grasslands is nearly twice as large.

Unlike tropical forests, where carbon is stored primarily in above-ground vegetation, soils store most of the carbon in grasslands (Middleton and Thomas 1997:141). In grasslands large amounts of carbon are deposited into the soil as organic litter and secretions from roots, and as nutrients for microbial organisms and insects. For example, in one savanna in South Africa, soil organic matter accounts for approximately two-thirds of the total carbon pool of about 9 kg C/m^2 (Scholes and Walker 1993:84).

A variety of human activities can disturb the carbon storage capacity of grasslands. When grasslands are converted to croplands, the removal of vegetation and subsequent cultivation reduces surface cover and destabilizes soil, leading to the release of organic carbon. Degradation of grass cover in drylands can also be a significant source of carbon loss in grasslands, as can the widespread practice of burning grasslands to improve their pasture value (Andreae 1991:5; Sala and Paruelo 1997:238). Even the growing threat of invasive species in grasslands may bode ill for carbon storage. For example, recent experiments suggest that crested wheatgrass–a shallow-rooted grass introduced to North American prairies from North Asia to improve cattle forage–stores less carbon than native perennial prairie grasses with their extensive root systems (Christian and Wilson 1999:2397).

On the other hand, programs aimed at curbing land degradation and rehabilitating grassland cover could increase carbon storage in the world's grasslands. Projections for carbon storage in the world's drylands from 1990 to 2040 show a difference of 37 gigatons in carbon emissions between a "business as usual" scenario where current degradation patterns continue, and a sustainable management scenario if programs for land rehabilitation are implemented (Ojima et al. 1993:108).

The Bottom Line for Carbon Storage. Although they store less carbon than world forests, grasslands do store approximately 33 percent of all carbon stored in terrestrial ecosystems, mostly in the soil. Thus the potential for soil degradation to decrease carbon storage in grasslands is significant. Current practices of grassland conversion and degradation of dry grassland areas are reducing the carbon storage potential in many regions of the world, especially the arid zones.

TOURISM

Grasslands provide important cultural, aesthetic, and recreational services. Many grasslands serve as choice hiking, hunting, and fishing areas, while other grasslands are sites of historical importance and religious and ceremonial activities. For example, Native American religious, ceremonial, and historical sites have been preserved in many places throughout the prairies of the United States (Williams and Diebel 1996:27).

The economic contribution of the recreational services provided by grasslands can be significant. For example, in Tanzania, gross earnings from tourism related to game hunting were $13.9 million in 1992–93, a threefold increase over 1988 (Planning and Assessment for Wildlife Management 1996:78). Similarly, total annual earnings in Zimbabwe's hunting industry grew from approximately $3 million in 1984 to close to $9 million in 1990 (Price Waterhouse 1996:85).

Other developing countries with extensive grasslands have also shown tremendous growth in international tourist receipts (income from visitors coming from out of the country) over the 10-year interval between 1985–87 and 1995–97. In Tanzania, for example, international tourist receipts rose 1441 percent, while in Ghana and Madagascar, receipts increased more than 800 percent (Honey 1999:368–369). Of course, not all this tourist growth necessarily corresponds to grassland tourism, but in some countries, such as Kenya, grasslands and their wildlife are clearly the most popular tourist destination (Honey 1999:329).

Given the growing importance of tourism as an income source, it is important to recognize that tourism also can become a pressure on ecosystems. Wildlife-seeking hunters and camera-wielding tourists can disturb wildlife, degrade grasslands with off-road excursions, pollute grasslands with a variety of pollutants including trash, and increase consumption of water and other resources in fragile areas. All these can impair the long-term ability of grassland ecosystems to provide the beauty and biodiversity that draws tourists in the first place. Analyses of tourist impacts in Kenya, Tanzania, and South Africa show mixed impacts in parks and other grassland areas, with damage mostly confined to heavily visited areas so far (Honey 1999:256).

Poaching is another modifying and degrading influence on grasslands that continues to be a problem in several African countries. In Kenya, elephant populations dropped 85 percent between 1975 and 1990 to approximately 20,000, and the rhinoceros population declined by 97 percent to less than 500 animals (Honey 1999:298).

The Bottom Line for Tourism. Growth in tourist numbers and tourism receipts in grassland-rich countries speaks to the significant economic contribution of grasslands tourism. But it is difficult to evaluate the present quality and long-term prognosis for grasslands tourism because of the lack of consistent, comprehensive data on wildlife exploitation, tourist impacts, and the size and quality of trophy animals, among other indicators. Nonetheless, the continued conversion of grasslands to agriculture and urban areas, increased fire frequency, the spread of invasive species, and the impacts of tourism itself suggest a potential decline in the capacity of grasslands to maintain tourism and recreational services over the long term.

APPENDIX: Although mountain, polar, and urban ecosystems were not included in the PAGE study, they are fundamentally important to human health and well-being. Mountain areas are the source of water for more than half of the world's population. Polar regions play a critical role in controlling global climate and sea level. Urban areas are home to half of all people, and urban populations are rising, especially in the developing world. This appendix gives brief profiles of each of these ecosystems.

MOUNTAIN ECOSYSTEMS

The grandeur of mountain ecosystems belies their delicacy. Weathering processes and gravity constantly pull rocks, soil, snow, and water downhill, inhibiting the development of soils. Thin soils and slope instability, in turn, limit plant growth, raise the vulnerability of mountains to human disturbance, and require lengthy recovery time once damaged. Mountain regions also have a long history of political neglect and economic exploitation.

Nevertheless, millions of people who live far beyond mountains' boundaries benefit from the water, timber, rich biodiversity, and awe-inspiring scenery that mountain ecosystems supply. Yet, it is the people who live in mountain and upland regions, about a tenth of the world's population, who depend most immediately on mountain ecosystems for subsistence (Grötzbach and Stadel 1997:17). Within mountainous regions of developing countries, transport links may be scarce, access to supplies and markets poor, population growth rates high, and employment opportunities limited. Mountain populations in Nepal, Ethiopia, and Peru, for example, rank among the world's poorest (FAO 1995).

Extent of Mountain Ecosystems

The definition of a *mountain region* can be based on numerous criteria–including height, slope, climate, and vegetation. A simple definition is "areas above 3,000 m"–a category that encompasses about 5 percent of the world's terrestrial surface and an estimated 120 million people. For simplicity, again, upland area is defined as the 27 percent of the world's surface above 1,000 m (Grötzbach and Stadel 1997:17; Ives et al. 1997:6–8). A total of about half a billion people live in uplands and mountains (Ives et al. 1997:8) Mountain ecosystems encompass a range of shapes, climates, and compositions of vegetation and animal species depending on elevation and latitude.

Goods and Services from Mountain Ecosystems

FOOD AND FIBER PRODUCTION

Mountains are not world centers of agriculture in terms of volume, but subsistence agriculture in mountains is the primary food source for most mountain inhabitants in developing countries–millions of people (Messerli and Ives 1997:10). Mountain agroecosystems also are valuable storehouses of food crop genes; many of the major food crops originated in uplands. Much of the world's remaining agricultural genetic diversity is believed to exist in the fields of subsistence mountain farmers or in still more remote areas.

Potatoes are a perfect example. Andean subsistence farmers have actively maintained the genetic diversity of potatoes.

In Paucartambo, Peru, about 21 potato varieties are planted in each field, and the International Potato Center in Lima maintains the world's largest bank of potato germplasm, including some 5,000 distinct types of wild and cultivated potato and more than 160 noncultivated wild species (Tripp and van der Heide 1997; CIP 2000). By comparison, in most producer countries, a few commercial varieties dominate; and these monocultures are susceptible to epidemics of pests and diseases.

Mountains also have traditionally supplied timber resources to the world and fuel to local populations, but deforestation has reduced standing timber in many areas. In the tropics, mountain forests have had the fastest rates of loss over the last decade, compared with all types of lowland forests–about 1.1 percent a year (FAO 1993:ix).

WATER QUALITY AND QUANTITY

Half the world's population depends on mountain water. All the major rivers of the world originate in mountains, which receive high levels of precipitation as rain and snow that they store temporarily as ice, then release during spring and summer melt periods (Liniger et al 1998:5). Mountain forests help filter the water and protect its quality. On average, mountains in semiarid and arid environments provide 70–95 percent of downstream freshwater. In regions with higher rainfall, mountains provide 30–60 percent of the water supply (Liniger et al. 1998:18). High elevation water flows also power many of the world's hydroelectric plants.

Mountain watersheds will be expected to meet much of the projected increase in demand for freshwater by 2025. Will they be able to? Few assessments of the biological integrity of mountain rivers have been attempted, but trends in population growth, inadequate wastewater treatment, global warming, and increasingly extensive montane forest destruction and pollution all suggest that mountain ecosystems' ability to supply ample high-quality water is being degraded.

Mining is one of the greatest threats to the supply of clean water from mountains. Many countries have lax mining laws, regulatory controls, or enforcement, particularly in remote areas where citizens may be uninformed about mining impacts. Water drained or pumped directly from mines is often highly acidic and laden with cyanide and other heavy metals. Liquid wastes may be pumped directly into local waterways, or stored in ponds or behind earthen dams that are vulnerable to overflow or leaks. A partial survey of tailings dam failures by an NGO identified more than 70 spills and accidents in the last several decades, with considerable environmental damage (D'Esposito and Feiler 2000:5).

BIODIVERSITY

Mountains encompass numerous and varied habitats informed by altitude, soil and rock type, temperature, and sun exposure; their isolation has further enabled species diversity and endemism to flourish. The mountains of Central Asia, for example, are home to more than 5,500 species of flowering plants, with more than 4,200 species concentrated in Tajikistan alone (Jeník 1997:201). Mount Kinabalu in Sabah (Borneo) is estimated to harbor more than 4,000 plant species (Price et al. 1999:5).

Mountains also function as sanctuaries for plants and animals whose lowland habitats have been lost to conversion. Tropical montane forests, for example, are refuges for some of the world's rarest species including the mountain gorillas of Central Africa, the Quetzel of Central America, the red panda of the Eastern Himalaya, the Andean spectacled bear, and the European lynx found in isolated parts of Central

Europe. Ten percent of all bird species–already reduced to restricted ranges worldwide–are found solely or primarily in cloud forests, where the atmospheric environment is characterized by persistent, frequent, or seasonal cloud cover, usually on tropical or subtropical mountains exposed to oceanic climates.

Some protection of mountain biodiversity and other services is afforded by the designation of 141 biosphere reserves, 150 parks and reserves (above 1,500 m), and 39 World Heritage Sites in mountain and upland areas–more than in any other major landscape category. Still, numerous pressures–air and water pollutants, people–cross the boundaries of protected areas (Messerli and Ives 1997:20; Schaaf 1999).

Conversion

One sign of the potential decline in the capacity of some mountains to provide biodiversity is the reduction of unique mountain habitats, like tropical montane cloud forests, to just fragments of their original extent. Perhaps 90 percent of mountain forests have disappeared from the northern Andes (WCMC 1997, citing Weutrich 1993). Although half of the world's remaining montane cloud forests have some degree of protection, WCMC reports that many continue to be fragmented or cleared at a rapid rate for agriculture, fuel wood, grazing areas, mining, and road building, and as a result of fires that spread from adjacent cultivated areas (WCMC 1997:4).

Pollution

Air pollution is another pressure with documented impacts on mountain biodiversity. As high land masses, mountains intercept more air currents, and generally receive more precipitation, than other land forms. Most researchers believe that elevated ambient levels of sulfur and nitrogen oxides and ozone are responsible for the death or decline of extensive areas of montane forest in the northeastern United States and Canada. Long-range air pollutants also have damaged the mountain ranges along the border of the Czech Republic, Southeast Germany, and Southwest Poland (FRCFFP 1998:9).

RECREATION

Mountain tourism generates about US$70–$90 billion annually worldwide, about 15–20 percent of the global tourism industry. That total only begins to capture the value of mountains as sites of sacred rituals, sacrifice, and pilgrimage for all the major world religions, many minor ones, and as places for reverence of nature and wilderness (Price et al. 1999:4).

But mountains may have a difficult time sustainably accommodating further growth in tourist numbers. Tourism can significantly increase the employment and income levels of mountain communities, and sometimes provides funds for ecosystem protection. At the same time, tourism can be a primary degradation force. For example, mountains are heavily used by the 65–70 million downhill skiers worldwide (Price et al. 1999:36). They consume local supplies of food and water, generate solid waste and sewage, and require access to once pristine locales via roads, rail lines, airports, and hotels. Skiing also involves forest clearance and consumption of large volumes of water for snowmaking or watering.

High in the San Juan Mountains of Colorado, near the Continental Divide, the Summitville gold mine leaked contaminants into the Alamosa River in 1992, killing all aquatic life along a 27-km stretch. Clean-up is slated to cost $170 million (Carlson 2000:10).

The Bottom Line for Mountain Ecosystems. The demand for mountain areas' mineral resources, timber, scenic beauty, and water is growing. Yet there is a chronic lack of data regarding the state of mountain ecosystems and the extent and growth rates of activities damaging to mountain ecosystems. Agenda 21—the environmental blueprint crafted at the Rio Earth Summit in 1992—argued that mountains, as fragile areas, require integrated ecosystem treatment, like islands, polar regions, or tropical rainforests. Although acceptance of this viewpoint is growing, mountains are still low on the priority list of most national and international agendas. They remain vulnerable to exploitation by lowland populations through damaging extraction of natural resources and tourism development, for example, and by poorly designed government policies that contribute to the demise of traditional mountain farming systems and indigenous knowledge.

POLAR ECOSYSTEMS

The polar regions are the most remote places on Earth, yet their extreme conditions—cold, high, dry, windy, and largely removed from the public eye and political priority list—heighten their vulnerability. How the Arctic and Antarctica will respond to global environmental changes is a growing concern because these regions strongly influence the global climate system, hold a wealth of mineral and biological resources, and contain most of the world's freshwater as ice and permafrost. The fate of polar resources may signal dangers that will later become apparent in the rest of the world.

Managing the polar ecosystems requires cooperation. Eight countries share jurisdiction over the Arctic: Canada, Denmark/Greenland, Finland, Iceland, Norway, Russia, Sweden, and the United States. Antarctica is managed by interested countries on the basis of international agreements, although various countries have claims of sovereignty—some contested—over the continent, some sub-Antarctic islands, and adjacent territorial seas (UNEP 1999:327,329).

Extent of Polar Ecosystems

The areas surrounding the two poles have some things in common—cold climate, snow, and ice. Otherwise, their land and marine ecosystems are significantly different. A thick ice sheet covers the Antarctic continent; even during the summer season, only a few mountain and coastal areas are snow-free. The size of the ice sheet ranges from 4 to 19 million km^2, depending on the season; it is, on average, 2.3 km thick; and it represents 91 percent of the world's ice and the majority of the world's freshwater (GLACIER 1998; UNEP 1998:178). Surrounding Antarctica are open seas that have a productive shelf and upwelling areas where the shelf meets warmer waters. Other than about 4,000 researchers, Antarctica is uninhabited (Watson et al. 1998:89).

The Arctic, in contrast, consists of a large, deep ocean covered by drifting ice sheets a few meters thick. The land areas, which surround the ocean and are usually considered part of the Arctic region, are dominated by polar desert and tundra vegetation, although they include some prominent ice caps such as Greenland's inland ice. The Arctic's marine waters include the shallow and deep waters south and west of Alaska, the Barents Sea, and the northern Atlantic. The Arctic tundra is home to about 3.5 million people, many of whom make a living from marine and freshwater fishing, hunting, and reindeer husbandry (UNEP 1999:179).

Goods and Services from Polar Ecosystems

Although polar regions include some of the last large areas where human activity has not overtly altered the landscape, scientists have found solid evidence that human activities—often occurring in other parts of the world—are modifying polar environments and the goods and services they provide.

REGULATION OF GLOBAL CLIMATE, OCEAN CURRENTS, AND SEA LEVEL

Earth's vast polar ice sheets serve as a mirror, reflecting a large percentage of the sun's heat back into space, thus keeping the planet cool. Without the ice sheets, more heat from the sun would be retained in the ocean and more would be released into the atmosphere, feeding the warming process.

A warmer climate would also promote the release of more CO_2. For the past 10,000 years, tundra ecosystems in the Arctic have sequestered atmospheric carbon and stored it in the soil;

the tundra and boreal region store about 14 percent of the world's carbon (AMAP 1997:161). Some parts of the Arctic may now be sources of CO_2 emissions, however, because of the faster decomposition of dead plant matter in a warmer climate. If the permafrost under the tundra thaws, methane releases could also accelerate global warming (AMAP 1997:161).

The planet's weather patterns are driven largely by water circulation in the world's oceans, which is, in turn, driven by Arctic marine ecosystems. Warmer surface waters, including those from the nine major freshwater systems that drain into the Arctic Ocean, cool when they enter the North Atlantic (AMAP 1997:11). They become denser and sink to the bottom of the ocean—several million km^3 of water each winter–and slowly push water south along the bottom of the Atlantic. These water currents affect rainfall and climate worldwide (AMAP 1997:12).

The vast ice sheets in Antarctica and Greenland also control the world's sea level. If they shrink, sea level could rise, ocean currents could shift, and weather patterns could change and bring drought, severe storms, and the spread of tropical diseases.

Gradual disintegration and ice melt in polar regions are part of natural processes, but scientists are exploring the possibility that climate change may be altering those processes. Measures of ice thickness taken by U.S. submarines between the 1950s and 1970s compared with recent measurements indicate that the ice covering the Arctic Ocean may have thinned dramatically during the last few decades. The older submarine data showed an average thickness of 3.1 m, whereas data at the same sites in the 1990s show an average thickness of 1.8 m (Rothrock et al. 1999:3469). Satellite observations since the 1970s show the Arctic Sea cover to be shrinking at about 3 percent per decade (USGCRP 1999).

BIODIVERSITY

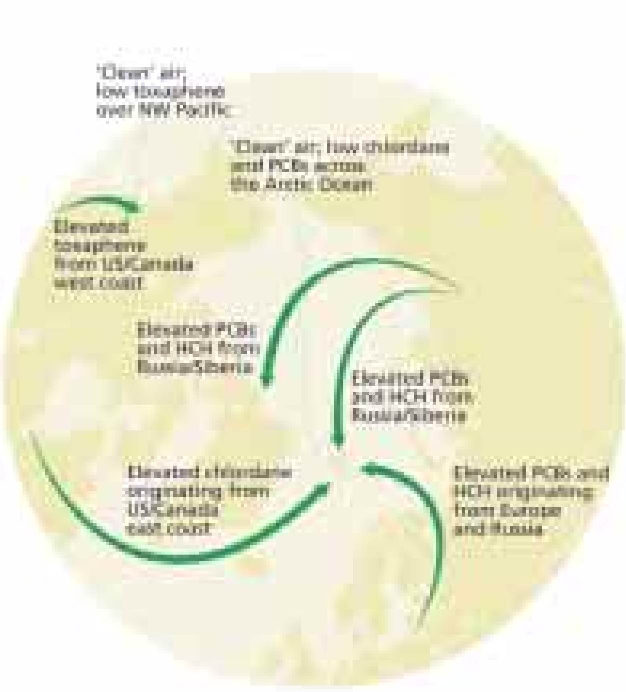
Hundreds of species are endemic to the Arctic, a place where organisms have adapted to the extremes of temperature, daylight, snow and ice found in polar regions. The Arctic also serves as habitat for several migratory bird species. Similarly, some islands of Antarctica have high levels of endemic species—some of New Zealand's southern islands are home to about 250 species, including 35 endemics. Still, much remains to be learned about the terrestrial fauna of the Antarctic, just as little is known about the fauna of the area's deep sea (UNEP 1999:183, 191, 192).

Pollution

Pollution may be the most immediate and evident threat to polar biodiversity. Airborne pollutants have turned the Arctic into a "sink" for contaminants from all over the world. Persistent organic pollutants (POPs) and other toxic chemicals travel on air, water, and wind currents until they settle in the Arctic, where they bioaccumulate in the food chain (AMAP 1997:viii). Radioactive materials have also accumulated in the Arctic; sources are fall-out from nuclear bomb tests, the accident at Chernobyl, and releases from European nuclear fuel reprocessing plants. For the general population in the Arctic and sub-Arctic, exposure to radioactive contamination is about five times higher than expected levels in a temperate area. Indigenous populations, who rely mainly on terrestrial food products, such as reindeer meat, have about 50 times higher exposure than other Arctic citizens (AMAP 1997:122–126).

The effects of POPs on wildlife are not fully understood, but it is clear that the biomagnification effects on certain species—birds, seals, polar bears, and others at the top of the food chain—are grave and will continue to worsen (UNEP 1999:184, 185). Polychlorinated biphenyls (PCBs), for exam-

Polar Pollution: Source regions for contaminated air



Source: AMAP 1997:79.

ple, are already found in polar bears in concentrations likely to affect their reproductive ability (AMAP 1997:89). People living in the polar regions exhibit similar high exposure to toxins with contaminant levels that can be 10–20 times higher than in most temperate regions (AMAP 1997:172). Numerous studies have linked even low-level or short-term exposure to dysfunction of the immune system, neurological deficits, endocrine disruption, and cancer.

Resource Extraction

Natural resource extraction is a growing threat to the biodiversity of polar ecosystems. Oil exploration is increasing, for example, and already its track record for pollution control includes 103 major pipeline failures in the Russian Federation between 1991 and 1993 (AMAP 1997:150). Natural resource extraction also causes damage to tundra, which is vulnerable to vehicular traffic. During the summer season, only the top few feet of soil melt, creating a layer of very wet soil between the permafrost and the thin vegetative cover. Erosion of the top vegetation easily leads to large-scale soil erosion that, because of Arctic ecological and climatic conditions, will take centuries to repair, while inducing further melting of the permafrost.

Ozone Depletion

It is not clear how ozone depletion in polar regions will affect biodiversity. Ozone depletion is more pronounced near the poles than elsewhere in the world. In 1985, a massive ozone hole was discovered over Antarctica in the spring. In recent years, ozone depletion over the Arctic has also been evident in smaller, less frequent holes (generally a few hundred kilometers in diameter, lasting a few days each), but the trend was clearly one of decreasing ozone levels through the 1990s in all seasons (Fergusson and Wardle 1998:8, 19; UNEP 1999:177). Ultraviolet (UV) radiation levels estimated in the spring, compared to the 1970s, are now about 130 percent higher in Antarctica and 22 percent higher in the Arctic (UNEP 1998:1). Polar ecosystems' heightened exposure to the sun's harmful UV-B rays could increase the incidence of cataracts and eye and skin cancer for humans, adversely affect plants and plankton accustomed to low-UV radiation, and perhaps harm algae at the base of the marine food web (UNEP 1998:xi–xiii).

Climate Change

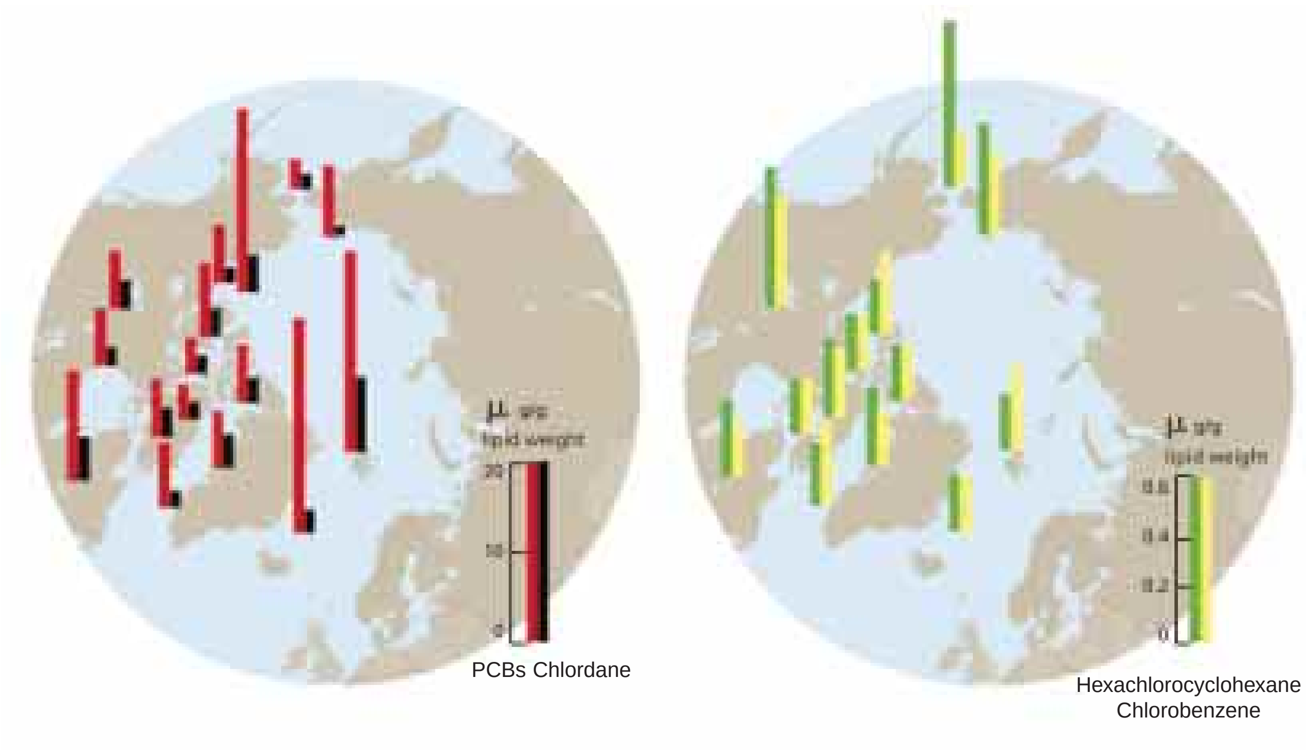
The effect of climate change on polar biodiversity is another unknown. Warmer temperatures could convert tundra to boreal forests, change migration patterns of polar bears and caribou, alter the distribution of some small mammals whose food sources may be disrupted, and change fish species composition, among other effects (Watson et al. 1998:95–99).

FOOD PRODUCTION

The Arctic marine waters are among the richest fishing regions in the world and a major contributor to the world's fish catches. In much of Newfoundland, Greenland, Iceland, the Faroe Islands, and northern Norway, fishing is the primary livelihood (Hamilton et al. 1998:28). Local populations, particularly rural indigenous communities, are particularly reliant on hunting and fishing. Indigenous groups comprise about 50 percent of the population of Arctic Canada; and in some regions of the Yukon as much as one-third of the population lives off the land and another 30 percent support their families with activities that are not part of the cash economy (AMAP 1997:57). In much of Arctic Russia, reindeer meat is the primary food source and herding the main occupation. Secondary food sources may include moose, brown bear, bighorn sheep, alpine hare, ducks, geese, and other birds and fish.

Several polar fish stocks have been adversely affected in recent years, including salmon, cod, northern char, herring, and capelin. In the Faroe Islands, for example, cod landings decreased from about 200,000 tons to less than 70,000 tons between 1987 and 1993 after Faroese investments in catching and processing led to overfishing (Hamilton et al. 1998:30). Sometimes poaching is the biggest problem; Patagonian toothfish harvests have been driven to the brink of collapse in the Antarctic in the last 6–7 years because of illegal fishing

Polar Bears at Risk: Persistent organic pollutant (POPs) levels in polar bear tissues at several arctic locations



Source: AMAP 1997:89

and lax catch-limit enforcement. In 1997 the reported legal catch of Patagonian toothfish was 10,245 tons; the illegal catch was estimated at more than 100,000 tons in the Indian Ocean sector of the Southern Ocean alone (UNEP 1999:176).

RECREATION

There is a growing desire to explore polar areas. In the early 1990s, more than a million tourists were drawn to the Arctic (UNEP 1999:182). About 10,000 visited Antarctica in 1998–99, and a more than 50 percent increase to almost 16,000 was projected for 1999–2000 (IAATO 2000). Those may seem small numbers relative to the vast areas, but they have the potential for detrimental effects. Tourists are thought to frighten wildlife like breeding penguins in Antarctica, leave behind garbage, and create noise and pollution.

FEEDBACK

The poles are important to the world as early indicators of the pressures we are placing on global resources. For example, we can use analyses of the condition of the Arctic to better understand stratospheric ozone production, atmospheric cleansing, and pollution transport in northern latitudes. The massive ice sheets also serve as a kind of "time capsule" of information about volcanic activity, storminess, solar activity, and atmospheric composition (Stauffer 1999:412). Ice cores recently excavated from Vostok station in East Antarctica show that atmospheric concentrations of carbon dioxide and methane, two important greenhouse gases, are higher now than they have been in the past 420,000 years (Petit et al. 1999:429).

The Bottom Line for Polar Ecosystems. The polar ecosystems are still relatively unmodified when compared to other ecosystems, but their once-pristine condition already shows signs of climate change and other pressures. The effects of climate change are greater in polar regions than anywhere else on Earth. It is still unclear whether the ice thinning that has been observed in select areas is part of a natural climate variation or the result of human activities; nor is it clear whether the overall mass of the world's polar ice sheets is growing, shrinking, or fluctuating within normal parameters. But polar regions provide ample evidence of warming via ice cores and glacier retreat (Watson et al. 1998:90–91). Meanwhile, the immediate disruption caused by pollution and unsustainable levels of commercial fishing of some stocks is significant and growing.

URBAN ECOSYSTEMS

Urban areas are some of the most significant sectors on the planet in terms of human well-being, productivity, and ecological impact. Cities are centers of commerce, industrial output, education, culture, and technological innovation. As nexuses of the world's market economies and home to more than 2.7 billion people (World Bank 2000:152), cities are also centers of natural resource consumption and generators of enormous amounts of wastes, with environmental ramifications both locally and in distant ecosystems.

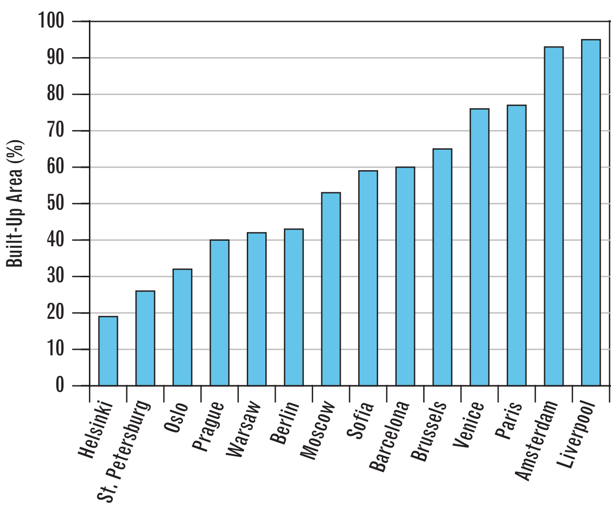
Urbanization's tremendous influence on humans and the environment will surely grow, as it is projected that global urban populations will nearly double by 2030 to 5.1 billion (UN Population Division 1996). But do urban areas–or portions of them–function as ecosystems? What defines an urban ecosystem?

Urban Ecosystems: Extent and Modifications

The concept of urban areas as ecosystems is new and controversial. There is no agreed-upon definition of an urban ecosystem, but the simplest and most useful one may be "a biological community where humans represent the dominant or keystone species and the built environment is the dominant element controlling the physical structure of the ecosystem." The physical extent of urban ecosystems is determined by the densities of both population and infrastructure. Administrative boundaries of cities generally are not reliable indicators of urban ecosystem boundaries for a number of reasons. For example, the U.S. Census Bureau defines urban areas as "areas where population density is at least 1,000 people/mi^2 (621 people/km^2)" (US Census Bureau 1995) but doesn't define a minimum infrastructure density. Another complicating factor is that urban areas are not sharply delineated but blend into suburbs and then rural areas. The PAGE estimate, however, is that urban ecosystems cover about 4 percent of the world's surface (see Box 1.10 Domesticating the World: Conversion of Natural Ecosystems, pp. 24–25).

Urban ecosystems, unlike natural ecosystems, are highly modified, with buildings, streets, roads, parking lots, and other artificial constructions forming a largely impenetrable

Built-Up Area of Selected European Cities



Source: Eurostat et al. 1995:202. 205.

Urban Tree Cover in Selected Cities

Tree cover in cities varies because of differences both in management and in the natural environment, particularly precipitation.

City	Tree Cover (%)
Baton Rouge, Louisiana (USA)	55
Waterbury, Connecticut (USA)	44
Portland, Oregon (USA)	42
Dallas, Texas (USA)	28
Denver, Colorado (USA)	26
Zurich, Switzerland	24
Windsor, Canada	20
Colima, Mexico	15–20
Hong Kong	16
Los Angeles, California (USA)	15
Chicago, Illinois (USA)	11
Ciudad Juarez, Mexico	4

Source: Nowak et al. 1996.

covering of the soil. Cities do contain natural and seminatural ecosystems–lawns and parks, forests, cultivated land, wetlands, lakes, streams–but the vegetation in those areas may be altered or highly managed, too.

Urbanization can change the structure and composition of vegetation of a region, whereby indigenous plants are replaced by nonnative species. For example, in the former West Berlin, approximately 40 percent of more than 1,400 plant species currently identified in the city are nonnative, and nearly 60 percent of native species are endangered (Kowarik 1990:47). In wooded areas, the ground leaf layer may be removed and replaced with shade-tolerant grass, disrupting the natural processes that create healthy soils and reducing an area's suitability as habitat for wildlife (Adams 1994:34).

Environmental stresses also modify the natural elements of urban ecosystems. Urban trees are subject to high levels of air pollutants, road salts and runoff, physical barriers to root growth, disease, poor soil quality, and reduced sunlight. Animal and bird populations are inhibited by the loss of habitat and food sources, toxic substances, and vehicles, among other intrusions.

Open space and tree cover vary widely in cities, depending on the natural environment and land use. In the United States, one analysis of more than 50 cities found that urban tree cover ranged from 0.4 percent in Lancaster, California, to 55 percent in Baton Rouge, Louisiana (Nowak et al. 1996:51).

Goods and Services Provided by Urban Ecosystems

The human elements of the city–its man-made infrastructure and economy–provide goods and services of enormous value, including human habitat, transportation networks, and a wide variety of income opportunities. But green spaces, which often form the vital heart of urban ecosystems, also contribute a wide range of goods and services. Just a few of them are focused on here.

AIR QUALITY ENHANCEMENT AND TEMPERATURE REGULATION

Temperatures in heavily urbanized areas may be 0.6–1.3 °C warmer than in rural areas (Goudie 2000:350). This "heat island" effect is the result of large areas of heat-absorbing surfaces, like asphalt, combined with a city's building density and high energy use. Higher temperatures, in turn, make cities incubators for smog. Air pollution levels in megacities like Beijing, Delhi, Jakarta, and Mexico City sometimes exceed WHO health standards by a factor of three or more (WRI et al. 1998:63).

Green space within cities significantly lowers overall temperatures and thus reduces energy consumption and air pollution (Lyle and Quinn 1991:106, citing Bryson and Ross 1972:106). A single large tree can transpire as much as 450 liters of water per day, consuming 1,000 megajoules (239,000 kcal) of heat energy to drive the evaporation process (Bolund and Hunhammer 1999:296). Urban lakes and streams also help moderate seasonal temperature variations. Urban trees and forests remove nitrogen dioxide, sulfur dioxide, carbon monoxide, ozone, and particulate matter. Trees in Chicago, for example, have been estimated to remove 5,575 tons of air pollutants per year, providing air cleansing worth more than US$9 million (Nowak 1994:71, 76). Urban forests in the Baltimore/Washington region remove 17,000 tons of pollutants per year, providing a service valued at $88 million (American Forests 1999:5). Even peripheral forests help urban air quality. Wind currents over the central city of Stuttgart, Germany draw cooler air from surrounding forest belts, cooling the downtown areas–one reason why Stuttgart has discouraged urban sprawl (Miller 1997:65, citing Miller 1983).

BIODIVERSITY AND WILDLIFE HABITAT

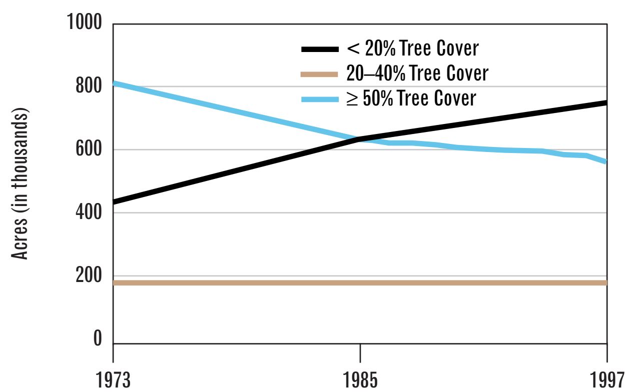
Cities support a relatively wide variety of plants and animals–both the native species that have specifically adapted to the urban landscape and its extreme ecological conditions and the numerous nonnative species humans have introduced.

Many of the animals, birds and fish that inhabit urban areas are valuable for the excitement and pleasure they bring to many urbanites, though some species are perceived as nuisances or dangerous. Almost a third of urban residents surveyed in the United States–more than 40 million people–report that they participate in wildlife watching activities

Changes in Tree Cover in the Baltimore-Washington Corridor, 1973–97

Overall tree cover has declined steadily in the rapidly growing Baltimore-Washington, D.C., urban corridor in the eastern United States. Urban and suburban expansion, as well as diminishing budgets for urban tree care, have shrunk tree cover from 51 percent of the land area in 1973 to 37 percent in 1997. Land with heavy tree cover (>50 percent wooded) declined by one-third, while land with little or no tree cover increased by nearly 60 percent.

Tree Cover Trends, 1973–97



Source: American Forests 1999.

within 1 mile of their homes (U.S. Department of the Interior 1997:94).

Some urban wildlife also is valuable from the perspective of conservation and biodiversity. Urban parks and other green spaces are critical to migratory species and provide wildlife corridors, even though these corridors are often too fragmented to afford animals sufficient area to maintain diverse populations. Nevertheless, in many North American urban areas, deer and small herbivores such as squirrels are prevalent. Muskrats and beavers may be widespread in urban water areas, and some smaller predators like bats, opossum, raccoon, coyote, fox, mink, and weasels adapt well to the habitat changes wrought by development (Adams 1994:57–65). Rats, as scavengers, have adapted particularly well to crowded human living conditions.

Many urban streams are so polluted, littered, or channelized, or their riparian zone so substantially reduced and cleared of vegetation, that only the most pollution-tolerant species survive. Yet urban rivers also offer some of the greatest potential for restoration and the return of aquatic diversity. For example, in 1957 London's Thames was virtually devoid of fish in one stretch, but by 1975 efforts to improve the biological conditions were rewarded with the return of 86 different species of marine and freshwater fish (Douglas 1983:137).

Bird diversity in urban areas may provide a good indicator of urban environmental quality, since birds require differentiated habitat and are influenced by air and aquatic pollution through the food chain. For example, a 1993 survey of Washington, D.C., bird species richness identified 115 species–an

In Cuba in 1999, urban agriculture produced 800,000 tons of fresh organic produce and employed 165,000 people. Urban agriculture produced 65 percent of the nation's rice, 43 percent of the fruits and vegetables, and 12 percent of the roots and tubers.

estimate that agreed closely with totals from surveys decades earlier, and was almost as high as the number found in larger, surrounding counties. This suggests that Washington, D.C.–perhaps because parks and low to moderate density residential areas cover 70 percent of the metropolitan area–is providing diverse and good-quality habitat for birds. Unfortunately, such citywide studies are rare (U.S. National Biological Survey 2000).

STORM-WATER CONTROL

Urban forests, wetlands, and streamside vegetation buffer storm-water runoff, control pollution, help recharge natural groundwater reservoirs, and minimize flooding in urban areas. In contrast, buildings and roads cover much urban land with impervious surfaces and eliminate vegetation that provides natural water storage capacity.

Some studies have attempted to put a monetary value on the benefit of urban forests to storm-water control. Forests in the Baltimore/Washington area save the region more than $1 billion–money that would otherwise have to be spent on storm-water retention ponds and other systems to intercept runoff (American Forests 1999:2). Unfortunately, in most cities worldwide, urban trees are a resource at risk. Since the 1970s, three major U.S. metropolitan areas–Seattle, Baltimore/Washington, and Atlanta–have lost more than a third of their heavy tree cover (Smith 1999:35).

FOOD AND FIBER PRODUCTION

Many urban areas contribute substantially to their food supply. Urban agriculture includes aquaculture, orchards, and livestock and crops raised in backyards and vacant lots, on rooftops and roadsides, and on small suburban farms (UNCHS 1996:410). Urban and periurban agriculture is estimated to involve 800 million urban residents worldwide (FAO 1999). In Kenya and Tanzania, 2 of 3 urban families are engaged in farming; in Taiwan, more than half of all urban families are members of farming associations; in Bangkok, Madrid, and San Jose, California, up to 60 percent of the metropolitan area is cultivated (Smit and Nasr 1992:142; Chaplowe 1998:47). In Ghana's capital, Accra, urban agriculture provides the city with 90 percent of its fresh vegetables (The MegaCities Project 1994). Urban agriculture also provides subsistence opportunities and income enhancement for the poor and offers a way to recycle the high volumes of wastewater and organic solid wastes that cities produce.

RECREATIONAL OPPORTUNITIES AND AESTHETIC HAVENS

Trees provide visual relief, privacy, shade, and wind breaks. Trees and shrubs can also reduce cities' typically high noise levels; a 30-m belt of tall dense trees combined with soft ground surfaces can reduce noise by 50 percent (Nowak and Dwyer 1996:471). Parks provide urban dwellers with easy access to recreational opportunities and places to relax–an enormously valuable service where open space and escape from asphalt are often at a premium. Some urban parks, lakes, and rivers are also tourist attractions and enhance values of downtown areas. Furthermore, urban water bodies provide places for sportfishing, kayaking, sailing, and canoeing.

Managing Urban Areas as Ecosystems

One of the primary challenges to managing urban areas as ecosystems is the lack of information. Because the science of urban ecology is in its infancy, the knowledge base for urban areas as ecosystems is less comprehensive than for other ecosystems. In particular, there is a dearth of data concerning the "green" elements of cities. Air and water quality, sewerage connections, water withdrawals and solid waste per capita, and trends in the extent of urban forests and wildlife diversity are critical indicators of the condition and capacity of the more natural areas in urban spaces to provide environmental goods and services.

Another problem is lack of planning and budgeting for the care of green spaces; most budgets are geared toward removing dead trees. Many cities lack systematic tree-care programs, and little attention is paid to effects of soil conditions, restrictions to root growth, droughts caused of the channeling off of rain, the heat island effect, and the lack of undergrowth (Sampson 1994:165).

Managing urban consumption and its impact on neighboring ecosystems is perhaps the biggest challenge. Urban areas consume massive amounts of environmental goods and services–imported from ecosystems beyond their borders–and export wastes. It is estimated that a city with a population of 1 million in Europe requires, every day, an average of 11,500 tons of fossil fuels, 320,000 tons of water, and 2,000 tons of food, much of which is produced outside the city. The same city produces 300,000 tons of wastewater, 25,000 tons of CO_2, and 1,600 tons of solid waste (Stanners and Bordeau 1995:263). The total area required to sustain a city is called its "ecological footprint" (Rees 1992). In a study of the 29 largest cities in the Baltic Sea region, it was estimated that cities claim ecosystem support areas 500–1,000 times larger than the area of the cities (Folke et al. 1997:167). Any attempt to improve the sustainability of urban ecosystems must identify ways for cities to exist in greater equalibrium with surrounding ecosystems.

The good news is that urban areas present tremendous opportunities for greater efficiencies in energy and water use, housing, and waste management. Strategies that encourage better planning, mixed-use development, urban road pricing, and integrated public transportation, among other efforts, can dramatically lessen the environmental impacts of billions of people. The fact that land use changes rapidly in urban areas is a management and planning challenge, but also an opportunity as well. For example, the million or more brownfields (urban land parcels that once supported industry or commerce but lie abandoned or contaminated) that scar cities worldwide offer the chance to create new green spaces or lessen congestion and development pressure on remaining green areas (Mountford 1999). If well-managed, urban green spaces can add to the already proven health and education benefits of urban ecosystems.

The Bottom Line for Urban Ecosystems. Urban ecosystems are dominated by human activities and the built environment, but they contain vital green spaces that confer many important services. These range from removing air pollution and absorbing runoff to producing food through urban agriculture. Urban forests, parks, and yards also soften the urban experience and provide invaluable recreation and relaxation. The science of urban ecosystems is new and there is no comprehensive data showing urban ecosystem trends on a global basis. However, more localized data show that loss of urban tree cover, and the consequent decline of urban green spaces, is a widespread problem. The rapid growth in urban populations worldwide adds to the mounting stress on urban ecosystems. Continued decline in the green elements of urban ecosystems will erode the other values—economic, educational, and cultural. Urban population increases heighten the need to incorporate the care of city green spaces as a key element in urban planning.