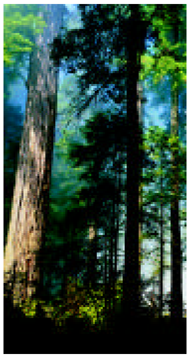
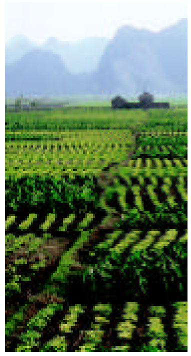
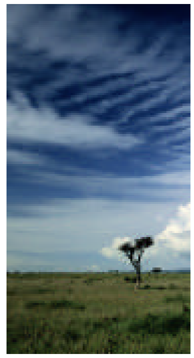
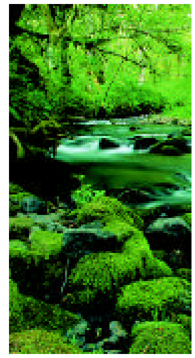
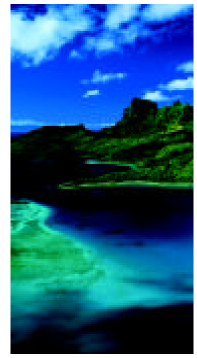

PILOT ANALYSIS OF GLOBAL ECOSYSTEMS

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ISBN: 1-56793-459-3

Library of Congress Catalog No. 00-109787

Printed in the United States of America on chlorine-free paper with recycled content of 50%, 20% of which is post-consumer.

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Published by World Resources Institute
Washington, DC
This report is also available at http://www.wri.org/wr2000

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November 2000 / paperback / ISBN 1-56973-461-5 / US$20.00

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The agroecosystem report is also available at http://www.ifpri.org. Printed copies may be ordered by mail from the International Food Policy Research Institute, Communications Service, 2033 K Street, NW, Washington, D.C. 20006-5670, USA.

Contents

Foreword

Earth's ecosystems and its peoples are bound together in a grand and complex symbiosis. We depend on ecosystems to sustain us, but the continued health of ecosystems depends, in turn, on our use and care. Ecosystems are the productive engines of the planet, providing us with everything from the water we drink to the food we eat and the fiber we use for clothing, paper, or lumber. Yet, nearly every measure we use to assess the health of ecosystems tells us we are drawing on them more than ever and degrading them, in some cases at an accelerating pace.

Our knowledge of ecosystems has increased dramatically in recent decades, but it has not kept pace with our ability to alter them. Economic development and human well-being will depend in large part on our ability to manage ecosystems more sustainably. We must learn to evaluate our decisions on land and resource use in terms of how they affect the capacity of ecosystems to sustain life — not only human life, but also the health and productive potential of plants, animals, and natural systems.

A critical step in improving the way we manage the earth's ecosystems is to take stock of their extent, their condition, and their capacity to provide the goods and services we will need in years to come. To date, no such comprehensive assessment of the state of the world's ecosystems has been undertaken.

The Pilot Analysis of Global Ecosystems (PAGE) begins to address this gap. This study is the result of a remarkable collaborative effort between the World Resources Institute (WRI), the International Food Policy Research Institute (IFPRI), intergovernmental organizations, agencies, research institutes, and individual experts in more than 25 countries worldwide. The PAGE compares information already available on a global scale about the condition of five major classes of ecosystems: agroecosystems, coastal areas, forests, freshwater systems, and grasslands. IFPRI led the agroecosystem analysis, while the others were led by WRI. The pilot analysis examines not only the quantity and quality of outputs but also the biological basis for production, including soil and water condition, biodiversity, and changes in land use over time. Rather than looking just at marketed products, such as food and timber, the study also analyzes the condition of a broad array of ecosystem goods and services that people need, or enjoy, but do not buy in the marketplace.

The five PAGE reports show that human action has profoundly changed the extent, condition, and capacity of all major ecosystem types. Agriculture has expanded at the expense of grasslands and forests, engineering projects have altered the hydrological regime of most of the world's major rivers, settlement and other forms of development have converted habitats around the world's coastlines. Human activities have adversely altered the earth's most important biogeochemical cycles — the water, carbon, and nitrogen cycles — on which all life forms depend. Intensive management regimes and infrastructure development have contributed positively to providing some goods and services, such as food and fiber from forest plantations. They have also led to habitat fragmentation, pollution, and increased ecosystem vulnerability to pest attack, fires, and invasion by non-native species. Information is often incomplete and the picture confused, but there are many signs that the overall capacity of ecosystems to continue to produce many of the goods and services on which we depend is declining.

The results of the PAGE are summarized in *World Resources 2000–2001*, a biennial report on the global environment published by the World Resources Institute in partnership with the United Nations Development Programme, the United Nations Environment Programme, and the World Bank. These institutions have affirmed their commitment to making the viability of the world's ecosystems a critical development priority for the 21st century. WRI and its partners began work with a conviction that the challenge of managing earth's ecosystems — and the consequences of failure — will increase significantly in coming decades. We end with a keen awareness that the scientific knowledge and political will required to meet this challenge are often lacking today. To make sound ecosystem management decisions in the future, significant changes are needed in the way we use the knowledge and experience at hand, as well as the range of information brought to bear on resource management decisions.

A truly comprehensive and integrated assessment of global ecosystems that goes well beyond our pilot analysis is necessary to meet information needs and to catalyze regional and local assessments. Planning for such a Millennium Ecosystem Assessment is already under way. In 1998, representatives from international scientific and political bodies began to explore the merits of, and recommend the structure for, such an assessment. After consulting for a year and considering the preliminary findings of the PAGE report, they concluded that an international scientific assessment of the present and likely future condition of the world's ecosystems was both feasible and urgently needed. They urged local, national, and international institutions to support the effort as stakeholders, users, and sources of expertise. If concluded successfully, the Millennium Ecosystem Assessment will generate new information, integrate current knowledge, develop methodological tools, and increase public understanding.

Human dominance of the earth's productive systems gives us enormous responsibilities, but great opportunities as well. The challenge for the 21st century is to understand the vulnerabilities and resilience of ecosystems, so that we can find ways to reconcile the demands of human development with the tolerances of nature.

We deeply appreciate support for this project from the Australian Centre for International Agricultural Research, The David and Lucile Packard Foundation, The Netherlands Ministry of Foreign Affairs, the Swedish International Development Cooperation Agency, the United Nations Development Programme, the United Nations Environment Programme, the Global Bureau of the United States Agency for International Development, and The World Bank.

A special thank you goes to the AVINA Foundation, the Global Environment Facility, and the United Nations Fund for International Partnerships for their early support of PAGE and the Millennium Ecosystem Assessment, which was instrumental in launching our efforts.

JONATHAN LASH
President
World Resources Institute

Acknowledgments

The World Resources Institute and the International Food Policy Research Institute would like to acknowledge the members of the Millennium Assessment Steering Committee, who generously gave their time, insights, and expert review comments in support of the Pilot Analysis of Global Ecosystems.

Edward Ayensu, Ghana; Mark Collins, United Nations Environment Programme-World Conservation Monitoring Centre (UNEP-WCMC), United Kingdom; Angela Cropper, Trinidad and Tobago; Andrew Dearing, World Business Council for Sustainable Development (WBCSD); Janos Pasztor, UNFCCC; Louise Fresco, FAO; Madhav Gadgil, Indian Institute of Science, Bangalore, India; Habiba Gitay, Australian National University, Australia; Gisbert Glaser, UNESCO; Zuzana Guziova, Ministry of the Environment, Slovak Republic; He Changchui, FAO; Calestous Juma, Harvard University; John Krebs, National Environment Research Council, United Kingdom; Jonathan Lash, World Resources Institute; Roberto Lenton, UNDP; Jane Lubchenco, Oregon State University; Jeffrey McNeely, World Conservation Union (IUCN), Switzerland; Harold Mooney, International Council for Science (ICSU); Ndegwa Ndiangui, Convention to Combat Desertification; Prabhu L. Pingali, CIMMYT; Per Pinstrup-Andersen, Consultative Group on International Agricultural Research; Mario Ramos, Global Environment Facility; Peter Raven, Missouri Botanical Garden; Walter Reid, Secretariat; Cristian Samper, Instituto Alexander Von Humboldt, Colombia; José Sarukhán, CONABIO, Mexico; Peter Schei, Directorate for Nature Management, Norway; Klaus Töpfer, UNEP; José Galízia Tundisi, International Institute of Ecology, Brazil; Robert Watson, World Bank; Xu Guanhua, Ministry of Science and Technology, People's Republic of China; A.H. Zakri, Universiti Kebangsaan Malaysia, Malaysia.

The Pilot Analysis of Global Ecosystems would not have been possible without the data provided by numerous institutions and agencies. The authors of the forest ecosystem analysis wish to express their gratitude for the generous cooperation and invaluable information they received from the following organizations:

BirdLife International; Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory; Consortium for International Earth Science Information Network (CIESIN); Environmental Systems Research Institute (ESRI); European Forest Institute (EFI); Food and Agriculture Organization of the United Nations (FAO); International Energy Agency (IEA); International Institute for Applied Systems Analysis (IIASA); International Soil Reference and Information Centre (ISRIC); National Oceanic and Atmospheric Administration-National Geophysical Data Center (NOAA-NGDC); United Nations Environment Programme (UNEP); United Nations-Economic Commission for Europe (UN-ECE); University of Maryland, Geography Department; U.S. Department of Agriculture, Forest Service (USDA-FS); U.S. Geological Survey (USGS) Earth Resources Observation Systems (EROS) Data Center; The World Bank; World Conservation Union (IUCN); World Wildlife Fund-U.S. (WWF-U.S.).

The authors would also like to express their gratitude to the many individuals who contributed information and advice, attended expert workshops, and reviewed successive drafts of this report.

Mark Ashton (Yale University), Jim Ball (FAO), Ian Bowles (Conservation International), Daniel Binkley (Colorado State University), Richard Birdsey (USDA Forest Service), Chris Brown (FAO), Jesslyn Brown (USGS-EROS Data Center), Sandra Brown (Winrock International), Dan Claasen (UNEP), Virginia Dale (ORNL), Braulio de Souza Dias (Ministry of Environment, Brazil), Robert Davis (FAO), Ruth de Fries (University of Maryland), Uwe Deichmann (The World Bank), Eric Dinerstein (WWF-U.S.), John Dixon (ORNL), John Dixon (The World Bank), Robert Dixon (DOE), Nigel Dudley (Equilibrium, U.K.), Curt Flather (USDA Forest Service), Jeffrey Fox (East-West Center), Robert Friedman (The H. John Heinz III Center for Science, Economics and the Environment), Peter Frumhoff (Union of Concerned Scientists), Jack Gibbons, Alan Grainger (Leeds University, United Kingdom), Scott Hajost (IUCN), David Hall (Kings College, London), John Hart, Richard Haynes (USDA Forest Service), Derek Holmes (The

World Bank), Richard Houghton (Woods Hole Research Center), Bill Jackson (Pacific Northwest Research Station, USDA Forest Service), Karen Jorgensen (UNDP), Deborah Jensen (The Nature Conservancy), Valerie Kapos (UNEP-WCMC), Tony King (ORNL), Jonathan Loh (WWF International), Tim Moermond (University of Wisconsin, Madison), John Morrison (WWF-U.S.), Robin O'Malley (H. John Heinz III Center for Science, Economics and the Environment), Gordon Orians (University of Washington), N.H. Ravindranath (ASTRA and Centre for Ecological Sciences, India), Don Pryor (Office of Science Technology and Policy), Kent Redford (Wildlife Conservation Society), Barry Rock (University of New Hampshire), Mike Rodemeyer (Office of Science Technology and Policy), Mark Sagoff (University of Maryland), Dan Simberloff (University of Tennessee), Ashbindu Singh (UNEP), Jorge Soberon (University of Kansas), Robert Socolow (Princeton University), Miguel Trossero (FAO), Compton Tucker (University of Maryland), Emma Underwood (WWF-U.S.), and Karen Waddell (USDA Forest Service).

We also wish to thank the many individuals at WRI who were generous with their help as this report progressed: Jake Brunner, Dirk Bryant, Tony Janetos, Nels Johnson, and Lars Laestadius. Kirsten Thompson and Siobhan Murray worked tirelessly in the GIS lab to produce the PAGE maps. Hyacinth Billings, Kathy Doucette, Carollyne Hutter, and Maggie Powell guided the report through production with their usual calm skill, and provided editorial and design assistance.

Introduction to the Pilot Analysis of Global Ecosystems

PEOPLE AND ECOSYSTEMS

The world's economies are based on the goods and services derived from ecosystems. Human life itself depends on the continuing capacity of biological processes to provide their multitude of benefits. Yet, for too long in both rich and poor countries, development priorities have focused on how much humanity can take from ecosystems, and too little attention has been paid to the impact of our actions. We are now experiencing the effects of ecosystem decline in numerous ways: water shortages in the Punjab, India; soil erosion in Tuva, Russia; fish kills off the coast of North Carolina in the United States; landslides on the deforested slopes of Honduras; fires in the forests of Borneo and Sumatra in Indonesia. The poor, who often depend directly on ecosystems for their livelihoods, suffer most when ecosystems are degraded.

A critical step in managing our ecosystems is to take stock of their extent, their condition, and their capacity to continue to provide what we need. Although the information available today is more comprehensive than at any time previously, it does not provide a complete picture of the state of the world's ecosystems and falls far short of management and policy needs. Information is being collected in abundance but efforts are often poorly coordinated. Scales are noncomparable, baseline data are lacking, time series are incomplete, differing measures defy integration, and different information sources may not know of each other's relevant findings.

OBJECTIVES

The Pilot Analysis of Global Ecosystems (PAGE) is the first attempt to synthesize information from national, regional, and global assessments. Information sources include state of the environment reports; sectoral assessments of agriculture, forestry, biodiversity, water, and fisheries, as well as national and global assessments of ecosystem extent and change; scientific research articles; and various national and international datasets. The study reports on five major categories of ecosystems:

- Agroecosystems;
- Coastal ecosystems;
- Forest ecosystems;
- Freshwater systems;
- Grassland ecosystems.

These ecosystems account for about 90 percent of the earth's land surface, excluding Greenland and Antarctica. PAGE results are being published as a series of five technical reports, each covering one ecosystem. Electronic versions of the reports are posted on the Website of the World Resources Institute [http://www.wri.org/wr2000] and the agroecosystems report also is available on the Website of the International Food Policy Research Institute [http://www/ifpri.org].

The primary objective of the pilot analysis is to provide an overview of ecosystem condition at the global and continental levels. The analysis documents the extent and distribution of the five major ecosystem types and identifies ecosystem change over time. It analyzes the quantity and quality of ecosystem goods and services and, where data exist, reviews trends relevant to the production of these goods and services over the past 30 to 40 years. Finally, PAGE attempts to assess the capacity of ecosystems to continue to provide goods and services, using measures of biological productivity, including soil and water conditions, biodiversity, and land use. Wherever possible, information is presented in the form of indicators and maps.

A second objective of PAGE is to identify the most serious information gaps that limit our current understanding of ecosystem condition. The information base necessary to assess ecosystem condition and productive capacity has not improved in recent years, and may even be shrinking as funding for environmental monitoring and record-keeping diminishes in some regions.

Most importantly, PAGE supports the launch of a Millennium Ecosystem Assessment, a more ambitious, detailed, and integrated assessment of global ecosystems that will provide a firmer basis for policy- and decision-making at the national and subnational scale.

AN INTEGRATED APPROACH TO ASSESSING ECOSYSTEM GOODS AND SERVICES

Ecosystems provide humans with a wealth of goods and services, including food, building and clothing materials, medicines, climate regulation, water purification, nutrient cycling, recreation opportunities, and amenity value. At present, we tend to manage ecosystems for one dominant good or service, such as grain, fish, timber, or hydropower, without fully realizing the trade-offs we are making. In so doing, we may be sacrificing goods or services more valuable than those we receive — often those goods and services that are not yet valued in the market, such as biodiversity and flood control. An integrated ecosystem approach considers the entire range of possible goods and services a given ecosystem provides and attempts to optimize the benefits that society can derive from that ecosystem and across ecosystems. Its purpose is to help make trade-offs efficient, transparent, and sustainable.

Such an approach, however, presents significant methodological challenges. Unlike a living organism, which might be either healthy or unhealthy but cannot be both simultaneously, ecosystems can be in good condition for producing certain goods and services but in poor condition for others. PAGE attempts to evaluate the condition of ecosystems by assessing separately their capacity to provide a variety of goods and services and examining the trade-offs humans have made among those goods and services. As one example, analysis of a particular region might reveal that food production is high but, because of irrigation and heavy fertilizer application, the ability of the system to provide clean water has been diminished.

Given data inadequacies, this systematic approach was not always feasible. For each of the five ecosystems, PAGE researchers, therefore, focus on documenting the extent and distribution of ecosystems and changes over time. We develop indicators of ecosystem condition — indicators that inform us about the current provision of goods and services and the likely capacity of the ecosystem to continue providing those goods and services. Goods and services are selected on the basis of their perceived importance to human development. Most of the ecosystem studies examine food production, water quality and quantity, biodiversity, and carbon sequestration. The analysis of forests also studies timber and woodfuel production; coastal and grassland studies examine recreational and tourism services; and the agroecosystem study reviews the soil resource as an indicator of both agricultural potential and its current condition.

PARTNERS AND THE RESEARCH PROCESS

The Pilot Analysis of Global Ecosystems was a truly international collaborative effort. The World Resources Institute and the International Food Policy Research Institute carried out their research in partnership with numerous institutions worldwide (see *Acknowledgments*). In addition to these partnerships, PAGE researchers relied on a network of international experts for ideas, comments, and formal reviews. The research process included meetings in Washington, D.C., attended by more than 50 experts from developed and developing countries. The meetings proved invaluable in developing the conceptual approach and guiding the research program toward the most promising indicators given time, budget, and data constraints. Drafts of PAGE reports were sent to over 70 experts worldwide, presented and critiqued at a technical meeting of the Convention on Biological Diversity in Montreal (June, 1999) and discussed at a Millennium Assessment planning meeting in Kuala Lumpur, Malaysia (September, 1999). Draft PAGE materials and indicators were also presented and discussed at a Millennium Assessment planning meeting in Winnipeg, Canada, (September, 1999) and at the meeting of the Parties to the Convention to Combat Desertification, held in Recife, Brazil (November, 1999).

KEY FINDINGS

Key findings of PAGE relate both to ecosystem condition and the information base that supported our conclusions.

The Current State of Ecosystems

The PAGE reports show that human action has profoundly changed the extent, distribution, and condition of all major ecosystem types. Agriculture has expanded at the expense of grasslands and forests, engineering projects have altered the hydrological regime of most of the world's major rivers, settlement and other forms of development have converted habitats around the world's coastlines.

The picture we get from PAGE results is complex. Ecosystems are in good condition for producing some goods and services but in poor condition for producing others. Overall, however, there are many signs that the capacity of ecosystems to continue to produce many of the goods and services on which we depend is declining. Human activities have significantly disturbed the global water, carbon, and nitrogen cycles on which all life depends. Agriculture, industry, and the spread of human settlements have permanently converted extensive areas of natural habitat and contributed to ecosystem degradation through fragmentation, pollution, and increased incidence of pest attacks, fires, and invasion by non-native species.

The following paragraphs look across ecosystems to summarize trends in production of the most important goods and services and the outlook for ecosystem productivity in the future.

Food Production

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. Production is likely to continue to rise as demand increases in the short to medium term. Long-term productivity, however, is threatened by increasing water scarcity and soil degradation, which is now severe enough to reduce yields on about 16 percent of agricultural land, especially cropland in Africa and Central America and pastures in Africa. Irrigated agriculture, an important component in the productivity gains of the Green Revolution, has contributed to waterlogging and salinization, as well as to the depletion and chemical contamination of surface and groundwater supplies. Widespread use of pesticides on crops has lead to the emergence of many pesticide-resistant pests and pathogens, and intensive livestock production has created problems of manure disposal and water pollution. Food production from marine fisheries has risen sixfold since 1950 but the rate of increase has slowed dramatically as fisheries have been overexploited. More than 70 percent of the world's fishery resources for which there is information are now fully fished or overfished (yields are static or declining). Coastal fisheries are under threat from pollution, development, and degradation of coral reef and mangrove habitats. Future increases in production are expected to come largely from aquaculture.

Water Quantity

Dams, diversions, and other engineering works have transformed the quantity and location of freshwater available for human use and sustaining aquatic ecosystems. Water engineering has profoundly improved living standards, by providing fresh drinking water, water for irrigation, energy, transport, and flood control. In the twentieth century, water withdrawals have risen at more than double the rate of population increase and surface and groundwater sources in many parts of Asia, North Africa, and North America are being depleted. About 70 percent of water is used in irrigation systems where efficiency is often so low that, on average, less than half the water withdrawn reaches crops. On almost every continent, river modification has affected the flow of rivers to the point where some no longer reach the ocean during the dry season. Freshwater wetlands, which store water, reduce flooding, and provide specialized biodiversity habitat, have been reduced by as much as 50 percent worldwide. Currently almost 40 percent of the world's population experience serious water shortages. Water scarcity is expected to grow dramatically in some regions as competition for water grows between agricultural, urban, and commercial sectors.

Water Quality

Surface water quality has improved with respect to some pollutants in developed countries but water quality in developing countries, especially near urban and industrial areas, has worsened. Water is degraded directly by chemical or nutrient pollution, and indirectly when land use change increases soil erosion or reduces the capacity of ecosystems to filter water. Nutrient runoff from agriculture is a serious problem around the world, resulting in eutrophication and human health hazards in coastal regions, especially in the Mediterranean, Black Sea, and northwestern Gulf of Mexico. Water-borne diseases caused by fecal contamination of water by untreated sewage are a major source of morbidity and mortality in the developing world. Pollution and the introduction of non-native species to freshwater ecosystems have contributed to serious declines in freshwater biodiversity.

Carbon Storage

The world's plants and soil organisms absorb carbon dioxide (CO_2) during photosynthesis and store it in their tissues, which helps to slow the accumulation of CO_2 in the atmosphere and mitigate climate change. Land use change that has increased production of food and other commodities has reduced the net capacity of ecosystems to sequester and store carbon. Carbon-rich grasslands and forests in the temperate zone have been extensively converted to cropland and pasture, which store less carbon per unit area of land. Deforestation is itself a significant source of carbon emissions, because carbon stored in plant tissue is released by burning and accelerated decomposition. Forests currently store about 40 percent of all the carbon held in terrestrial ecosystems. Forests in the northern hemisphere are slowly increasing their storage capacity as they regrow after historic clearance. This gain, however, is more than offset by deforestation in the tropics. Land use change accounts for about 20 percent of anthropogenic carbon emissions to the atmosphere. Globally, forests today are a net source of carbon.

Biodiversity

Biodiversity provides many direct benefits to humans: genetic material for crop and livestock breeding, chemicals for medicines, and raw materials for industry. Diversity of living organisms and the abundance of populations of many species are also critical to maintaining biological services, such as pollination and nutrient cycling. Less tangibly, but no less importantly, diversity in nature is regarded by most people as valuable in its own right, a source of aesthetic pleasure, spiritual solace, beauty, and wonder. Alarming losses in global biodiversity have occurred over the past century. Most are the result of habitat destruction. Forests, grasslands, wetlands, and mangroves have been extensively converted to other uses; only tundra, the Poles, and deep-sea ecosystems have experienced relatively little change. Biodiversity has suffered as agricultural land, which supports far less biodiversity than natural forest, has expanded primarily at the expense of forest areas. Biodiversity is also diminished by intensification, which reduces the area allotted to hedgerows, copses, or wildlife corridors and displaces traditional varieties of seeds with modern high-yield, but genetically uniform, crops. Pollution, overexploitation, and competition from invasive species represent further threats to biodiversity. Freshwater ecosystems appear to be the most severely degraded overall, with an estimated 20 percent of freshwater fish species becoming extinct, threatened, or endangered in recent decades.

Information Status and Needs

Ecosystem Extent and Land Use Characterization

Available data proved adequate to map approximate ecosystem extent for most regions and to estimate historic change in grassland and forest area by comparing current with potential vegetation cover. PAGE was able to report only on recent changes in ecosystem extent at the global level for forests and agricultural land.

PAGE provides an overview of human modifications to ecosystems through conversion, cultivation, firesetting, fragmentation by roads and dams, and trawling of continental shelves. The study develops a number of indicators that quantify the degree of human modification but more information is needed to document adequately the nature and rate of human modifications to ecosystems. Relevant data at the global level are incomplete and some existing datasets are out of date.

Perhaps the most urgent need is for better information on the spatial distribution of ecosystems and land uses. Remote sensing has greatly enhanced our knowledge of the global extent of vegetation types. Satellite data can provide invaluable information on the spatial pattern and extent of ecosystems, on their physical structure and attributes, and on rates of change in the landscape. However, while gross spatial changes in vegetation extent can be monitored using coarse-resolution satellite data, quantifying land cover change at the national or subnational level requires high-resolution data with a resolution of tens of meters rather than kilometers.

Much of the information that would allow these needs to be met, at both the national and global levels, already exists, but is not yet in the public domain. New remote sensing techniques and improved capabilities to manage complex global datasets mean that a complete satellite-based global picture of the earth could now be made available, although at significant cost. This information would need to be supplemented by extensive ground-truthing, involving additional costs. If sufficient resources were committed, fundamentally important information on ecosystem extent, land cover, and land use patterns around the world could be provided at the level of detail needed for national planning. Such information would also prove invaluable to international environmental conventions, such as those dealing with wetlands, biological diversity, desertification, and climate change, as well as the international agriculture, forest, and fishery research community.

Ecosystem Condition and Capacity to Provide Goods and Services

In contrast to information on spatial extent, data that can be used to analyze ecosystem condition are often unavailable or incomplete. Indicator development is also beset by methodological difficulties. Traditional indicators, for example, those relating to pressures on environments, environmental status, or societal responses (pressure-state-response model indicators) provide only a partial view and reveal little about the underlying capacity of the ecosystem to deliver desired goods and services. Equally, indicators of human modification tell us about changes in land use or biological parameters, but do not necessarily inform us about potentially positive or negative outcomes.

Ecosystem conditions tend to be highly site-specific. Information on rates of soil erosion or species diversity in one area may have little relevance to an apparently similar system a few miles away. It is expensive and challenging to monitor and synthesize site-specific data and present it in a form suitable for national policy and resource management decisions. Finally, even where data are available, scientific understanding of how changes in biological systems will affect goods and services is limited. For example, experimental evidence shows that loss of biological diversity tends to reduce the resilience of a system to perturbations, such as storms, pest outbreaks, or climate change. But scientists are not yet able to quantify how much resilience is lost as a result of the loss of biodiversity in a particular site or how that loss of resilience might affect the long-term production of goods and services.

Overall, the availability and quality of information tend to match the recognition accorded to various goods and services by markets. Generally good data are available for traded goods, such as grains, fish, meat, and timber products and some of the more basic relevant productivity factors, such as fertilizer application rates, water inputs, and yields. Data on products that are exchanged in informal markets, or consumed directly, are patchy and often modeled. Examples include fish landings from artisanal fisheries, woodfuels, subsistence food crops and livestock, and nonwood forest products. Information on the biological factors that support production of these goods — including size of fish spawning stocks, biomass densities, subsistence food yields, and forest food harvests — are generally absent.

The future capacity (long-term productivity) of ecosystems is influenced by biological processes, such as soil formation, nutrient cycling, pollination, and water purification and cycling. Few of these environmental services have, as yet, been accorded economic value that is recognized in any functioning market. There is a corresponding lack of support for data collection and monitoring. This is changing in the case of carbon storage and cycling. Interest in the possibilities of carbon trading mechanisms has stimulated research and generated much improved data on carbon stores in terrestrial ecosystems and the dimensions of the global carbon cycle. Few comparable datasets exist for elements such as nitrogen or sulfur, despite their fundamental importance in maintaining living systems.

Although the economic value of genetic diversity is growing, information on biodiversity is uniformly poor. Baseline and trend data are largely lacking; only an estimated 15 to 20 percent of the world's species have been identified. The OECD Megascience Forum has launched a new international program to accelerate the identification and cataloging of species around the world. This information will need to be supplemented with improved data on species population trends and the numbers and abundance of invasive species. Developing databases on population trends (and threat status) is likely to be a major challenge, because most countries still need to establish basic monitoring programs.

The PAGE divides the world's ecosystems to examine them at a global scale and think in broad terms about the challenges of managing them sustainably. In reality, ecosystems are linked by countless flows of material and human actions. The PAGE analysis does not make a distinction between natural and managed ecosystems; human intervention affects all ecosystems to some degree. Our aim is to take a first step toward understanding the collective impacts of those interventions on the full range of goods and services that ecosystems provide. We conclude that we lack much of the baseline information necessary to determine ecosystem conditions at a global, regional or, in many instances, even a local scale. We also lack systematic approaches necessary to integrate analyses undertaken at different locations and spatial scales.

Finally, it should be noted that PAGE looks at past trends and current status, but does not try to project future situations where, for example, technological development might increase dramatically the capacity of ecosystems to deliver the goods and services we need. Such considerations were beyond the scope of the study. However, technologies tend to be developed and applied in response to market-related opportunities. A significant challenge is to find those technologies, such as integrated pest management and zero tillage cultivation practices in the case of agriculture, that can simultaneously offer market-related as well as environmental benefits. It has to be recognized, nonetheless, that this type of "win-win" solution may not always be possible. In such cases, we need to understand the nature of the trade-offs we must make when choosing among different combinations of goods and services. At present our knowledge is often insufficient to tell us where and when those trade-offs are occurring and how we might minimize their effects.

Forest Ecosystems: Executive Summary

Scope of Analysis

This study analyzes datasets at the global, national, and subnational levels, and draws on published and unpublished scientific studies. It develops selected indicators that describe the condition of the world's forests, where condition is defined as the current and future capacity of forests to provide the full range of goods and services that humans need and consume.

FOREST EXTENT, CHANGE, AND HUMAN MODIFICATION

In this study, WRI defines forests as terrestrial ecosystems dominated by trees, where the tree canopy covers at least 10 percent of the ground area. The researchers chose this broad definition to allow use of a variety of datasets and to avoid somewhat arbitrary distinctions among different land cover types. The study examines the spatial extent of forests and modifications by humans that have altered the extent and structure of forest ecosystems over time. Forest extent is a basic measure of condition: if global forest cover shrinks, provision of goods and services from forest ecosystems – in the absence of compensating human action – will be reduced. Measures of the biological condition of the world's forests are extremely difficult to develop, given data limitations and controversy over such concepts as ecosystem health. Therefore, we examine three forms of human modification of forests that are known to be leading indicators of environmental change: the spread of "transition zones" (agriculture practiced at the margins of intact forest), road construction, and the use of fire.

FOREST GOODS AND SERVICES

As further measures of condition, we compile data on the current "yield" of forest goods and services, whether measured as stocks (the amount of carbon stored), or annual production (the quantity of timber harvested). We present available data on trends over the past 30 to 40 years and assess forest capacity to continue to provide goods and services in future, based on indicators of changing forest extent and biological condition. We also look at human modifications to forests that have been undertaken deliberately to maximize production of a particular good or service or that have occurred as an unintended by-product (externality) of human action. What are some of the trade-offs that humans have made as they extended cropland or increased timber production?

We focus on a limited number of forest goods and services. The choice was determined partly in consultation with forestry experts in many countries and partly by data availability. Our preference was to use global datasets; where global data were not available, we used regional and national level information. Sometimes, local-level case studies were used to illustrate trends that appear to be important but for which national or global data do not exist. The data and indicators presented in this pilot analysis are concerned with the following:

- Global forest cover;
- Human modification (transition zones, road construction, fire);
- Industrial roundwood production;
- Woodfuel production;
- Biodiversity;
- Carbon storage and sequestration; and
- Watershed protection.

Clearly, important issues are missing from this list. Nonwood forest products, including food (nuts, berries, fruits, mushrooms, honey, game), cash crops (coffee, palm oil, rubber) and industrial raw materials, have not been assessed. Data for most nonmarketed goods are patchy and noncomparable among countries, while information on industrial raw materials is usually commercially sensitive. In the case of cash crops, many of these products can be, and increasingly are, supplied from nonforest environments, such as agroecosystems and plantations. The condition of forests is not necessarily relevant to their future supply. In the longer term, this may be true also of industrial roundwood and woodfuels but forests will remain the dominant source of supply of these commodities for the foreseeable future.

The spiritual and aesthetic qualities of forests constitute perhaps the most important omissions from this study. People commonly respond to forests with a sense of awe, exhilaration, and reverence. Human values conferred on nature, however, cannot readily be captured by the kind of quantitative analysis presented here. Scattered data exist on tourism revenues and visitor numbers to forest reserves, which some analysts have used as proxy measures of human appreciation. A number of economists have attempted to monetize forest "existence" or "intrinsic" values. Such exercises have not been considered here. The very concept of analyzing forest goods and services is essentially utilitarian, while appreciation of forests as objects of expressive power is essentially aesthetic. The two perspectives cannot logically be combined. Further, any attempt to develop quantitative indicators of qualitative values risks removing the latter from their proper arena of political, moral, and cultural debate.

Key Findings and Information Issues

The following tables (pp. 3–7) summarize key findings of the study regarding forest condition and trends and the quality and availability of data.

Forest Extent and Change

PAGE MEASURES AND INDICATORS	DATA SOURCES AND COMMENTS
Global Forest Cover	FAO, 1997a. Area estimates based on national inventories, maps, some remote sensing data. IGBP, 1998, and DeFries et al., 2000. Both based on AVHRR 1-km resolution remote sensing data.
Historic Forest Loss	Matthews, 1983. Estimates of historic forest loss supplemented with FAO data for post-1980 period. WCMC. Estimates of original forest cover for WRI's Frontier Forests study (Bryant et al., 1997).
Recent Deforestation	FAO, 1997a. INPE and Pathfinder, remote sensing of Amazon basin. Holmes, 2000. Analysis of remote sensing data for Indonesia.
Degree of Naturalness	Bryant et al., 1997. Forest intactness determined by presence of roads, other development and expert opinion. FAO, FRA 2000 (unpublished). Forest naturalness determined by intensity of human intervention.
Forest/Cropland Transition Zones	GLCCD, 1998. Land cover classification scheme modified by WRI. Methodology may overstate degree of forest modification.
Fragmentation by Roads	CARPE, 1998. Roads database, updated by WRI for 6 Central African countries.
Forest Fires	Various remote sensing sources. Fires can be detected and monitored through thermal and mid-infrared imaging during the day, and by the light they emit at night.

CONDITIONS AND TRENDS

- Forests cover about one quarter of the world's land surface, excluding Greenland and Antarctica. Just over half are found in developing countries.
- Global forest cover has been reduced by at least 20 percent since preagricultural times, possibly by 50 percent. Forest area has increased slightly since 1980 in industrial countries, but has declined by at least 10 percent in developing countries.
- Tropical deforestation rates are uncertain, but probably exceed 130,000 km^2 per year. About 40 percent of forests are relatively undisturbed by human activity, though nearly half of these are likely to be developed soon.
- Nearly all forests in Europe and the United States are under some degree of management.
- Mixed forest/agriculture zones are spreading rapidly at the edges of formerly intact forest, but this form of land use change is often not recorded as forest conversion.
- Roads are a useful proxy indicator of habitat fragmentation and degradation. The world's expanding road network is opening up remote forests to logging, mining, and pioneer settlement. Roads also increase hunting and poaching.
- The area burned by natural forest fires is now insignificant in comparison with human-initiated fires. Tropical forest fires have increased in area and intensity in recent years, because of drought, clearance for agriculture, and land tenure disputes.

INFORMATION QUALITY AND NEEDS

- National level forest maps are often outdated and forest inventories unreliable in developing countries. Global estimates of forest area are complicated by different definitions of forest land and deforestation.
- Remote sensing data expected to become available in the next few years should improve the information base. Priority information needs include more frequent satellite surveys and higher sampling rates to catch nonrandomly distributed deforestation. Ground truthing will remain important to verify maps generated by remote sensing data.
- Knowledge of forest biological condition lags behind that for forest extent. Classification schemes for forest condition are simplistic but still difficult to implement. There is a need for agreement on what constitutes good condition in different forest types, managed for different purposes, and for indicators to monitor change, applicable at the national and subnational levels.
- Data on mixed forest/cropland land cover are poor. Vegetation classification schemes based on thresholds and discrete boundaries work against fine scale interpretation of land use data. There is a need for higher resolution remote sensing data and information on biomass quantities.
- The global roads dataset is out of date. Information is poor in developing countries where the road network is expanding fastest. Updated digitized information on existing and planned roads would be useful.
- There is an urgent need is to improve national and international ability to estimate forest fire potential and to detect and monitor wildfires while they are still small enough to control. A number of satellite systems have been evaluated for fire detection, including AVHRR, the Defense Meteorological Satellite Program (DMSP) Operational Linescan System sensor, and the NOAA Geostationary Operational Environmental Satellite (GOES) sensor. At present all three systems, each with unique characteristics, are required to provide the best results.

Industrial Roundwood

PAGE Measures and Indicators	Data Sources and Comments
Production Volume	FAOSTAT. On-line database (global). Generally good data on production volume and value, although some estimation involved for Africa.
Availability of Productive Forest Land	FAO, 1998. Area of economically available forest will change with fiber prices.
Harvesting Intensity	FAO, 1998. Data incomplete for many developing countries.
Plantation Area	FAO. Pandey, 1997 and Brown, 1999. Global coverage but data uncertain for many countries
Plantation Productivity	FAO. Pandey, 1997 and Brown, 1999. Good yield data available but scattered.
Tree Diameter Size	Haynes et al., 1995. Case study of United States production forests.
Impacts of Logging on Biodiversity	Survey of local studies in tropical countries of impacts on birds, butterflies and moths.

Conditions and Trends

- ♦ Global industrial fiber production totals 1.5 billion cubic meters. Production has risen by 50 percent since 1960 and is expected to rise by between 20 and 50 percent by 2020. Nearly 80 percent of fiber production today comes from primary and secondary-growth forests.
- ♦ Less than half of global forest area is defined by FAO as currently available for fiber production. The remainder is restricted either by current market conditions or by legal protection. Production is concentrated in North America, Europe, and Asia. The greatest reserves of currently unexploited mature trees exist in Canada, Russia, and Brazil.
- ♦ Only the United States and Western European countries currently harvest less wood from available forest land than regrows annually. Canada, Russia, Central and Eastern Europe, and most developing countries harvest above replacement rates in their available forest areas.
- ♦ Industrial wood plantations now supply just over 20 percent of fiber production. This share is expected to increase in future, but increased production from plantations will not necessarily decrease harvest rates in natural forests.
- ♦ Well-managed industrial wood plantations, especially those in the Southern Hemisphere, are capable of yields 5, 10, or even 50 times greater than those obtained from natural forests. However, some plantations in developing countries appear to have high planting failure rates.
- ♦ Production forests which have been managed for decades tend to become more uniform in structure; their trees, on average, are younger and smaller in size than in unmanaged forests.
- ♦ Immediate local-level impacts of logging on tropical forest biodiversity can be severe, but many groups of species appear to recover over time. Different taxa vary in their requirement for large, intact areas of undisturbed forest.

Information Quality and Needs

- ♦ Data on production volume and value are generally good, although estimates are involved for some developing countries. Information needs include spatial information at the subnational level on timber harvests, national-level data on the share of production from primary and secondary forest, and better monitoring of the extent and location of illegal logging.
- ♦ More economic analysis is required of the relationship between fiber prices, wood industry technologies, and the likely balance of supply from plantations and natural forests.
- ♦ Good forest inventory information is available for most industrial countries, but is incomplete for developing countries, where better information on growth rates, age and diameter class, harvest rates, tree mortality and planting, and methods of harvesting is needed at the national and subnational levels.
- ♦ Reporting on plantation establishment and success rates is uneven in some developing countries. Definitional difficulties among seminatural and plantation forests obscure plantation extent in industrial countries. Better information is needed on the amount and types of land converted to plantations (closed or open forest, degraded land, other) each year. Information on reported and net plantation area should distinguish between failed and harvested plantations.
- ♦ Good yield data are available for individual plantations but usually not at national level. High yields are recorded on some plantations and in field trials but it is not clear how far these have been translated to the field. More information and indicators are needed on long-term yields and biological and management parameters of plantations.
- ♦ The impacts of logging on biodiversity are still poorly understood. Information is needed on impacts on species other than birds, moths, and butterflies, especially invertebrates. More studies are needed of impacts in nontropical forests. There is an urgent need for agreement on relatively simple biodiversity indicators that can be monitored as logging operations progress.

Woodfuels

PAGE MEASURES AND INDICATORS	DATA SOURCES AND COMMENTS
Production Volume	FAOSTAT. On-line database (global). Mostly modeled data. IEA, 1996. Combustible Renewables and Waste Database (global). Data based on questionnaires and local databases.
Wood Energy Share of National Final Energy Consumption	IEA, 1996. Combustible Renewables and Waste Database (global). Good disaggregation of biomass fuels but time series not available.
Sources of Woodfuel	RWEDP, 1997a. Regional studies in 16 Asian countries. Few systematic data on woodfuel collection or consumption are available.
Woodfuel Scarcity	CIESIN, 2000. New estimate of global population density. DeFries et al., 2000. 1-km dataset of percentage tree cover (global). Areas of high population density, high dependence on woodfuel and low tree cover may be at risk of scarcity.

CONDITIONS AND TRENDS

- About 1.8 billion cubic meters of wood are burned directly as fuel each year, equivalent to over half the total roundwood harvest. Production and consumption are concentrated in low-income countries.
- Woodfuels account for about 15 percent on average of primary energy supply in developing countries and up to 80 percent of total energy in some countries in Sub-Saharan Africa and Asia.
- In the industrialized countries, burning of industrial wood residues, as well as wood harvested directly for fuel, means that between 30 and 50 percent of total wood removed from forests is ultimately used for energy, but wood contributes only about 3 percent of total energy supply throughout the OECD region.
- Forests appear to supply only about one third of woodfuels. The balance is obtained from other sources, including woodlands, roadsides, backyards, community woodlots, and wood industry residues.
- Shortages of woodfuel exist at the local level but, at the global level, forecasts of scarcity have probably been exaggerated. Poor data mean that the likelihood of a future woodfuel crisis cannot be accurately assessed. Scarcity hotspots appear concentrated in areas of high population density, low tree cover, and low income.

INFORMATION QUALITY AND NEEDS

- Data on woodfuel production and consumption in most developing countries are limited, unreliable, and largely dependent on modeled estimates. Wood energy is generally accorded low priority in national energy planning, despite its major role in energy supply.
- Information is needed at the subnational and national levels on the sources of woodfuel and household and industrial consumption to develop better estimates of demand and integrate woodfuels into national energy planning.
- Development of the FAO Wood Energy Database can be expected to improve knowledge of nonforest sources of wood fuels and patterns of supply and demand. Information on the ecological impacts of woodfuel collection is patchy.
- More use of remote sensing data and and the development of low-cost sampling and analysis techniques could help to determine biomass balances associated with woodfuel collection. Such data would be relevant to both energy planning and environmental analysis.

Biodiversity

PAGE MEASURES AND INDICATORS	DATA SOURCES AND COMMENTS
Global 200 Ecoregions	Olson and Dinerstein, 1998. Categorization scheme based on broad environmental characteristics and expert opinion.
Endemic Bird Areas	Stattersfield et al., 1998. Global sites identified through field observation and expert judgment.
Centers of Plant Diversity	WWF and IUCN, 1994. Global sites identified through field observation and expert judgment.
Protected Forest Areas	WCMC, 1999. Global database, based on IUCN management categories I-V.
Threatened Trees	Oldfield et al., 1998. Global list developed through field observation and expert judgment.
Threatened Birds	Wege and Long, 1995. Key Areas in Latin America mapped through field observation and expert judgment.
Non-Native Plant Species (% of total)	Ricketts et al., 1997. Data compiled from county level observation in North America. Data do not distinguish between benign non-natives and harmful invasives.
Projected Extinction Rates	Various studies and theoretical estimates, most based on data from tropical rainforest areas and tropical islands.

CONDITIONS AND TRENDS

- ♦ WWF has identified more than 200 ecoregions as outstanding representatives of the world's diverse ecoystems and, therefore, priority areas for conservation. Forest types account for two thirds of all terrestrial ecoregions.
- ♦ Nearly three quarters of the world's threatened bird species have restricted breeding ranges and remain confined to relatively small areas. Endemic bird areas (EBAs) encompass the range of the majority of these birds and more than 80 percent of EBAs are found in forests.
- ♦ Centers of plant diversity have been identified as conservation priority areas, rich in plant diversity or endemism. More than three quarters of the centers are found in forests.
- ♦ Less than 8 percent of global forest area is legally protected. Legal safeguards appear ineffective against logging, poaching, and other forms of development in many countries.
- ♦ Nearly 9 percent of trees globally are now at some risk of extinction. The leading threat is logging, followed by conversion to agriculture and expansion of human settlements.
- ♦ One quarter of the world's threatened birds occur in the non-Caribbean neotropical region. BirdLife International has identified nearly 600 sites that are key to the survival of these species and more than 80 percent of the sites occur in forests.
- ♦ Forests near human settlement or transportation routes have high concentrations of non-native species, which have been introduced deliberately or accidentally. Most are benign, but some invasive plants and insect pests have done extensive damage to both production and amenity forests.
- ♦ Moderate estimates of future species extinction rates in tropical forests range from 1 to 5 percent per decade. However, such estimates have high and largely unknown levels of uncertainty, because of both the uncertainty of the underlying data and the assumptions on which they are based.

INFORMATION QUALITY AND NEEDS

- ♦ Information on biodiversity is not currently adequate as a basis for forest management planning decisions or land use decisions at the landscape level.
- ♦ Detailed field-based biodiversity surveying over wide areas is not economically feasible, even in high-income countries. There is an urgent need for local and regional biodiversity management tools that can be developed from remote sensing and GIS.
- ♦ Other priority needs include better baseline information at the level of ecosystem types, species, and genetic resources, and agreed indicators of biodiversity condition, including habitat heterogeneity monitored over time that can be used to assess the impacts of habitat loss and modification.
- ♦ More information is urgently needed on the current status of protected areas and the effectiveness of logging bans or other conservation measures within these areas.

Carbon Storage and Sequestration

PAGE INDICATOR	DATA SOURCES AND COMMENTS
Total Carbon Stored in Forests (tons)	Olson et al., 1983. Global estimates of carbon in above- and below-ground live vegetation, modified by EDC and WRI (USGS/EDC, 1999). Soil carbon estimates based on ISRIC-WISE global dataset of derived soil properties (Batjes, 1996; Batjes and Bridges, 1994) and FAO digital soil map of the world (FAO, 1995). All datasets are coarse but globally consistent.

CONDITIONS AND TRENDS

- Forest soils and vegetation store about 40 percent of all carbon in the terrestrial biosphere, more than any other ecosystem.
- Globally, more carbon is stored in forest soils than in forest vegetation. Boreal forests are especially rich in soil carbon, while tropical forests probably store more in their vegetation.
- Regrowth of forests in the Northern Hemisphere may account in part for the increasing terrestrial sink that absorbs some of the carbon dioxide emissions released by fossil fuel combustion. However, land use change, primarily tropical deforestation, currently releases an estimated 1.6 billion tons of carbon to the atmosphere each year, equivalent to 25 percent of emissions from fossil fuel combustion.
- Globally, deforestation far exceeds regrowth. The world's forests are currently a net source of carbon.

INFORMATION QUALITY AND NEEDS

- Uncertainty still exists over rates of carbon sequestration, carbon stores, and the size and location of the terrestrial "missing carbon sink."
- Improving information is available from local and regional studies on carbon stores in different vegetation types but a variety of measurement methodologies used yields conflicting results.
- Many more soil samples are required globally for more accurate determination of soil carbon stores.
- Better information is needed on carbon sequestration rates at the site-specific level to provide an adequate basis for calculating carbon offsets achievable through afforestation programs under climate mitigation programs.

Watershed Protection

PAGE MEASURES AND INDICATORS	DATA SOURCES AND COMMENTS
Forest Cover in Major Watersheds (% Remaining)	Revenga et al., 1998. Global survey of 145 major and secondary watersheds. FAO, 1993. Estimates of deforestation rates in montane areas.
Vegetation Cover and Soil Erosion	Survey of local studies, mostly in tropical and subtropical region.

CONDITIONS AND TRENDS

- One third of the world's major watersheds have lost more than 75 percent of their original forest cover.
- Tropical montane forests, which are often located in the upper reaches of watersheds, are disappearing faster than any other tropical forest type.
- Deforestation is associated with alteration of stream flow quantity, quality and regularity, although links to major floods are more complicated than sometimes portrayed.
- Ground cover vegetation appears to be more important than tree cover in preventing erosion, but erosion rates under shifting cultivation are ten times higher than in natural forest. Erosion rates can be 100 times higher in plantations where weeds and leaf litter are removed.

INFORMATION QUALITY AND NEEDS

- The relationships between forest cover, forest type, and hydrological regimes are still inadequately understood.
- Information is most valuable at the site-specific and river basin levels, which can provide a sound basis for land use planning decisions affecting watersheds and downstream populations.
- Information is needed on the evaporative characteristics of different tree species and soil combinations, background and human-induced rates of soil erosion, and sedimentation rates and flooding incidence.
- Site-specific models are required to predict the impacts of afforestation or deforestation in catchment areas.

CONCLUSIONS

This study relied heavily on access to global and regional information collected and analyzed by many organizations, including FAO, UN-ECE, the European Commission, and NASA among others. We are indebted to their efforts, often in the face of tight budgetary constraints. A great deal of information and expertise also exists at the national level. PAGE researchers experienced few, if any, obstacles in accessing these information sources but noncomparability among datasets proved a major problem. Despite the abundance of information available, its quality is often poor. The uncertainty surrounding much of what we think we know about forests is sobering.

Virtually no hard (measured) forestry datasets exist at the global level, with the exception of industrial roundwood production. Even production data are estimated for some countries. All the other data cited in this report rely largely on modeled estimates and expert opinion. The weakest data of all relate to woodfuel production and biodiversity.

Remote sensing data that have become available over the past 10 years have improved our knowledge of forest extent and deforestation rates. Satellites have reduced data uncertainties but they are far from being eliminated. Most official data on forest extent and production still depend on conventional maps and forest inventories. The plethora of definitions – over 100 definitions of "forest" are currently in use globally – and outdated inventory data are major obstacles to interpreting these sources.

The single biggest change over time has been the clearance of forests to make way for agricultural land. In this century, the location of change has shifted from the temperate to the tropical zone, and the pace of conversion has quickened.

Of all the goods and services humans derive from forests, we currently manage most actively for wood products. Technology and markets have enabled us to compensate for reduced forest area by raising productivity. Forest plantations, in principle, could provide all our fiber needs, sparing natural forests altogether. Experience to date suggests that such a degree of substitution is unlikely over the medium-term in the absence of additional policy incentives.

We have not applied our management skills with equal energy to protect or enhance production of other goods and services from forests. Woodfuel supply, carbon storage, watershed protection, and biodiversity are obtained, exploited, or enjoyed rather opportunistically at the global level – until recently they have been assumed, more or less, to take care of themselves. (Numerous exceptions to this generalization exist at the local level but this report is concerned with the big picture.) However, substitution of such environmental services as carbon storage and watershed protection is infeasible for many countries under current economic and institutional conditions. Forest biodiversity, in all its complexity and beauty, appears irreplaceable.

There are some signs of change in both industrialized and developing countries. Forest management practices and legal protection reflect increasing recognition of the need to manage forests for multiple benefits and actors, and to make conscious decisions about trade-offs when they become inevitable. However, the full range of goods and services that forests provide is rarely factored into development decisions and our current information base does not allow us to consider and weight different goods and services in an integrated way.

RECOMMENDATIONS FOR THE MILLENNIUM ECOSYSTEM ASSESSMENT

This pilot analysis concludes that the generally poor quality of land cover and land use information means that the degree and speed of change in forest extent are difficult to determine. Changes in the condition of forest ecosystems are even harder to monitor because good baseline data are largely lacking and indicators of forest condition, applicable to different forest types that may be managed for different purposes, are still controversial.

Specific recommendations to document goods and services provided by forest ecosystems include the following:

- Use of higher resolution satellite data to provide a clear baseline of forest area and monitor change year on year.
- Ground-truthing to verify satellite-derived land cover classification.
- Remote sensing techniques and methodologies that can help with interpretation of below-canopy forest parameters, such as biomass density.
- Further work to harmonize national and agency definitions of forests and deforestation to improve comparability of national and international reporting.
- Improved spatial information on legal and illegal logging operations.
- Improved forest inventory information, including data on growth rates, harvest rates, mortality, disease, age and size classes, felling rates, in countries where these are not currently available.
- Compilation of reliable woodfuel energy statistics for developing countries.
- Further research on carbon sequestration and storage rates in specific tree species and climate and soil conditions.
- Greatly expanded systematic data collection on biodiversity, using nationally comparable parameters.
- Development of indicators that can be based on data obtainable from remote sensing and GIS, because comprehensive ground surveys are not economically feasible.

PROLOGUE: FORESTS IN HISTORY

Forests, woodlands, and scattered trees have provided humans with shelter, building materials, fuel, food, and medicines throughout recorded history. Patterns of forest use have evolved continuously, with different forest goods and services being regarded more or less highly by different societies in different eras.

In prehistoric and medieval times, forests were often regarded with fear — the home of wild animals, evil spirits, and outlaws. Forests also inspired religious awe; from the Druid circles of southern England to the Sacred Groves of Ghana worshippers have invested trees with spiritual or miraculous powers. For centuries, preindustrial societies used forests as a source of cooking and heating fuel, construction materials, and food — edible plants, nuts and fruits, animals, birds, and fish. Forests were playgrounds, too. Hunting was so highly esteemed in Europe that huge tracts of forests were protected as the special preserve of kings and nobles. Infringements of their exclusive hunting rights were punishable by death.

From the 16th Century onward, population growth and economic expansion in Europe and parts of Asia led to widespread forest clearance to make way for agriculture and new settlements. Forests then became valued principally for their timber, which was used in construction, and — of critical importance in an age of growing international trade and colonization — ship-building. As a result, forest cover declined dramatically. The great sea-powers, England, Spain, Portugal, and the Netherlands, found themselves increasingly dependent on timber from Norway, Sweden, and Russia. The British especially prized the American colonies for their seemingly limitless supplies of mature trees. The British Government commandeered the best specimens for its navy (following a tradition established by the Egyptian Pharaohs, who built their ships with timber taken from modern-day Lebanon).

Forests next provided a springboard for industrial development in the West. With the shift from mercantilism to industrialization, forests became a source of commercial energy. Where coal was scarce or expensive, trees supplied charcoal to power the new steam-driven machinery and engines. Forests were often recklessly cut down, but former forest lands usually became productive agricultural lands and many cleared forests in the eastern United States have since regrown. Today, despite greatly reduced forest cover, the industrialized countries — with the important exception of Japan — are still broadly self-sufficient in wood, thanks to efficient forest management and extensive trading among themselves. (Tropical hardwoods, by definition, must still be imported). Efficient wood production, however, has been achieved at the expense of other forest goods, most notably biodiversity.

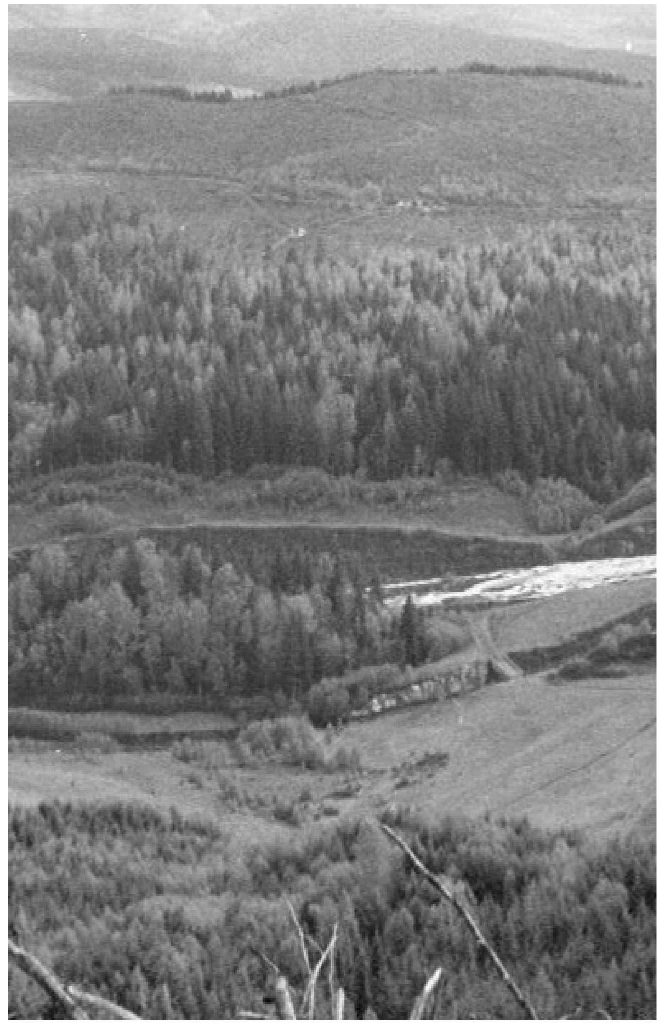
In developing countries, forests are now playing a similar role in socioeconomic development. Wooden housing frames, railway sleepers, telephone poles, and mining pit props are among the most important nonfuel uses of timber in these countries. Biomass energy, of which wood is by far the largest component, is the most important source of energy in the developing world (35 percent of total energy use), and is virtually the only source of fuel for over 2 billion rural people. Even in urban areas, charcoal is still an important energy source for households and industry in many parts of Asia, Latin America, and Africa.

Forests in developing countries may be under greater pressure than they were in the industrializing West. Traditional forest goods and services — timber, fuel, food, and medicines — continue to support rural populations who depend directly on the surrounding environment for their living. Population increase and economic growth are driving the conversion of forests to agricultural land to grow food and cash crops, just as they did in Europe and North America. The presence of important industrial minerals in developing country forests stimulates mining, which fragments forest stands. Logging activities are increasing in order to supply industrial wood, both for domestic use and for export to generate foreign currency earnings. On top of all these demands, growing numbers of environmental groups are advocating forest conservation, especially in the tropics, in order to protect habitat and endangered species, or to slow the pace of global climate change.

Today, forests worldwide are commercially valued for a vast range of industrial products: wood is processed into veneers, plywoods, panels, pulp for board and packaging, and paper for myriad uses. Biotechnology industries transform extracts from trees and other forest species into an array of pharmaceuticals, industrial raw materials, and personal care products. Cork oaks in the Mediterranean countries supply corks to the wine industry, Brazil nuts and wild latex are harvested in Amazonia, tagua nuts are processed into buttons in Ecuador, Norway Spruce and holly trees in the Northern Hemisphere provide decoration for millions of homes during the Christmas season. In addition to these goods, wealthy consumers are demanding, and celebrating, a range of post-industrial amenity services offered by forests. Hiking, bird-watching, ecotourism, recreational hunting, even survival training courses, are all becoming more popular. Forests are increasingly managed to meet leisure demands, legally protected to safeguard popular plants, animals, and landscapes, and cherished as remnants of an almost vanished "natural world." In such ways, 21st Century industrial societies are reviving some of the cultural and religious associations of the ancient forests.

Today, we look to forests for fiber, fuel, food, and pharmaceuticals, for watershed protection, climate regulation, and biodiversity conservation, for recreation, peace, and natural beauty, and for enduring symbols of national history and culture. Human demands for the world's forests to supply preindustrial, industrial, and postindustrial goods and services are overlapping and colliding.

Forest Extent and Change



A Working Definition of Forest Ecosystems

Within terrestrial ecosystems, the largest subdivision is the biome, a total assemblage of plant and animal life. Biomes are generally defined and mapped according to the structure or physiognomy of the vegetation, in particular the recognized dominant vegetation type. There is a fairly close correlation between biome boundaries and climate and soil types. Forests are found predominantly in moist climates that enjoy at least one moderately warm season. Trees that form a closed, or partially closed, canopy are the dominant vegetation type within the forest biome. Within this biome, ecologists define anywhere between five and twelve major forest types. Table 1 summarizes the location and vegetation characteristics of the world's major forest types, and the principal goods and services they provide.

Land cover maps define forest areas according to minimum thresholds of area, tree height, and percentage of land area covered by the tree canopy (percent canopy cover). These thresholds are a necessary, but essentially arbitrary, means of distinguishing forests from neighboring ecosystems, such as woodlands or savanna. Sometimes forest boundaries are naturally distinct, as in the tree line that marks the upper limit of tree growth on mountain slopes. Human modification often creates clear and abrupt transitions in vegetation cover, for example, where agricultural land abuts closed canopy forest. In many other areas, forests shade gradually into other ecosystems, in a complex mosaic of vegetation types. Under such circumstances, land cover maps impose artificial, discrete boundaries where none exist on the ground.

This study examines the extent of, and changes in, the world's forested areas, as defined by a number of leading land cover classification schemes. It is further concerned with the current and future capacity of those forested areas to produce a range of goods and services of benefit both to humans and nonhuman species.

Extent of Global Forest Cover

Experts have attempted repeatedly to map the extent and distribution of the world's forests and woodlands. Between 1923 and 1985, at least 26 calculations of closed forest land were made; they ranged from 24 million km^2 to 65 million km^2, with no discernible trend over time (Williams, M., 1994:97-124). The difficulty stems from aggregating national inventory data, which date from different years and use different definitions of

Table 1
Major Forest Types of the World

Forest Type	Climate Zone	Vegetation Characteristics	Principal Goods and Services
Tropical rainforest	Low latitude (ca 10º N to 10º S), i.e., the equatorial and tropical zones. Continuously warm, frost-free, abundant rainfall (>180 cm annually). Typically found in the Amazon lowland, central lowlands of Africa, and a belt from Sumatra, Indonesia to the islands of the western Pacific. Some extensions found poleward along the monsoon and trade wind coasts.	Tall, closely set trees form continuous canopy of foliage, dense shade. Trees usually smooth-barked and unbranched in lower two thirds. Multilayered crowns, with tall emergent trees above closed canopy and lower level of smaller trees. Broadleaf evergreen foliage. Forests contain numerous lianas and epiphytes, mosses, lichens, and algae. Heavy shade results in little vegetation on forest floor. High temperatures and humidity cause rapid decomposition of organic matter and low accumulation of litter. Many trees compensate by developing mats of horizontal roots, to capture nutrients. At higher elevations, rainforest structure gradually changes to montane (cloud) forest. Cloud forest characterized by lower tree height, more open structure, trees are gnarled instead of smooth.	Biodiversity: richest of all terrestrial ecosystems. Up to 3,000 tree species in a few square kilometers, and world's highest diversity of arboreal insects and other invertebrates. High concentrations of rare, endemic, and endangered animal and bird species. Carbon storage: second biggest terrestrial carbon store. Soil maintenance: tropical forest soils leach nutrients rapidly when forest cover is removed. Water cycling: large tracts of forest believed to regulate local hydrology and climate. Nonwood products: food, medicines, fibers support numerous indigenous peoples. Ecotourism: Major popular destination for ecotourists. Note: Tropical rainforests experiencing fastest rates of deforestation of all forest types.
Tropical deciduous forest (including moist tropical, dry tropical, and monsoon forest)	Hot lowlands outside the equatorial zone (ca 10º to 30º latitude). Rainfall more seasonal, dry season more pronounced, especially in dry tropical forests. Monsoon forest found in southern Asia, Myanmar, Thailand, and Cambodia; also south-central Africa and South America bordering the equatorial rainforest.	Canopy lower and more open than equatorial rainforest. More light penetration and more understory vegetation. Leaves shed in dry season to conserve soil moisture. Most luxuriant form is monsoon forest, with large-leaved foliage and dense undergrowth rich in bamboos.	Biodiversity: less diverse than low-latitude rainforest, but rich in many taxa. Up to 40 tree species in small forest tracts. Timber: monsoon forests the source of highly valued species such as teak. Woodfuels: major source for rural and urban populations. Carbon storage: major global store. Note: monsoon forests now largely logged out in SE Asia. Dry tropical forests also heavily logged, nearly vanished in Indonesia.
Subtropical evergreen forest	Moist, subtropical zones, with mild winters and ample rainfall. Often at intermediate elevation (montane forest). Broadleaf once covered extensive areas of southern China and southern Japan. Needleleaf occurs only in southeastern United States.	Broadleaf evergreen forests differ from tropical rainforest in having relatively few tree species, lower tree height, less dense canopy. Often have well-developed lower vegetation layer, including tree ferns, small palms, bamboos, lianas, and epiphytes. Oaks, laurels, magnolias predominate in Northern Hemisphere, Southern beeches in Southern Hemisphere.	Soil stabilization and water flow regulation: montane forests particularly important in hydrological cycle. Timber: broadleaf species provide valuable hardwoods. Needleleaf pines of southeastern United States valued for lumber and pulp. Carbon storage: important store. Nonwood forest products: major source. Note: Asian forests now largely cleared for cultivation.
Temperate needleleaf forest	Temperate zones (ca 30º to boreal region). Mostly Western Hemisphere. In western North America extends southward into United States on the Sierra Nevada and Rocky Mountain ranges and higher plateaus of southwestern states. Commonly found in Pacific coast of Central America, and in upland and mountainous regions of Europe and Asia.	Straight-trunked, cone shaped trees, with relatively short branches and small, narrow, needle-like leaves. Needleleaf forests of western and southeastern United States dominated by species of pine. Fir and spruce common in other regions. In Europe and Asia, sometimes found in association with hardwood species.	Timber and wood products: temperate needleleaf species the world's largest supplier, probably supply more than half of total pulp production. Energy: wood industry residues increasingly used as commercial energy source. Carbon storage: moderate carbon store. Note: Many pine forests throughout entire range now converted to plantations.

Major Forest Types of the World *(continued)*

Forest Type	Climate Zone	Vegetation Characteristics	Principal Goods and Services
Sclerophyll forest and woodland	Native vegetation of the Mediterranean climate, found in narrow coastal belt around the Mediterranean Sea, Central and southern California coast, central Chile, Cape Region of South Africa and southern Australia. Moderate winter rainfall, but long, hot, drought condition summers.	Dominant tree species (sclerophylls) have small, leathery, evergreen leaves. Range from tall, open forest, to sparser woodland and scrub. Mediterranean region dominated by cork oak, live oak, Aleppo pine, stone pine, and olive. Higher rainfall regions support eucalypts and acacia (Australia), live oak and white oak (California). Lower rainfall areas produce pinon-juniper woodlands and pine barrens and scrubby land known as chapparal or maquis, which support scattered oak, mountain mahogany.	Nonwood products: source of commercially important products, including cork, honey, olives. Shade trees: important resource in agrosilviculture. Timber and fuel: important source of local construction material and energy. Biodiversity: important as high endemism regions. Note: much of Mediterranean forest cleared, now consists of dense scrub. Many Australian eucalypt tracts and parts of central Chile converted to plantations.
Temperate deciduous forest	Native vegetation of eastern North America and Western Europe. Also found in eastern Asia. Found almost entirely in Northern Hemisphere, though a small area is located in Patagonia. Associated with moist continental climate, rainfall in all months and a strong annual temperature cycle.	Common trees in North America, southeastern Europe, and eastern Asia are oak, beech, birch, hickory, walnut, maple, elm, and ash. In Western Europe, dominant trees are oak and ash; cooler, moister areas also support beech. Trees are dormant and leafless in winter, full leaf in summer. Forests are extremely variable in structure and composition, in accordance with local climate, soil type, elevation, and frequency of fires. Extensive accumulation of organic matter and high moisture capacity of soils makes forests relatively less prone to fires than many other biomes. These forests are extensively associated with other forest types, and many hybrid types are recognized.	Timber: many hardwood species valued for high quality end uses. Energy: wood industry residues increasingly used as commercial energy source. Carbon storage: moderate carbon store. Biodiversity: high diversity and endemism. Recreation: increasingly important. Note: Most remaining temperate deciduous forests significantly affected by logging. Earlier clearance and slow growth rates means most are secondary-growth. Climax vegetation not yet fully reestablished.
Temperate rainforest	Vegetation type limited to the west coasts of continents and large islands in the mid-latitudes, where precipitation exceeds 150 cm/year and falls during at least 10 months. Temperatures are cool year-round, but always above freezing. Frequent fogs and high humidity permit the growth of large evergreen trees.	Relatively few species of tree. Cool temperatures slow growth rates but high moisture inhibits fire, and these forests contain some of the world's oldest and largest trees. Coniferous species such as spruce and firs dominate in the Northern Hemisphere; giant redwoods grow extensively on the Pacific coast of North America. Temperate rainforests of the Southern Hemisphere dominated by trees with broad evergreen leaves, such as eucalyptus. Canopies usually closed, with many dead, standing trees. In understory, epiphyte diversity is high, consisting of mosses, lichens, fungi, and ferns.	Biodiversity: tree diversity limited but rich diversity of animals, birds, invertebrates, vascular plants, and fungi. Many still undocumented. Timber and woodfuels: Valuable local and traded resource. Nonwood forest products: foods and winter greenery particularly valued. Carbon storage: together with boreal forests, these forests sequester more carbon annually than any other ecosystem. Recreation: hiking, nature appreciation, and camping growing in popularity. Note: old-growth forests of the U.S. Pacific Northwest and South America still subject to extensive clear cutting.
Boreal Forest	High latitude forests, found in two broad continental belts in North America and Europe and Siberia. They require cold climate and adequate moisture. Boreal forests extend into lower latitudes where mountain ranges and high plateaux exist, such as the cordilleras of western North America, extending to southern Mexico.	North America, highland Europe and western Siberia dominated by evergreen conifers such as spruce and fir. North-central and eastern Siberia dominated by larch, a deciduous needleleaf. Cool temperatures and waterlogged soil inhibit decomposition rates, resulting in accumulation of peat and humic acids, which make many soil nutrients unavailable for plant growth. Canopy is often not dense, and a well-developed understory of acid-tolerant shrubs, mosses, and lichens may be present. Stressful conditions inhibit variety of tree species. However, where boreal forests are burned over, broadleaf deciduous trees such as aspen, balsam poplar, willow, and birch can take over rapidly. In northernmost range, needleleaf forests grade into cold woodland with sparse tree cover, then finally tundra.	Carbon storage: boreal forests of Canada and Russia form the greatest carbon store of all forest ecosystems. Timber: Canada a leading world producer of softwood. Siberian forest the world's greatest remaining standing reserve of softwood timber. Biodiversity: low diversity but high endemism, remains relatively unstudied. Note: Russian boreal forest the largest contiguous area of forested land remaining in the world.

forest, particularly in the distinction between closed and open forest. (*See Table 2.*) In a recent survey, the International Union of Forestry Research Organizations (IUFRO) identified over 90 different definitions of forest land (Lund, 1999). Definitions vary among countries and international organizations, and even among agencies within countries. Over the past decade, efforts to understand the global climate, and the regulating role played by the world's ecosystems, has encouraged "top down" analysis, in which satellite data are used to generate data at the regional, continental, and global levels. This approach provides a more consistent picture of forest cover than attempts to sum and harmonize national data, but requires verification in the field.

The Food and Agriculture Organization of the United Nations (FAO), in collaboration with other partners including the U.N. Economic Commission for Europe (UN-ECE) and the United Nations Environment Programme (UNEP), attempts to provide an overall picture of global forest resources every 10 years. FAO assessments are the most widely cited, despite the acknowledged problems of poor inventory quality and national data comparability.

The most recent FAO Forest Resources Assessment (FRA) dates from 1990 and comprises two main surveys. (The FRA 2000 will be published in 2000, but was not available in full during the preparation of this report.) The FRA 1990 assessed temperate and boreal forests in the developed countries by means of a questionnaire that elicited detailed information on forest area. This survey also asked for information on ownership and management status, growing stock, annual growth, and fellings. For the tropical, subtropical, and the few temperate forests in the developing countries, the FRA used existing inventory information, supplemented by remote-sensing based sampling plots and expert opinion. According to FRA 1990, as slightly amended in 1995, the world's forest cover totals 34.54 million km^2 (FAO, 1997a:185). In calculating this total, the FAO uses forest definition thresholds of 10 percent canopy cover and 5 meters tree height. In the tropical and subtropical zones, a 10-40 percent canopy defines open canopy forest, and 40-100 percent canopy cover classifies as closed canopy forest.

Somewhat different estimates are obtained when forest cover is estimated from land cover data provided by satellite-based remote sensing. (*See Maps 1 and 2.*)

Map 1 shows the world's forested areas as characterized in the land cover classification scheme of the International Geosphere-Biosphere Programme (IGBP, 1998). The IGBP assessment is an ongoing program that provides spatial information on forests over broad areas, but cannot provide fine detail at the country level. It is based on interpretation and classification of advanced very-high-resolution radiometer (AVHRR) satellite imagery with a 1-km resolution. The classification distinguishes five major forest types: evergreen needleleaf and evergreen broadleaf forests; deciduous needleleaf and deciduous broadleaf forests; and mixed forests, which consist of mixtures or mosaics of the other four forest types. The IGBP classification of forest is based on three parameters — the proportion of the 1-km cell (the remote sensing unit of analysis) covered by trees, percent canopy cover, and tree height. The minimum thresholds that define forest are: 60 percent of the cell domi-

Table 2

Threshold Values Used for Defining Forest Land

Selected Countries and Organizations	Minimum Area (ha)	Minimum Crown Cover (%)	Minimum Tree Height (m)
Austria	0.1	30	..
Chile	5	10	..
Estonia	0.5	30	1.3
France	2	10	..
Germany	..	50	..
Japan	..	30	5
Mexico	0.15	10	3
Papua New Guinea	100	10	5
Russia	..	30	..
South Africa	..	75	3
U.S. Fish and Wildlife Service	..	..	6
U.S. National Park Service	..	60	5
U.S. National Resources Conservation Service	0.4	25	4
USDA Forest Service	0.4	10	4
U.S. Geological Survey	0.4	20	2
U.N. Forest Resource Assessment (FAO)	0.5	10	5
UNESCO	..	40	5

Source: Lund, 1999
Note: .. means no threshold values were stipulated

nated by trees, 10 percent canopy cover, tree height of 2 meters. Mixed vegetation zones of forest and other vegetation, where no one vegetation type exceeds 60 percent of the cell, are classified as forest/other vegetation mosaics. (*See p. 19*: *Forest/Cropland Transition Zones*.)

Map 2 presents an alternative view of the world's tree cover. Researchers at the University of Maryland (UMD) have applied a linear mixture model to 1-km AVHRR data to estimate proportional land cover for various vegetation characteristics, such as woody or shrubby vegetation, evergreen or deciduous leaf type, and bare ground (DeFries et al., forthcoming, 2000). The map illustrates global cover of woody vegetation, on a continuous scale from 0 to 100 percent. Woody vegetation is defined as mature vegetation whose approximate height is greater than five meters and can thus be equated with trees. This technique avoids the problems inherent in traditional classification schemes with discrete numbers of vegetation types. The use of classification schemes introduces abrupt boundaries and unrealistic homogeneity into the depiction of land cover types that are, in practice, often finely graded and heterogeneous. The methodology used to develop the UMD map does not set minimum thresholds of tree cover within each cell, since the purpose is not to define "forest". The percent tree cover map helps to identify areas of partial tree cover that, while not formally classified as forest, nevertheless provide many of the same goods and services, especially food, fuelwood, habitat, and soil protection. These areas are vulnerable to clearance, because they receive less attention and formal protection than forests.

Table 3 compares the global forest cover estimate of the FAO with that of the PAGE study, which is based on the IGBP classification scheme, modified by the exclusion of urban areas. The table illustrates the wide differences that emerge when comparing inventory-based data and terrestrial maps on the one hand (FAO), with satellite-derived maps on the other (IGBP). The satellite-based percent tree cover map developed by UMD cannot readily be compared with that of the IGBP, because it defines tree cover by means of fewer parameters (percent tree cover and vegetation height). However, it is instructive to note that the absence of other thresholds, such as minimum area or percentage of tree cover within each cell, changes estimates of global tree cover substantially. WRI estimated global tree cover from the UMD percent tree cover database, using cut-offs of 10 percent and 60 percent tree cover, to enable comparison with the FAO and IGBP estimates, respectively. Using a threshold of 10 percent tree cover, the UMD map yields a global tree cover estimate of more than 60 million km^2. At a threshold of 60 percent tree cover, the estimate falls to under 17 million km^2.

Human Modification of Forest Cover

HISTORIC FOREST LOSS

It is not possible to state with certainty the degree to which humans have removed, or modified, the earth's original forest cover. "Original" has no clear baseline: geological and anthropological studies of the Quarternary period have revealed bewildering forest dynamics, particularly in the middle latitudes. Warming or cooling of the global climate at this time caused the retreat or advance of ice sheets and associated shifts in forest location. However, a number of attempts have been made to reconstruct forest area in the preagricultural era. The World Wildlife Fund (WWF-U.S.) has developed maps of the earth's Major Habitat Types (MHTs), which indicate areas of potential forest cover before major human intervention (Olson et al., 1999). (*See Map 3*.)

Map 3 is based on a biogeographic classification for biodiversity, developed by WWF-U.S. to help determine conservation priorities using a standardized approach and resolution. The basic conservation unit at the global or continental scale is an ecoregion. An ecoregion is defined as a relatively large area of land or water that contains a geographically distinct set of natural communities that: (1) share a majority of their species, ecological dynamics, and environmental conditions; and (2) function together as a conservation unit at global and regional scales (Dinerstein et al., 1995). Ecological processes, general patterns of biodiversity, and responses to disturbance vary widely in their scale and importance among habitat types, such as tropical moist forests, tropical dry forest, grasslands. To address this variation, WWF-U.S. grouped the ecoregions within major habitat types (MHTs). MHTs are not geographically defined units. Instead, they are defined by the dynamics of the ecological systems and the broad vegetative structures and patterns of species diversity within them. The forest MHTs shown on this map are, thus, indicative of the area *potentially* covered by different forest types, given the appropriate climatic and ecological conditions and no human intervention. They should not be regarded as actual maps of former forest cover.

Despite major uncertainties, it is clear that forest area has diminished over time. A study by Matthews in 1983 estimated that preagricultural closed forests once covered about 46.3 million km^2, and that this total had decreased to 39.3 million km^2 by about 1970, a decline of 15 percent (Matthews, 1983:474-487). Most of the decline occurred in European and North American temperate forests, as land was cleared — initially, for intensive small-scale agriculture and, more recently, for commercial farming. Intensive subsistence farming and cash crop production have reduced the tropical and subtropical forests of Asia. The study estimated that woodland cover declined from about 15.2 million km^2 to 13.1 million km^2, a reduction of 14

Table 3

Estimates of Forest Cover

Region	FAO[1] (million km²)	PAGE[2] (million km²)
Latin America & Caribbean	9.5	7.80
Russian Federation	7.64	5.80
Africa	5.20	2.71
Asia/Oceania	5.65	4.61
North America	4.57	7.11
Europe[3]	1.99	0.93
Developed Countries	14.93	not estimated
Developing Countries	19.61	not estimated
Total	**34.54**	**28.96**

Source: FAO, 1997a; IGBP, 1998.
Notes:
[1] FAO forest area estimates include plantation area.
[2] IGBP forest area has been modified slightly for the PAGE study by excluding human settlements. Human settlements are based on the Nighttime Lights of the World database (NOAA-NGDC, 1998). Human settlements in forests account for 0.95 million km^2.
[3] Includes countries of Former USSR, excluding Russian Federation.
FAO data are generally from the 1990s, though they vary from country to country. IGBP data are from the mid-1990s.

percent. Over the centuries, subsistence agriculture has removed or thinned woodlands, especially in the dry African miombo. The Matthews study produced estimates of current forest cover based on information dating largely from the early 1970s. If losses for closed forests converted to other land uses since then are added to loss estimates in the study, the global decline in forest cover since the dawn of agriculture totals about 20 percent.

The Matthews study was based on coarse-resolution vegetation and land use databases (1° resolution, equivalent to a 111 km by 111 km grid at the equator), and it may underestimate historic forest loss considerably. The World Conservation Monitoring Centre (WCMC) developed a higher resolution map (approximately 8 km by 8 km at the equator) of potential forest cover some 8,000 years ago as a baseline for the World Resources Institute's Frontier Forests study (Bryant et al., 1997:37). Comparison of this map with a map of current forest cover, also developed by WCMC, indicates that nearly 50 percent of the earth's preagricultural forest cover may have been cleared. The two studies differed somewhat on definitions of vegetation classes, and used markedly different methodologies. Perhaps surprisingly, their estimates of early forest cover were roughly comparable (if Matthews' forest and woodland areas are combined as one category). Despite their agreement on that measure, the two studies' estimates of current forest area differed widely. To conclude, given the difficulty of estimating preagricultural forest cover, and continuing uncertainty about current forest cover, it can be said that approximately one fifth to one half of the world's forest cover has been converted to other uses since preagricultural times.

Almost all of this change has resulted from human action. Although the greatest transformation occurred with the development of sedentary agriculture, pastoralists' use of fire to extend pasture area was not a negligible influence. Population growth, which accelerated dramatically from the mid-17th Century, has led to a steady decrease of forested area as people have claimed more land for food production, more timber for construction, and more fuelwood for warmth, cooking, and metal smelting.

Less than half of today's forest cover remains in its original state. Clearance has been followed by regrowth in much of the United States; most European forests are actively managed for timber production, recreation, erosion control, and other purposes. Many forests in the tropical and subtropical regions are affected by shifting cultivation. Human modification of forest *condition* as opposed to forest *extent* is discussed in more detail later in this chapter.

RECENT DEFORESTATION TRENDS

Estimates of recent changes in forest cover are subject to the same data constraints as noted above for current forest extent and distribution. FAO maintains the most detailed global datasets, although researchers both within and outside FAO acknowledge their limitations. Financial resources available to FAO to maintain and improve these data have been limited, and, as a U.N. agency, FAO must use, in some cases, national sources of information that are known to be less accurate than other sources.

National forest inventories are frequently outdated and noncomparable; many forest conversions go unrecorded or are illegal. Definitions of deforestation vary, because deforestation is not official until tree cover has fallen below the national thresholds for forest. (*See Table 2.*) Land use may also be a criterion: the FAO does not consider harvested areas to be deforested, since they might, in the foreseeable future, regenerate or be replanted. In addition, the high political profile of tropical deforestation has resulted in emotive claims and counter-claims. Taking these factors into consideration, recent estimates of tropical deforestation have ranged from about 50,000 km^2 to 170,000 km^2 annually (Tucker and Townshend, 2000:1461-1472).

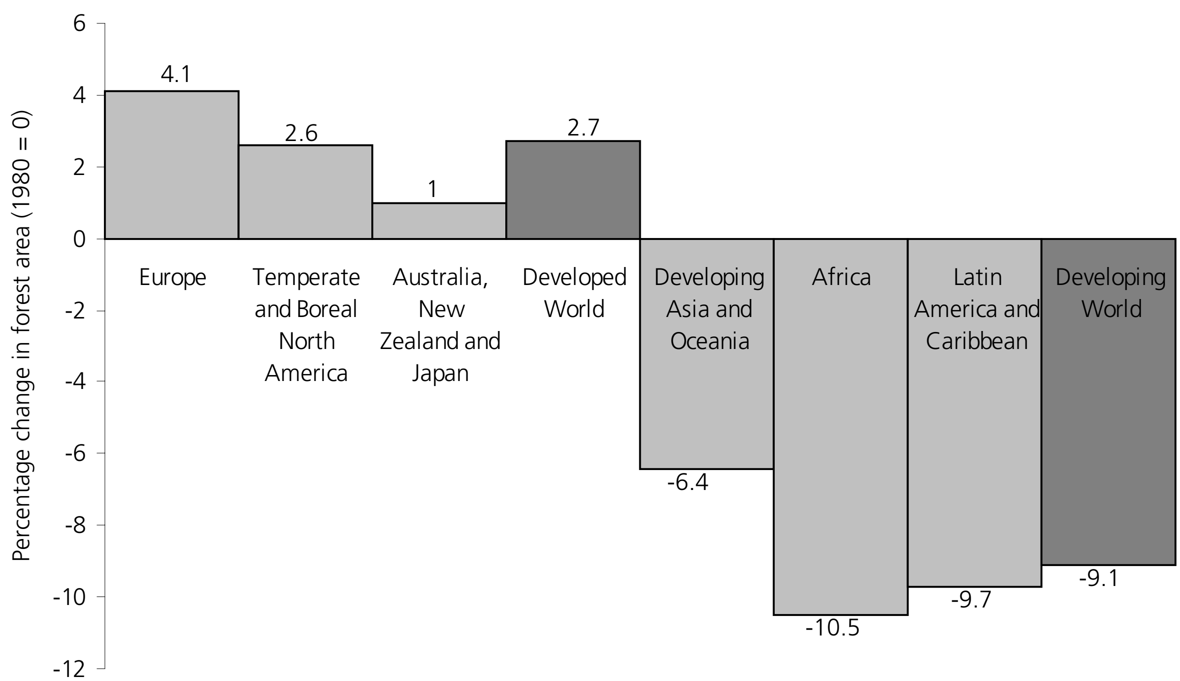
The most recent FAO assessment of changes in global forest cover between 1980 and 1995 concluded that forested area had increased by some 0.2 million km^2 in the developed world. Afforestation, reforestation, and natural regrowth on land abandoned by agriculture more than offset forest losses to urbanization and infrastructure development (FAO, 1997a:17). In contrast, forest cover in the developing countries decreased by an estimated 2 million km^2 (an annual average loss of 130,000 km^2) with distinct patterns of deforestation evident in different world regions. The FAO attributed forest loss in Africa principally to the extension of subsistence agriculture, under pressure of rural population growth. Clearance for government-planned settlement schemes, large-scale cattle ranching, and hydroelectric reservoirs dominated changes in Latin America. Forests in Asia were subjected about equally to pressure from subsistence agriculture and economic development schemes. (*See Figure 1.*)

The FAO estimates of rates of change in forest cover were based on national inventories and maps, supplemented by remote sensing data from random samples covering 10 percent of the surveyed area. Data were then adapted to the standard reference years of 1990 and 1995 through use of an adjustment function, called the deforestation model. This model correlates forest cover change over time with variables including population growth and density, initial forest cover, and ecological zone of the forest under consideration. Use of this method, however, tends to overemphasize the importance of population change, especially in countries where deforestation results principally from causes other than clearance for agriculture. The approach also records only net forest cover changes over long periods of time, missing significant year-to-year variability. Such variation is of great importance ecologically, affecting both biomass volumes and biodiversity.

The FAO's 1980-90 estimates of forest cover change rates were revised downward for the period 1990-95, to accord with new, lower estimates of population growth and more recent national assessments of forest cover. Despite continuing high deforestation rates in the tropics, the FAO claims that, looking at natural forest cover trends in developing countries as a whole, deforestation rates have slowed since 1990. (*See Table 4.*)

Figure 1

Global Deforestation Between 1980 and 1995



Source: FAO, 1997a:17

Table 4

Estimated Annual Forest Loss in Developing Regions

Region	Annual Change in Natural Forest Area (km^2) 1980-90	1990-95
Africa	-42,800	-37,500
Tropical	*-41,900*	*-37,000*
Nontropical	*-900*	*-500*
Asia-Oceania	-44,100	-41,700
Tropical	*-39,700*	*-35,100*
Nontropical	*-4,500*	*-6,600*
Latin America & Caribbean	-67,700	-58,100
Tropical	*-64,800*	*-56,900*
Nontropical	*-2,900*	*-1,200*
Developing World	-154,600	-137,300
Tropical	*-146,300*	*-129,100*
Nontropical	*-8,200*	*-8,300*

Source: FAO, 1997a:18.

Some of these data now appear highly questionable, at least for some important tropical countries. According to the National Institute for Space Research (INPE) of Brazil, deforestation rates in the Legal Amazon increased after 1990, with a dramatic peak around 1994, although the analysis indicates that forest loss has since slowed again. (*See Figure 2.*) The discrepancy is caused partly by the fact that the FAO's population model does not work well in Brazil, where deforestation results more from the expansion of ranching than from subsistence farming. Additional measurement problems stem from unreliable forest inventories and illegal logging.

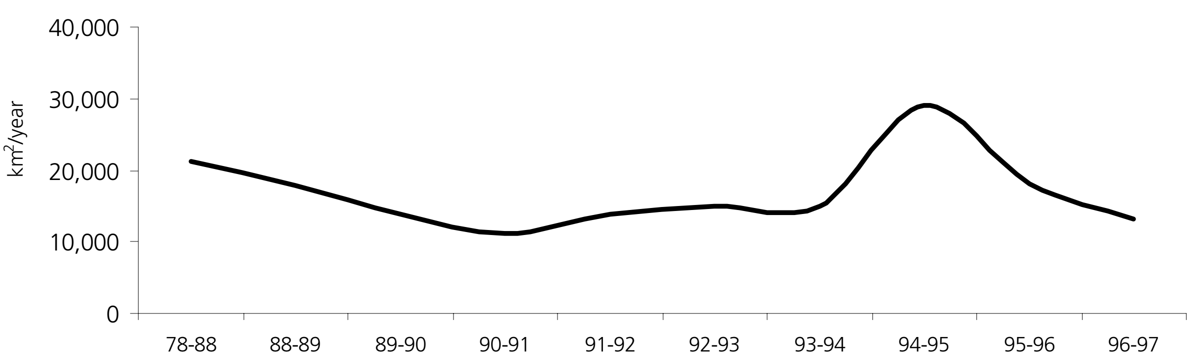
The FRA 1990 deforestation data were compromised to some extent by the limited use of remote sensing information. Accurate measurement of the extent of tropical deforestation using a random sampling analysis of Landsat, or similar high spatial resolution data, is difficult to achieve for other than localized areas. High sampling rates are required to improve accuracy. Deforestation tends to concentrate in highly localized areas, and a 10 percent random sampling rate, as used by FAO, can grossly under- or overrepresent the deforested area.

Researchers at the U.S. National Aeronautics and Space Administration (NASA) and the University of Maryland have conducted detailed studies of satellite data for Bolivia, Colombia, and Peru. They have determined that, in order to achieve a Landsat-derived estimate accurate within ±20 percent of actual deforestation 90 percent of the time, a sampling rate of between 80 and 90 percent of the survey area is required (Tucker and Townshend, 2000:1461-1472). The control of actual deforestation measures in these studies was determined by wall-to-wall analysis of digital satellite data from the mid-1970s, mid-1980s, and early 1990s, undertaken as part of the Landsat Pathfinder Humid Tropical Forest Inventory Programme. A sampling rate of 80-90 percent is far greater than the resources of FAO currently permit.

New deforestation data emerging from Indonesia also show much higher rates of forest loss than reported by FAO. Recent satellite images of Kalimantan, Sulawesi, and Sumatra, released by the Indonesian Ministry of Forestry and Estate Crops, indicate a loss of more than 170,000 km^2 in the period 1985-97, equivalent to an average annual loss of nearly 15,000 km^2. This loss amounts to one quarter of the country's total forest cover in 1985. When data for the rest of the country are fully analyzed, the average annual rate of deforestation is expected to be closer to 17,000 km^2. It should be noted that these data do not include forest loss caused by the extensive forest fires of 1997-98. (*See pp. 24-25.*) The long-term average deforestation figure masks what appears to be an even steeper increase in the last three

Figure 2

Brazilian Deforestation, 1978–1997



Source: INPE, 1999.

Note: The Legal Amazon forested region covers some 3.5 million km, equivalent to approximately 80 percent of total forested area in Brazil.

years, when rates of forest loss reached about 20,000 km^2 annually (Holmes, 2000). This contrasts with FAO reports of annual losses in Indonesia, which average under 11,000 km^2 for the period 1990-95.

Human Modification of Forest Condition

"FRONTIER FORESTS"AND DEGREE OF FOREST "NATURALNESS"

We know surprisingly little about the biological status of the world's forests. In a 1997 study, the World Resources Institute (WRI) coined the term "frontier forests" to describe forested areas that are relatively undisturbed by human activity and are large enough to maintain their biodiversity, including viable populations of wide-ranging species (Bryant et al., 1997:11). According to the study, frontier forests constitute about 40 percent of total forest area, but they are heavily concentrated in three large blocks — two areas of boreal forest (in Canada, Alaska, and Russia), and one relatively contiguous area of tropical forest spanning the northwestern Amazon Basin and Guyana Shield (in Brazil, Peru, Venezuela, and Colombia). Additional important outliers can still be found in Central Africa (Congo), and Papua New Guinea.

Nearly 40 percent of these remaining frontier forests are estimated to be under moderate or high threat of degradation or clearance. The principal threats to frontier forests, in order of importance, are logging, development for mining, roads and other infrastructure, agricultural clearance, and excessive vegetation removal. According to the FAO, in the world's forests *as a whole,* clearance for agriculture is the leading cause of forest loss. However, logging and mining, and the roads they require, represent the first step in opening previously inaccessible forests. Once built, these roads increase the likelihood of settlement by subsistence farmers, and other forms of development.

In the forthcoming *Temperate and Boreal Forest Resources Assessment* (TBFRA 2000), UN-ECE and FAO have attempted to gather official comparable international data on the naturalness of temperate and boreal forests. "Naturalness", in this exercise, refers to the degree of resemblance to the conditions that would obtain in the complete absence of human intervention. The UN-ECE/FAO categorized forests and other wooded land as natural (undisturbed by man), semi-natural (under some degree of management, or evincing past human intervention), or plantation (under active management). To be classified as undisturbed by man, forests must display what are called natural forest dynamics. In addition, no significant human intervention should be present, or it should have occurred long enough ago to allow the natural species composition and processes to become reestablished. Given the widely differing conditions among regions, a certain amount of judgment by national correspondents was necessary; to date, experts have not fully harmonized their interpretations of the definitions.

In practice, even this simple categorization scheme proved very hard to adhere to. Most countries in the study area, with the exception of the Russian Federation, reported little or no undisturbed forest area, despite the wide variety of their forest cover types. The study appears not to add greatly to our understanding of the biological condition of temperate and boreal forests. The distinction between the terms undisturbed (implying pristine) and seminatural (implying spoiled) should not be drawn too sharply; many seminatural forests are judged to be in good condition by forest managers and forest ecologists. No comparable exercise has been undertaken for tropical forests but it is likely that, even in remote areas, they may be less pristine than we imagine. Much "virgin" forest in Malaysia is less than 100 years old, for example, and tribal forest management in the Andes has been responsible for the introduction of numerous non-indigenous species (Dudley, personal communication, 14 October, 1999).

The following sections discuss some of the more important ways in which human actions modify forest condition. Population growth, economic growth, and government development programs, all encourage people to change forests in pursuit of a particular good or service. The indicators of such change presented here concern the growth of forest/cropland transition zones between closed forest and nonforest land (to raise production of food and cash crops); road construction in forested areas (to provide access for development); and fire-setting (to clear land for agriculture and cash-crop plantations).

FOREST/CROPLAND TRANSITION ZONES

Transition zones are defined here as mixed forest/cropland mosaics, that is, zones created within formerly closed canopy forests — usually for subsistence agriculture, agroforestry, or silvipastoralism. The zones form a border between closed canopy forest and other ecosystems, such as grasslands or agricultural lands, and they represent a rapidly growing land cover category. The transition area between forest and other land cover is one of the most dynamic portions of forest ecosystems and makes up a significant fraction of forest ecosystems in many parts of the world. Transition zones are commonly classified as forest, because canopy cover still exceeds national, IGBP, or FAO thresholds. For this reason, thinning of canopy cover, progressive reduction of forest biomass, or other forms of forest degradation, go largely unreported. Regrettably, trend data on the development of transition zones are not available.

Map 4 highlights the significant impact of humans in transforming closed canopy forest to open forest and mixed vegetation cover. Nearly 4 million km^2 of land in Africa now qualify as forest/cropland mosaics, where cropland accounts for between 30 percent and 40 percent of the vegetation cover and forests account for some part of the remainder. As Table 5 indicates, more than 1 million km^2 of land falls within the category of 30-40 percent cropland and 30-60 percent tree cover. A further 1.5 million km^2 of land falls within the category of 30-40 percent cropland and 10-30 percent tree cover. In total, therefore, more than 2.5 million km^2 of land in Africa that is commonly classified as forest should actually be seen as forest/cropland transition zone. Map 4 should be compared with Map 2 (Percent Tree Cover) in order to understand the interpenetration of forest and agriculture land cover, and the importance of transition zones in reducing areas of intact forest. (It should be noted that forest/cropland mosaics have been included as agricultural land in the Pilot Assessment of Agroecosystems [Wood et al., 2000]. This accounts for some overlap in PAGE area estimates of agroecosystems and forest ecosystems.)

Note to Map 4: The map is based on a modified version of the IGBP vegetation classification scheme. The IGBP vegetation classes represent an aggregation of 917 seasonal land cover categories defined in the Global Land Cover Characteristics Database (GLCCD, 1998). The IGBP classes do not distinguish cropland from other vegetation in the class Forest/Other Vegetation Mosaics. For the PAGE, therefore, WRI reaggregated the 917 seasonal land cover categories to highlight forest/cropland mosaics. These represent mosaics that are human, rather than natural, in origin. A weakness of our approach is that even a small percentage of cropland results in the pixel being characterized as forest/cropland, and the degree of forest modification may be visually overstated. The pink areas of the map do not include natural forest/other vegetation mosaics where, nevertheless, agriculture may play a small role. Despite these weaknesses, the map demonstrates the degree to which intact forests are being fragmented by agriculture.

Data on tropical forest biomass show widespread reductions over the past two decades, as closed forest has been converted to open or fragmented forest or disturbed by logging and shifting cultivation (Uhl and Vieira, 1989:98-106; Woods, 1989:290-298; Gajeseni and Jordan, 1990:114-118). One of the most significant changes to forest ecosystems in the transition zones is the overall biomass reduction as the forest is thinned out to allow cultivation.

The change from closed forest to various forms of transition zone should not necessarily be seen as a negative development. These areas may be sustainably managed to provide timber, tree and fodder crops, shelter for field crops, fuelwood, and habitat for wildlife. Some of the most productive subsistence agricultural areas in the world exist in forest transition zones. At the same time, loss of biomass and soil fertility in these areas can proceed rapidly under conditions of population growth and migration. Currently, neither national forest inventories nor global forest datasets reveal how fast transition zones are expanding at the expense of former intact forest, where they are, and whether they are functioning as sustainable systems. Some insights into the development and structure of a representative transition zone emerge from a case study on swidden agriculture in Cambodia. (*See Box 1.*)

ROAD CONSTRUCTION IN FORESTS

Roads provide people with many benefits, including mobility and communications, access to natural resources, and transportation routes for goods. At the same time, they adversely affect the numbers, diversity, and distribution of flora and fauna, and soil and water quality. Road networks in industrialized countries are often very dense — for example, 1.5 km/km^2 in the Netherlands, and 1.2 km/km^2 in the United States. In developing countries, road networks are expanding rapidly. The eco-

Table 5

Tree Cover and Cropland Mosaics in Africa

Land Area (km^2)					
	Percent Tree Cover Class				
Percent Cropland Class	<10	10-29	30-60	>60	Sum
30-40	1,128,050	1,467,021	1,067,179	117,806	3,780,056
40-60	658,770	359,924	508,723	81,949	1,609,366
>60	241,148	224,676	191,547	61,004	718,375
Sum	2,027,968	2,051,621	1,767,449	260,759	6,107,797

Source: WRI.

Box 1

Swidden Agriculture in Cambodian Forests

For swidden agriculturalists, or shifting cultivators, there is rarely a clearly defined boundary between forest and agricultural fields. To the swidden cultivator, forests and fields are both part of a dynamic agricultural system that continually rotates through the processes of ecological succession to meet the needs of local agricultural production (Boserup, 1965). This cycle is clearly observable in Southeast Asia, where swidden agriculture has been practiced in the uplands for centuries and supports millions of people.

Long-term studies of the land use dynamics of swidden cultivation in this region are beginning to shed light on the landscape-level effects of swidden agriculture on forest cover. In the northeastern province of Ratanakiri, Cambodia, forest cover has remained constant over the last 40 years despite almost continuous use for swidden agriculture. The study area comprised 10 villages, whose fields, each 1-3 hectares in size, are used for approximately 3 years before being abandoned to secondary forest. Data from aerial photographs and interviews with villagers in this heavily forested region show that, between 1953 and 1996, 77 percent of the total land cover remained in secondary forest, but that land cover in any given plot changed many times over that period. The net changes in land cover are shown in Figure 3.

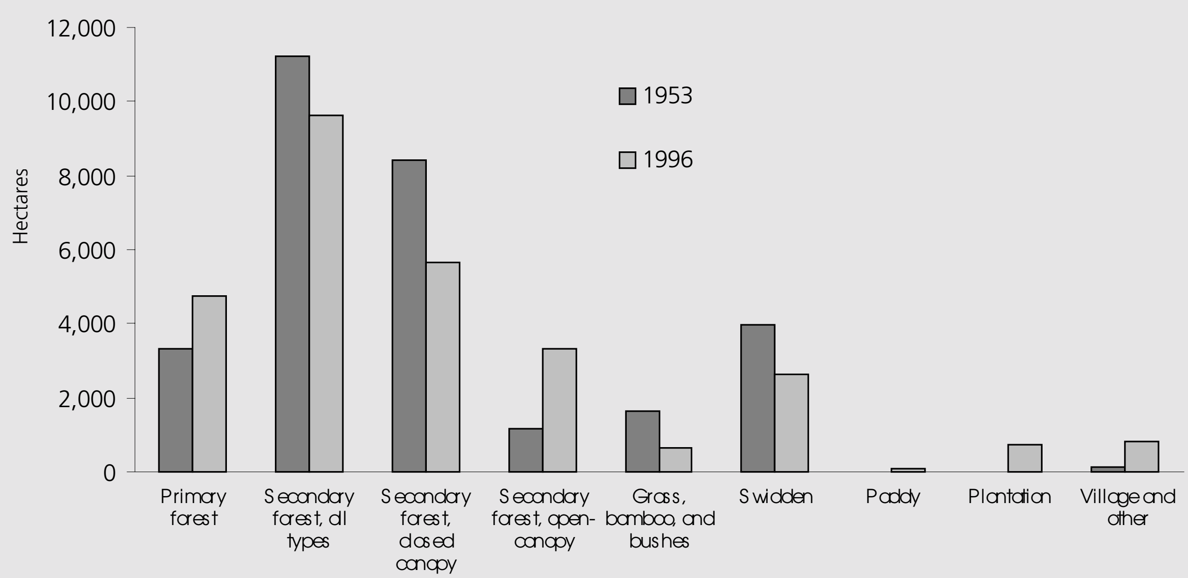
A notable change is the slicing of the landscape into many, smaller pieces, even though the total area of major land cover types, for example forest, remained constant or increased. (The increasing area of primary forest is explained by secondary forest being designated as primary forest after 25 years of undisturbed growth.) These changes can be clearly seen in the maps of land use cover change in Ban Lung village. (*See Map 5.*)

New market opportunities are also changing the agricultural practices of local residents, leading to landscape-level changes in the forest ecosystem. Formerly, ownership of the plot reverted to the community when villagers abandoned a swidden, but this tradition is changing as villagers begin to treat former swiddens as exclusive private property. Some villagers now cultivate cash crops, such as cashew trees, in former swidden plots to increase their monetary income, creating a more settled form of intensive agriculture. This change is reflected in the increase in village area, and the area under paddy or plantations.

Source: J. Fox. 1999. *Mapping a Changing Landscape: Land Use, Land Cover, and Resource Tenure in Northeastern Cambodia*. Submitted to Conservation Biology. EWC Working Papers: Environmental Series No. 50. East-West Center, Honolulu, Hawaii, and personal communication with the author.

Figure 3

Land Cover Changes in Ban Lung Village, 1953-1996



logical impact of roads extends beyond the road surface itself, to include parallel vegetated strips of land, and a disturbance zone created by pollution and noise that may extend for up to several hundred meters on either side of the road (Forman and Alexander, 1998: 207-231).

Roads can form physical barriers to wildlife movement, causing the effective fragmentation of formerly continuous blocks of habitat into smaller areas that may be less able to support complex communities of plants and animals (Dale and Pearson, 1997). Forest ecologists have identified a number of factors that influence how forest species respond to fragmentation: their gap-crossing ability, minimum area and specialized habitat requirements, and edge effects. *Gap-crossing ability* relates to the willingness and physical ability of a species to cross nonhabitat areas. For example, many beetles and spiders, small mammals, and amphibians are reluctant to cross gaps as narrow as 2.5 meters (Forman and Alexander, 998:215). *Area requirements* describe the minimum area required to maintain normal behavior patterns. Large mammals such as bears, tigers, and jaguars, all of which require large home ranges, have suffered significant population declines in North America, India, and South America respectively. *Specialized habitat requirements* concern species' exploitation of resources that are patchily distributed, often rare, and therefore vulnerable to habitat fragmentation. Finally, *edge effects,* which include changes in hunting and predation patterns, incidence of disease and pest attack, and changes in microclimate, affect species near the site of habitat modification.

Numerous studies record that many species avoid roads and are thus more confined than they are in roadless areas. African elephants in Gabon have been found to avoid a zone within 7 km of main roads because of human disturbance (Barnes et al., 1991:58). In the Netherlands, traffic noise in woodlands appears to drive down both total bird density and bird species richness with increasing proximity to roads and intensity of their use (Forman and Alexander, 1998:214).

Capital investment in roads is an important factor in deforestation. Rates of deforestation in capital-rich Brazil in the 1970s and 1980s, and in Indonesia in the 1980s and 1990s, were far higher than in capital-poor countries such as the Democratic Republic of Congo. Roads open up areas of undisturbed, mature forests to pioneer settlement, logging, and clearance for sometimes unsuitable forms of agriculture. An INPE study of Brazilian Amazonia found that, of 90,000 km^2 of forest lost between 1991 and 1996, 86 percent was within 25 km of an area of previous pioneer deforestation along major roads (Alves, 1999). Although the first settlers were ranchers, the local logging industry expanded as property rights stabilized and ranching became less profitable in the 1980s (Uhl and Vieira, 1989:98-106). Growing from a few small operations in the early 1970s, by 1990 the wood industry in Pará was logging nearly 680 km^2 annually. If this rate were sustained, logging would clear the entire Pará study region along the Belém-Brasilia Highway by the year 2050 (Verissimo et al., 1992:169-199).

Forest roads also provide access for human hunters and poachers. Forest-dwelling people have traditionally relied on bushmeat hunting for food. However, recent studies indicate that commercial logging greatly increases the harvest of wild animals from tropical forests by opening up remote areas, bringing in new people, and changing local economies and patterns of consumption. Hunting increases to supply food to logging camps; poaching and illegal animal trade increase with access to markets (and better weapons). In addition, rising incomes from logging stimulate local demand for more meat in the diet. In the tropical forests of Africa, the annual harvest of bushmeat may exceed 1 million metric tons, much of it from forest areas that are being opened up to logging. In kilograms of meat per square kilometer, this harvest is 20 to 50 times greater than the largely subsistence harvest of the Brazilian Amazon (Robinson et al., 1999: 595-596). The variance in population density between the two regions is not sufficient to account for this difference. However, African forests are home to many more large mammals than are found in Brazil; they may simply provide a richer and heavier harvest.

Numerous studies demonstrate that forest roads can lead to soil compaction, soil erosion, and water contamination (NRDC, 1999:67-71). It also appears that erosion which results from road construction associated with logging may greatly exceed erosion associated with removal of forest cover (Hodgson and Dixon, 1988:13-35).

The Road Access Indicator

As part of this pilot analysis, WRI developed a road access indicator, based on the density of road network, and the degree of habitat fragmentation that results from road construction. The worked example here applies to tropical forest in Central Africa. Such information is of particular value for Africa, which is home to large numbers of endangered or threatened forest-dependent species. In principle, the indicator is equally applicable to other ecosystems and regions, subject to the availability of an updated global road dataset.

The study area comprises just under 2 million km^2 of tropical forest in the Central African Republic, Congo, Democratic Republic of Congo, Cameroon, Equatorial Guinea, and Gabon. The IGBP 1-km AVHRR Land Cover map was used to represent current vegetation extent. Only forest cover defined as evergreen or deciduous needleleaf and broadleaf forest was included. At a resolution of 1 km, roads cannot be detected; information on roads was therefore obtained from the Central Africa Regional Environment Program (CARPE) database (CARPE, 1998). CARPE road data are based on the Digital Chart of the World (DCW) database (ESRI, 1993), but incorporate information from more recent national maps. A number of roads in the region have deteriorated over time, and are no longer recorded on newer national maps; CARPE data therefore show fewer roads than the DCW database. Such a situation is probably unique to sub-Saharan Africa. CARPE data, like the DCW, permit differentiation between permanent, all-weather roads and seasonal roads, which are less intrusive in the environment.

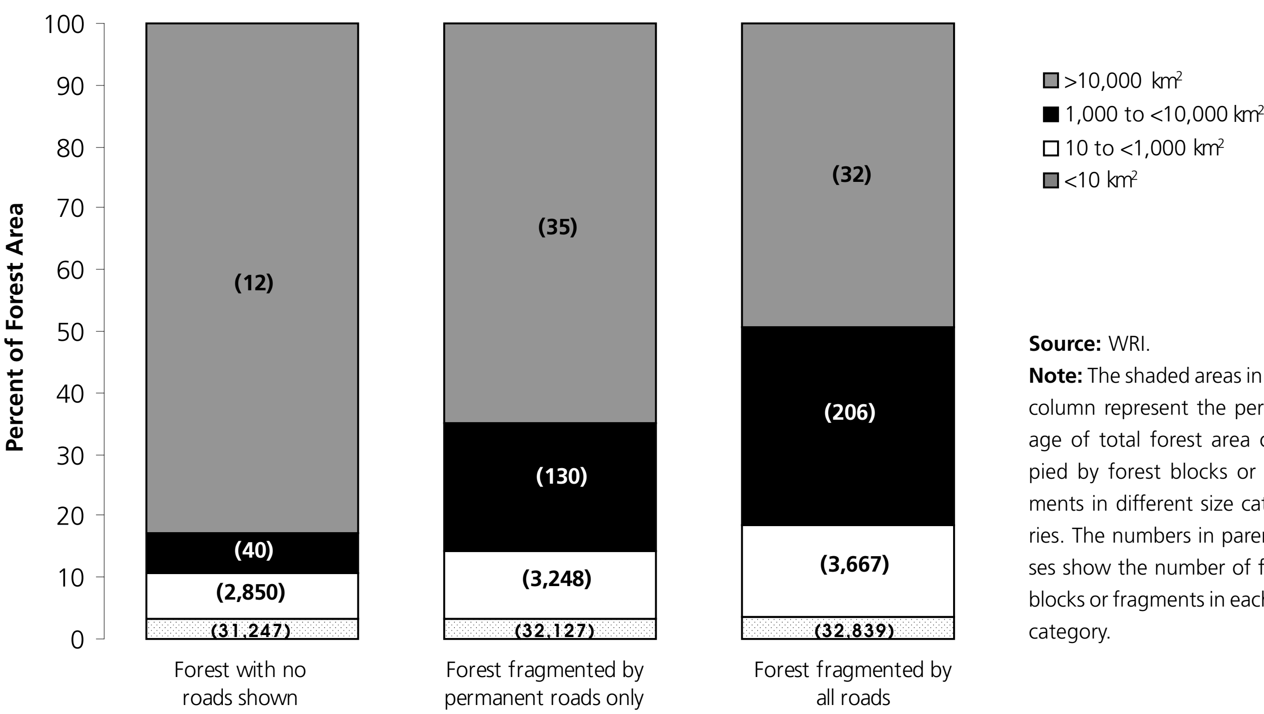
Map 6 depicts the degree of fragmentation introduced by permanent and seasonal roads. All roads were mapped as a linear 1 km² area. Using Geographic Information Systems (GIS), the indicator was developed through calculation of the *road density,* expressed as km of road/100 km², and the *degree of fragmentation,* expressed as the percentage of forest area and the number of forest blocks or fragments that fall into various area size categories. The size and distribution of forest blocks and fragments are calculated for the area covered by the six study countries (1) when the presence of roads is not considered, and (2) when roads are superimposed on forest cover. Area size categories were determined through extensive literature review and consultation with forest ecologists. The size categories reflect the generalized experience that populations tend to decrease in smaller fragments of habitat, and that species requiring large home ranges will be absent (Thiollay, 1989; Bierregaard et al., 1992). The largest size category (>10,000 km²) is considered appropriate to the wide-ranging umbrella species found in Central Africa. Large, contiguous areas of forest are referred to here as "blocks." Smaller areas resulting from bisection by roads are referred to as "fragments." The word "patches" was avoided, since this term may refer also to naturally occurring habitat heterogeneity.

The road density in the total study area ranges from 2.4 km/100 km² in the smallest (i.e. the most fragmented) forest fragments to 0.1 km/100 km² in blocks of more than 100 km². Another way of expressing the results is to calculate the percentage of forest area that is within a given distance of a road. Our study shows that 42 percent of forest area in the six countries is within 10 km of a road and more than 90 percent is within 50 km of a road. Only 7 percent of forest area is closer than 1 km or further than 50 km from a road.

Results of the fragmentation analysis are summarized in Figure 4. The chart shows that the proportion of total forest area found in the largest size category (more than 10,000 km²) falls from 83 percent of the total area to 49 percent when all roads are superimposed on forest cover. Not only has the total forest area in the largest size category declined, but the number of fragments in this size category has increased from 12 to 32. That is, formerly large contiguous blocks of forest are now divided into many more fragments, even though these fragments exceed the threshold of 10,000 km². The degree of fragmentation decreases when the analysis excludes seasonal roads. In

Figure 4

Forest Fragmentation By Roads in Central Africa



Source: WRI.
Note: The shaded areas in each column represent the percentage of total forest area occupied by forest blocks or fragments in different size categories. The numbers in parentheses show the number of forest blocks or fragments in each size category.

this case, 65 percent of total forest area remains in contiguous areas of more than 10,000 km^2, though the number of blocks increases slightly to 35. The proportion of total forest area and the number of forest fragments in the smaller size categories increase when permanent roads are superimposed on forest cover, and increase again when all roads are considered.

Given the numerous adverse impacts associated with road construction in forests, the road access indicator can serve as a component indicator of forest condition. To fully assess the impact on an ecosystem, it would need to be supplemented with data on fragmentation at the landscape level caused by land use change. Biodiversity declines cannot be reliably predicted from local changes in habitat area alone. (*See p. 52.*) If the road access indicator were calculated for study areas and found to correlate with specific documented species changes, or other impacts, it could serve as a proxy indicator of the potential impacts of proposed road construction.

FOREST FIRES

Wildfires are a natural and important phenomenon in many forests, helping to shape landscape structure, improve soil nutrient availability, and initiate natural cycles of vegetation succession that maintain biodiversity. Humans have long managed their environment with fire, for example, to clear forest land for crops or improve hunting territory. Today, the natural role of forest fires is changing, as humans introduce them to areas that have not traditionally burned, and suppress fires in areas that burned in the past. The United States, for example, has actively suppressed fires in managed forests, and the average area burned by wildfires in the country decreased by about 90 percent between 1920 and 1990 (MacCleery, 1992, cited in Dower et al., 1997:240). Fire suppression in forest ecosystems adapted to fire has become a major problem in many areas. Consequences include radically changed species composition, increased insect and pathogen epidemics, and increased vulnerability to catastrophic fires due to increased fuel build-up.

Worldwide, naturally occurring fires are now insignificant compared with the number started by humans. Globally, as much as 90 percent of total biomass burning (including savannas) may be initiated by humans (UNEP, 1999: iv). In the 1990s, drought conditions associated with El Niño weather patterns dried out formerly moist forests and increased the flammability of forest vegetation. At the same time, rapidly expanding demand for timber and agricultural land in tropical forests increased the incidence of fire-setting. Many controlled fires rapidly got out of hand in dry conditions. The result has been an unprecedented surge in the number and severity of forest fires, with 1997 and 1998 being the worst years for decades. Recent studies indicate that severe fires in tropical moist forest create positive feedback loops (increased future susceptibility, fuel loading, and fire intensity). The studies also show that, unless current land use and fire use practices change, the increased frequency and intensity of fires could permanently transform large areas of tropical forest into savanna or scrub (Cochrane et al., 1999:1832-1835).

Information on Forest Fires

Globally, few reliable statistics on the exact location and areas burned annually by forest fires are available. The FAO compiles statistics on national forest fires provided by national forest agencies, mainly in Europe and North America. Most developing countries do not maintain statistics on forest fires, but national and international organizations are increasing their use of satellite data to estimate burn areas in the tropical world.

The recent increase in forest fires, and media attention, have stimulated demand for up-to-date information on the location and development of major fires. In response, maps, reports, and other image products on the Internet have been produced by the European Space Agency (ESA), NASA, the U.S. National Oceanic and Atmospheric Administration (NOAA), the U.N. Global Resource Information Database, the Canadian Forest Service and the Canada Centre for Remote Sensing, among others. Satellite imagery and associated GIS data have provided a timely and cost-effective way to monitor and evaluate the impact of forest fires. However, many of these efforts are currently uncoordinated and noncomparable, preventing a global overview. Partly as a response, a new system known as the World Fire Web is being developed for global mapping of fires in vegetation. Satellite images are acquired by a worldwide network of receiving stations and daily global fire maps are built up at each station by sharing regional fire maps over the Internet. Information is available on-line in near real-time (World Fire Web, 2000).

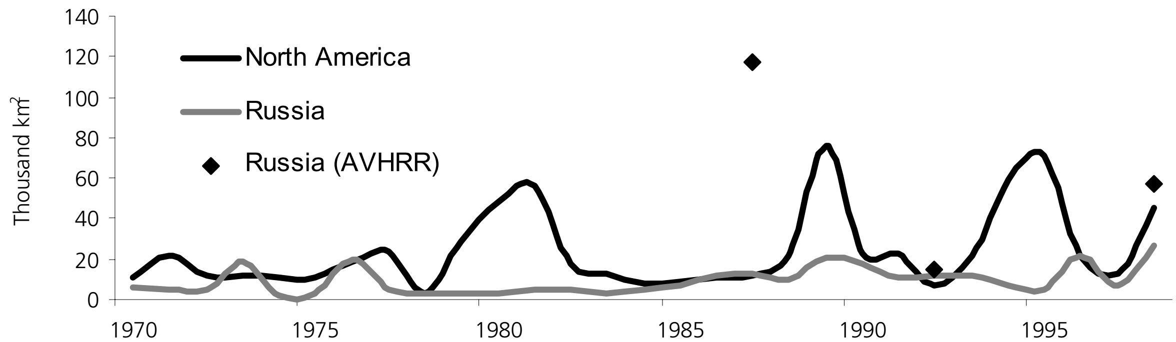
Tropical Forest Fires in 1997-98

The largest forest fires of this period occurred in Indonesia and Brazil. A recent technical report on wildland fires and the environment attributes the fires in Indonesia to persistent burning by farmers, and plantation and forest concession holders, despite official warnings about high fire danger (UNEP, 1999:7). Particular pressures arose from conflict between local rural populations, who are facing resource scarcity, and private and government companies in the timber, pulp, rubber, and palm oil industries. Uncertain land tenure laws and hostile relationships among these parties resulted in many fires being started intentionally. Estimates of the total area burned range from 6,000 km^2 (official Indonesian estimates) up to more than 45,000 km^2 (unofficial estimate based on analysis of 766 System Probatoire pour l'Observation de la Terre [SPOT] "quick look" images).

Natural phenomena also affected fire episodes in 1997 and 1998. Brazil experienced low rainfall in these years because of El Niño, and unusually prolonged fire seasons. Analysis of satellite data from NOAA shows an increase of over 50 percent in

Figure 5

Annual Area Burned in the Boreal Forest Region, 1970-1998



Source: Kasischke et al., 1999.

the number of fires from July to November 1997, compared with the same period in 1996. The data also show an 88 percent increase in fires occurring between June to September in 1998, relative to the same period in 1997. Pasture, which is the predominant use of cleared forest land in Brazil, is burned periodically to clear new growth and reduce pests. With normal rainfall, surrounding forests are too wet to burn and they serve as natural fire breaks. In 1997-98, Brazilian fires were notable for extending into areas which would not be expected to burn. (*See Map 7*.) As Map 7 shows, the northern Brazilian state of Roraima is dominated by tropical forest cover. There is a large area of cerrado in the northeast quarter, part of which is burned each year. Over the past decade, agricultural settlements have proliferated along the southwestern edge of the cerrado, bringing agricultural burning into contact with forest. Fires were detected in January 1998, and spread uncontrollably in March. The area burned in 1998 is conservatively estimated at over 9,000 km^2, a 20-fold increase over the estimated area burned in Roraima State in 1995 (Elvidge et al., 1999). Other estimates by the Brazilian National Institute of Space Research (INPE) and the National Institute of Amazonas Research (INPA) are 11,730 km^2 and 13,000 km^2 respectively. However, it is believed that nearly 80 percent of the heavily burned areas lay outside of the State's protected areas (national parks, reserves, indigenous areas), which are generally located further away from cerrado.

Researchers point to the influence of drought, which dries out forest vegetation and causes trees to drop leaves; in turn, this matter creates a dry fuel layer on the ground. More significant is the impact of repeated burning, which often unleashes the following sequence. A first fire serves to open up the canopy, allowing sun and air movement to increase drying. 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, despite their higher rates of spread. While initial fires have been demonstrated to kill no more than 45 percent of trees over 20 cm dbh (diameter at breast height), recurrent fires kill up to 98 percent of such trees (Cochrane et al., 1999:1832-1835).

Unusually large fires also burned immense tracts of forest in Central America. According to the FAO, fires in the region burned an estimated 15,000 km^2. About 13,000 fires burned in Mexico alone, destroying some 5,000 km^2, much of it unique cloud forest. Government officials blamed slash-and-burn farmers. Indigenous people and environmentalists blamed government-sponsored colonization by farmers and ranchers, and infiltration by drug traffickers, which have combined to set off violent land disputes. In Nicaragua, over 13,000 fires broke out in the 5 months between December 1997 and April 1998, destroying vegetation on over 8,000 km^2 of land.

Trends in Boreal Forest Fires

The boreal forests of North America and Russia represent the greatest expanse of relatively undisturbed forest remaining outside the tropics. Fires in the boreal region are believed to damage more forest land than logging or other development. Both the Canadian and U.S. Governments (the Canadian Forest Service and the Alaska Fire Service) have maintained long-term records of fire location, fire size, and fire boundary since about 1950. Fire area statistics have also been compiled for the Russian boreal region from official Forest Service records (Korovin, 1996:112-128). Based on observed fire frequencies in the different forest types of the Russian boreal forest, there is strong suspicion that the area represented in these statistics may be only 6-12 percent of the area actually burned (Conard and Ivanova, 1998:305-313). Analysis of satellite imagery collected by the AVHRR system confirms that the official Russian statistics underestimate total fire area during extreme fire years (Cahoon et al., 1994:627-638; Kasichke et al., 1999:141, 147).

Figure 5 compares the annual area burned in the Russian and North American boreal forest regions. On average, according to these statistics, 24,000 km^2 per year burned in North America and a little over 9,000 km^2 per year burned in Russia. Figure 5 also shows the much higher estimates of total area burned in Russia based on analysis of satellite imagery for 1987, 1992, and 1998.

Discussions with Russian scientists and foresters have provided a better understanding of the reasons for such low official fire estimates in Russia. First, not all the Russian boreal forest is monitored for fire. No fire observations are made in about one third of the region because of low population and low economic values assigned to the forest resources. Second, it appears that the total fire area in Russia has been systematically underreported because of financial incentives provided to fire fighters based on their success in controlling fire. The data from North America clearly indicate that the annual area burned between the 1970s and 1990s more than doubled. Assuming similar fire patterns in Russia and North America, extrapolating North American results to Russia indicates an annual area burned in the boreal forest of about 100,000 km^2.

Global Forest Cover: Information Status and Needs

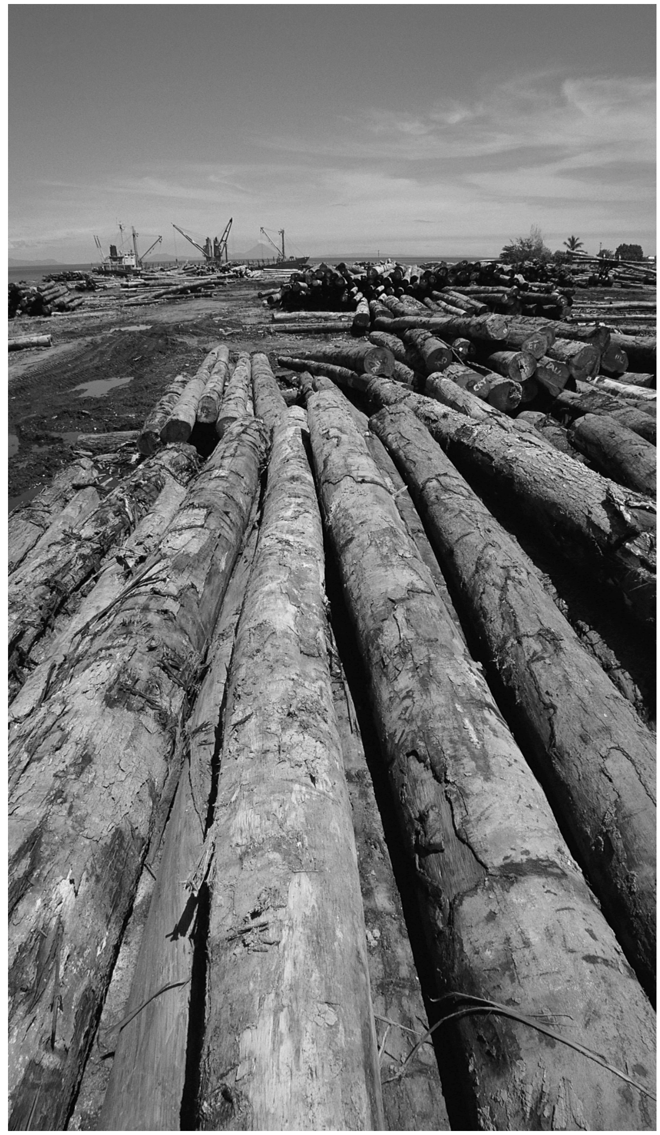
In the context of policy decisions concerning climate change, biodiversity conservation, and the need for sustainable resource management, international attention has become more focused on the need for accurate assessment of global forest extent and condition. Most industrialized countries have developed relatively detailed national forest inventories, though information on forest condition remains uneven. In contrast, an accurate assessment of tropical forest extent is currently lacking. Compilation of national maps and inventories remains hampered by institutional and resource constraints. The absence of standardized data collection and recording techniques introduces numerous errors. Increased use of remote sensing data, and more sophisticated interpretation techniques, are helping to resolve some uncertainties. But remote sensing is still subject to methodological and technical difficulties and, more to the point, is expensive. The uncertainty involved in estimating forest area and establishing baselines is reflected in widely ranging estimates of deforestation rates (though estimates among countries vary more widely than among regions).

We may expect significant improvements in the information base with increased access to high resolution remote sensing data and international collaboration in the near future. A number of projects are contributing to the international Global Observation of Forest Cover (GOFC) initiative, which aims to promote international networking for data access and sharing, and to make satellite-based datasets available to a wide audience.

- The forthcoming Global FRA 2000 will update FAO's 1990 assessment and should provide a more comprehensive picture. FAO is using imagery and GIS datasets from the IGBP, the European Commission's Joint Research Centre (JRC), and the Earth Resources Observation Systems (EROS) Data Center of the U.S. Geological Survey to develop a more consistent small-scale map showing global forest distribution. The map will be validated by national experts and existing reliable information. An accompanying database, spatially registered, may enable researchers to measure changes in land cover over time, and it should provide a baseline for comparisons beyond 2010.
- The TREES (Tropical Ecosystem Environment observation by Satellite) project established by the JRC has produced a consistent map of humid tropical forest cover based on 1-km resolution satellite data, and aims to provide a baseline inventory of forest area, continuous monitoring in areas of active deforestation, and spatio-temporal analysis of deforestation information.
- The Landsat Pathfinder Humid Tropical Forest Inventory Programme, involving NASA, the University of Maryland and Michigan State University, is designed to map deforestation rates in the tropics through intensive use of high-resolution satellite data from the early 1970s, mid-1980s, and mid-1990s. The project's classification scheme identifies forest, deforested areas, regrowth, nonforest vegetation, cloud, cloud shadow, and water. Currently, statistics are available only for the Amazon and Orinoco Basin countries, and parts of Southeast Asia.
- The Global Forest Mapping Program is an international collaborative program led by the Earth Observation Research Center of the National Space Development Agency of Japan (NASDA). It aims to produce consistent and contiguous datasets of both boreal and tropical rain forests.

In addition to these efforts, the World Conservation Monitoring Centre (WCMC), in collaboration with Worldwide Fund for Nature (WWF) has developed a World Forest Map and a set of national statistics. The map is based on GIS information compiled between the early 1980s and 1990s and shows forest extent and protected areas. The spatial dataset has formed the basis for a major statistical analysis of forest protection worldwide and has been published on CD-ROM. The Global Forest Watch project, initiated by the World Resources Institute, monitors forest development in collaboration with a global network of NGOs. The goal is to report and map logging concessions, roads, and other forms of development in all major forested countries within the next 5 years.

Industrial Roundwood



Global Production of Industrial Roundwood

Production of industrial roundwood, which comprises all wood fiber products from logs to pulp, is a major industry. In 1998, the FAO reported global production of 1.5 billion cubic meters (m^3) of fiber, which was used in the form of logs and sawnwood for construction (about 56 percent of consumption), processed wood products such as veneers, chipboard, and plywood (about 20 percent), and pulp for paper and paperboard (about 24 percent). This last figure is supplemented by the reuse of wood manufacturing residues like sawdust and chippings. In the early 1990s, production and manufacture of industrial wood products directly contributed about $US400 billion annually to the global economy, or about 2 percent of global GDP (Solberg et al., 1996:48). North America, Asia, and Western Europe dominate industrial roundwood production. (*See Figure 6.*) However, the timber industry is of greater economic importance to some developing countries, where wood exports can account for up to 80 percent of foreign currency earnings. Over the past three decades, international trade in forest products has increased roughly threefold in terms of value, adjusted for inflation, and now accounts for about 3 percent of total world trade.

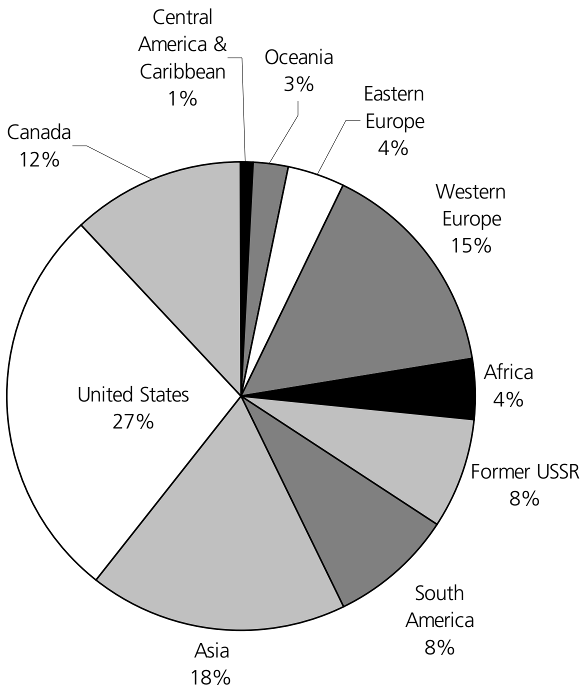
Trends in Industrial Roundwood Production

Industrial roundwood production rose by nearly 50 percent between 1961 and 1998. (*See Figure 7.*) Demand is directly related to income. The bulk of industrial roundwood production and consumption remains concentrated in the high-income countries, though consumption is leveling off, because of saturating demand for some products (such as construction lumber) and use of more efficient technologies. However, these declines are partially offset by strong demand for paper and some hardwood products, which continues to rise broadly in line with GDP. Industrial roundwood consumption is rising fastest in the rapidly growing economies of Asia and Latin America, where demand is strong for construction timber, processed wood products, and paper and paperboard.

Of all industrial roundwood products, paper and paperboard are growing the most rapidly. Globally, paper consumption has increased by a factor of 20 this century and has more than tripled over the past 30 years (IIED, 1996:20). In addition to the traditional print products (books, newspapers, stationery), new markets for mail order catalogues, marketing and promotional materials, household and sanitary papers, and packaging have kept consumption buoyant over recent decades. The advent of computers and other electronic equipment has fueled rather than

Figure 6

Global Industrial Wood Production, 1998



Source: FAOSTAT.

Note: Industrial roundwood production in 1998 totaled 1.5 billion m^3.

decreased demand. Paper consumption in the industrialized countries has risen to around 200 kilograms per capita per year (kg/capita/yr) in Western Europe, and over 300 kg/capita/year in North America (WRI, forthcoming 2000).

In the developing world, paper consumption is growing rapidly, but average per capita consumption remains low at about 17 kg/year (WRI, forthcoming 2000). However, total paper and paperboard consumption in Asia already exceeds that in Europe, and is projected to grow at nearly 4 percent per year until 2010. Such a rate of increase would make the region the biggest paper consumer in the world (FAO, 1997a:78).

Long-term prices for timber in international commodity markets have increased, indicating that demand is growing faster than supply. Between 1975 and 1996, the price of timber products (expressed in constant dollars, where 1990 prices = 100) rose by 30 percent (WRI, 1998:240). This trend is unique among the major categories of commodity; real prices of fuels, metals, nonfuel minerals, and cereals have all trended downward.

During the 1990s, numerous studies estimating future wood fiber demand were carried out by research organizations and the forest products industry (Apsey and Reed, 1995; Brooks et al., 1996; FAO, 1998; Nilsson, 1996; Sedjo and Lyon, 1995; Solberg et al., 1996). Naturally, these forecasts differ, given different assumptions about population growth, economic growth, fiber prices, and available technologies. A number of long-term scenarios serve to show the powerful effect of prices. Brooks et al. estimate that, under different assumptions of GDP growth and price increases, world consumption of industrial roundwood could rise by anywhere between 23 percent and 55 percent by 2020 (over 1998 consumption levels). All forecasts agree that demand will continue to rise, but projected annual rates of increase range by up to a factor of two.

Forest Modification to Increase Industrial Roundwood Production

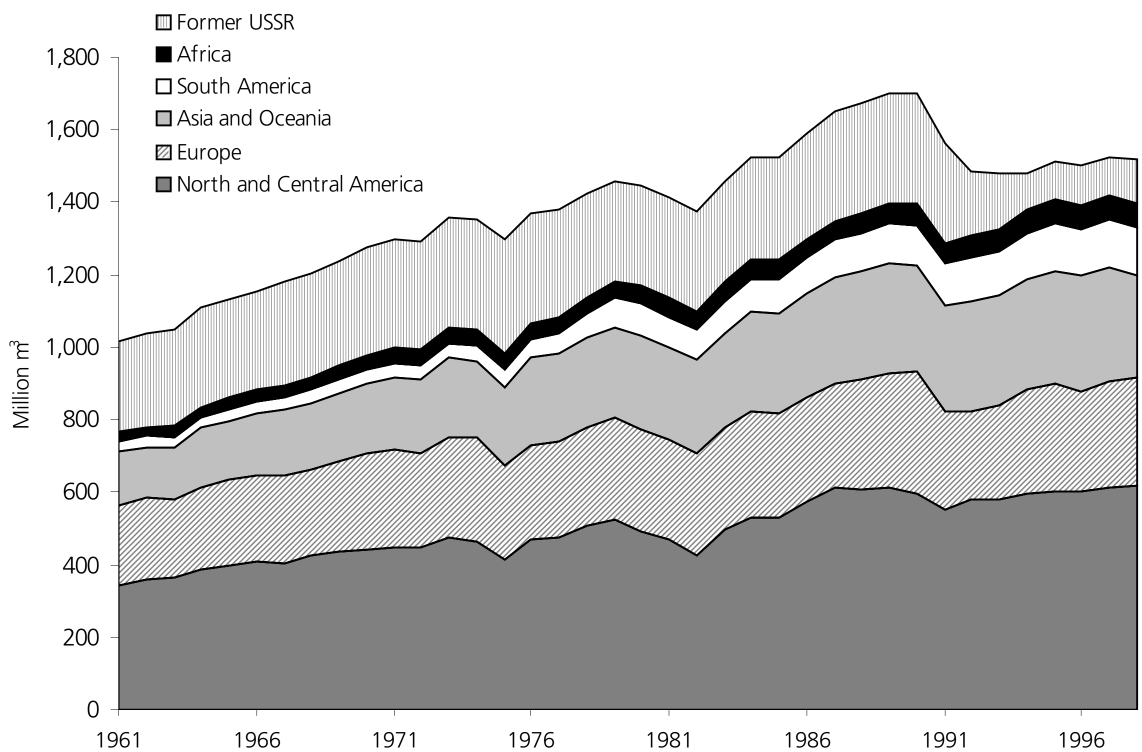
FOREST MANAGEMENT

The three main sources of industrial roundwood are primary forests (sometimes known as natural, old-growth, or virgin), secondary-growth forests (sometimes known as seminatural), and plantations. The highest wood fiber yields accrue through clearcutting mature trees in primary forests. This method of harvesting is still widespread, for example, in parts of Amazonia, Canada, and Siberia, but is obviously a one-time option. More fiber production today occurs in secondary-growth forests — those natural forests that have been cut but have regrown (sometimes several times), or have been partially replanted, and are now managed more or less intensively for wood production and other purposes.

Primary and secondary-growth forests currently produce about 78 percent of the world's industrial roundwood supply. There are no reliable breakdowns, at the global level, of the share of total industrial roundwood supplied by the two types of forest. However, secondary-growth forests have replaced virtually all the primary forests of eastern North America (including most of the United States), Europe, and large parts of South America and Asia. These areas produce the bulk of the world's wood supply (though an unknown quantity enters the market via illegal logging in primary forests). Some idea of the extent to which forests have been modified from a natural to a seminatural state, mainly for fiber production, can be gained from the FAO's assessment of naturalness in temperate and boreal forests. (*See p. 19.*) Seminatural forests now account for about 80 percent to 90 percent of forested land in Europe. Where the proportion is less, plantations almost invariably account for the difference. In Australia, seminatural forests make up nearly 90 percent of forests; they account for 60 percent in New Zealand, 85 percent in the United States, and 50 percent in Canada (Dudley, personal communication, 14 October, 1999). No general conclusions can be drawn about the biological condition of seminatural forests, since they are defined only as the residual category that is neither "undisturbed by man" nor "plantation."

Figure 7

Global Industrial Roundwood Production, 1961-1998



Source: FAOSTAT.

Note: The drop in industrial roundwood production after 1990 is due to political and economic disruption in the former Soviet Union and the countries of Central and Eastern Europe. The former USSR comprises Belarus, Estonia, Kyrgyzstan, Latvia, Lithuania, Republic of Moldova, Russian Federation, and Ukraine. The Russian Federation accounted for 65 percent of production in the region in 1998.

PLANTATION ESTABLISHMENT

The most intensive form of fiber production occurs in plantations, which are generally defined according to the extent of human intervention in a forest's establishment or management. Because a wide range of silvicultural practices is applied in intensive forest management, the difference between a seminatural and a plantation forest is essentially arbitrary. This is especially true in parts of Europe, the United States, and China. In tropical and subtropical countries, plantations are usually more easily identifiable, since they tend to have been established relatively recently or because they consist of fast-growing and often exotic (non-native) species. Industrial wood plantations can be highly profitable and they are expanding rapidly. Since 1980, plantation area in developing countries has risen by about 60 percent, while the area in industrialized countries has risen by anywhere between 60 and 100 percent.

According to recent FAO surveys, in 1995, industrial wood plantation forests covered approximately 1.03 million km^2 worldwide (Pandey, 1997; Brown, 1999). Despite their small extent — about 3 percent of global forest area — these plantations now provide an estimated 22 percent of the world's industrial roundwood supply (Brown, 1999:41). In Oceania, 80 percent of industrial wood is estimated to be sourced from plantations. Africa (35 percent), South America (27 percent), and Asia (23 percent) also harvest above average proportions of industrial roundwood from plantations (Brown, 1999:41).

Total plantation forest area is highly concentrated. Five countries — China, Russian Federation, the United States, India, and Japan — account for 65 percent of global plantation resources. (*See Table 6.*)

These data are the best currently available, at global level, but they must be viewed as uncertain, given difficulties with the availability and interpretation of national information sources.

Forest Capacity to Sustain Industrial Roundwood Production

Traditional thinking held a relatively simple view of sustainable forestry: it should maintain a dynamic balance between

Table 6

Estimated Regional Distribution of Plantations in 1995

Country or Region	Industrial Plantation Area (thousand km^2)	Nonindustrial Plantation Area (thousand km^2)	Total Plantation Area (thousand km^2)
North and Central America	189	3	192
United States	*184*	*0*	*184*
South America	54	28	82
Asia	418	151	569
China	*175*	*39*	*214*
India	*41*	*83*	*124*
Japan	*107*	*0*	*107*
Oceania	27	0.1	27
Africa	36	22	58
Europe	87	0	87
Former USSR	222	0	222
Russian Federation	*171*		*171*
TOTAL	**1,033**	**204**	**1,237**

Source: Brown, 1999:15.
Note: Nonindustrial plantations are grown for fuelwood, soil protection, amenity, or other purposes. They do not include plantations of agroforestry crops, such as rubber and palm oil, for which a separate FAO study is under way.

timber growth and harvest volume. Recently, more environmentally and socially sensitive forestry practices have evolved, under which timber production is viewed as one among many land management objectives, including recreation, watershed protection, and wildlife conservation. In most of the industrialized countries, and some developing countries, public concerns over clear-cutting, endangered species, and the loss of aesthetic and amenity value in intensively managed forests, have forced a substantial reconsideration of management objectives in the forestry sector. Accordingly, the area of protected forest, in which logging is prohibited or limited, is increasing worldwide. However, much of the world's timber originates from privately managed forest lands, and from poorly regulated state forests, where sustainable forest management (SFM) practices are not observed.

This study assesses the long-term capacity of forests to support fiber production by examining the following indicators: (1) the availability of productive forest lands; (2) rates of wood harvest relative to tree growth; and (3) plantation productivity and potential. Global-level information on forest area and its classification for purposes of wood production, and data on annual growth/harvest ratios, have been drawn from the FAO's *Global Fibre Supply Model* (FAO, 1998). This study, initiated in 1995, aimed to establish a database that would collect and harmonize all information relevant to forest inventory and fiber production. The purpose of the undertaking was to model alternative scenarios of future fiber supply. The FAO stresses the preliminary state of the database. Information is incomplete or missing for a number of countries and, in these cases, data were estimated from adjacent countries or subnational case studies.

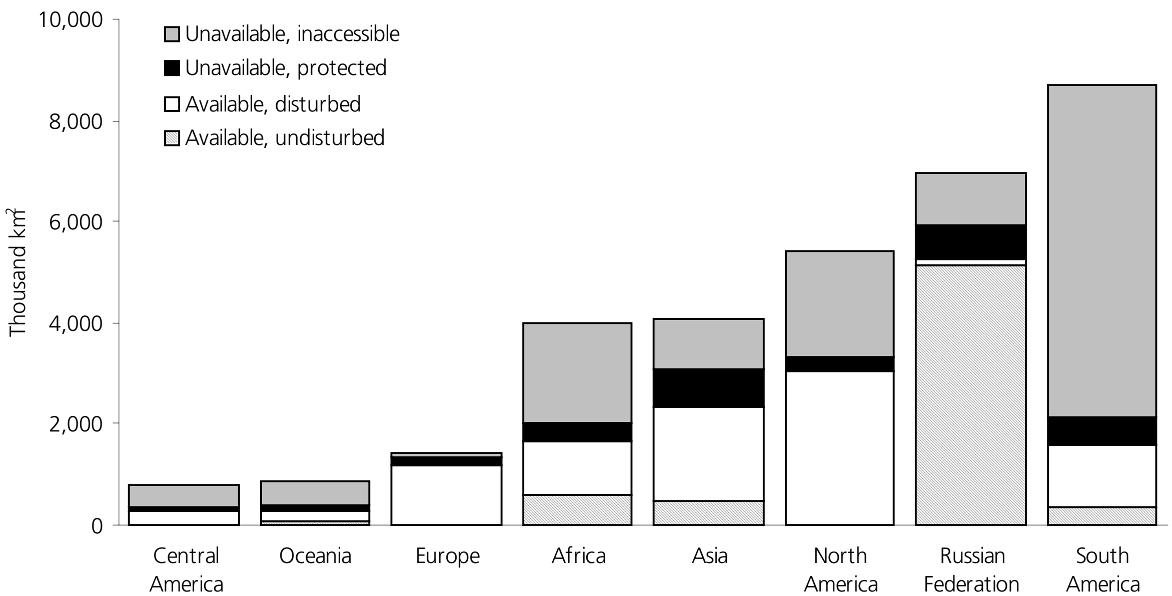
AVAILABILITY OF PRODUCTIVE FOREST LAND

The *Global Fibre Supply Model* estimated the world's forest cover (excluding plantations and forests in some countries with very low forest cover) at about 32 million km^2. However, the area available for wood supply under current market conditions is much less — approximately 48 percent of this total. (*See Figure 8.*) Available forest area is classified as either disturbed, that is, under some kind of management regime, or undisturbed. The latter class is defined as presenting natural forest dynamics, such as natural tree composition, age structure and regeneration processes, and forming an area large enough to maintain these characteristics. The terminology is somewhat confusing, since timber extraction occurs in some so-called undisturbed areas. (*See Figure 9.*) FAO defines unavailable forest area as forest land that is legally protected, or currently considered economically unproductive or physically inaccessible. The extent to which unavailable forest area is also undisturbed varies widely by region. In North and Central America and Asia, for example, more than half the unavailable forest is undisturbed, whereas in Africa, more than 60 percent of unavailable forest is already utilized in some way.

Figure 8 clearly shows that great reserves of timber remain unharvested. These stands are mainly in the hardwood forests of South America and the softwood forests of Russia and northern Canada. These forests are little exploited because of their remoteness and difficult terrain. For this reason, Brazil and the Russian Federation, despite their huge resources, account for only 6 percent and 5 percent respectively of total industrial roundwood production. This situation is likely to change if fi-

Figure 8

Global Forest Area Available for Production



Source: Based on FAO, 1998. Annex 1: Statistical Summary.

ber prices continue to rise with increasing demand, or if technological advances reduce the costs of extraction from remote areas. Already, more than 60 percent of Canada's forests are under logging tenures or within 10 km of development activity (Smith, W. et al., 2000:23). The various supply scenarios developed for the *Global Fibre Supply Model* all assume, to differing degrees, conversion of the world's remaining undisturbed forest to a disturbed state, and the extension of forestry management to currently inaccessible areas. These scenarios indicate no fiber scarcities in the foreseeable future, but they do foretell significant losses of primary forest and changes in forest condition.

ANNUAL GROWTH AND HARVESTING INTENSITY

Sustainable management of forest resources, narrowly defined, implies maintaining a positive balance between the volume of wood added to the growing stock each year (gross annual increment) and that removed by felling (the harvesting intensity). Both measures are commonly expressed in cubic meters per hectare. Figure 9 illustrates average gross annual increment values in the available forests of major world regions and harvesting intensity in both disturbed and undisturbed forests.

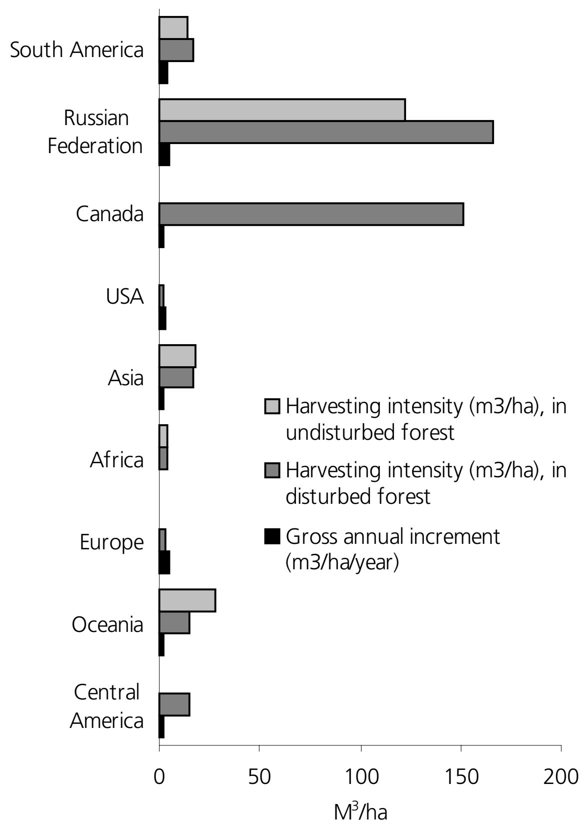
The FAO notes that information on growth rates and timber removal is sparse or entirely missing for some developing countries. Gross annual increment rates, and harvesting intensity rates in particular, also vary widely within regions. For example, South American harvesting intensities by country are commonly under 15 m^3/ha, but the regional total is biased by Chilean rates of more than 120 m^3/ha. Most variations are less extreme, however. Despite data weaknesses, it appears that only Europe and the United States currently harvest at rates below the annual growth increment. Production in both regions occurs almost entirely within managed, secondary-growth forests, where trees are harvested at a relatively young age and replaced by regular planting. The countries with the highest harvest intensities — Russia and Canada — both possess great standing reserves of primary forest, where average tree size is much larger than in secondary-growth forests. In these countries, clear-cutting is common and replanting is not systematic. Logging in the primary forests of British Columbia, Ontario, and Quebec dominates Canadian harvest figures and clear-cuts account for more than 80 percent of the annual harvest area (Smith et al., 2000:11). Russia, likewise, harvests mainly from primary forest though, in overall volume terms, its harvests remain very small. These data indicate that, in temperate forests with moderate growing rates (Europe and the United States), intensive fiber production does not appear to be reducing the overall stock of timber. However, in Canada and most tropical countries, harvest rates are not compensated by regrowth or replanting, and the overall stock of timber is being drawn down.

PLANTATION PRODUCTIVITY AND POTENTIAL

Plantation productivity is generally higher than that of managed forests. Tropical species commonly yield between 5 m^3 and 20 m^3 per hectare annually, and eucalyptus growth rates of 25 m^3 per hectare per year are not uncommon in South America. Trial plots in Brazil have recorded growth rates of up to 100 m^3 per hectare per year, though such results remain difficult to

Figure 9

Summary of Average Volume Growth and Harvesting Intensity (in Available Forest Area)



Source: FAO, 1998: Technical Annex I.

Notes: North American data are disaggregated because of the very different profiles of the United States and Canada. All data apply to available forest area only (see Figure 8). Forest inventories commonly refer to net annual increment (gross annual increment, minus tree mortality), but tree mortality has not been estimated in many countries.

translate to the field. By comparison, managed seminatural forests commonly yield between 1 m^3 and 3 m^3 per hectare.

Data on long-term productivity of plantations are scattered. One globally available indicator of plantation viability is the difference between *reported* and *net* plantation area. According to updated plantation data collected by Pandey, the 1995 reported area of forestry plantations in 90 tropical and subtropical countries was about 700,000 km^2. However, this figure was adjusted downward to take account of failed, harvested, or double-counted plantations. The resulting net plantation area was estimated at approximately 56 million hectares, a reduction of 20 percent. The reduction factor/success rates used were derived from inventories or surveys of plantations. The regional reduction factors used were: for tropical Asia and Pacific 0.61; for tropical America 0.84; and for tropical Africa 0.7. (No reduction factors were applied to recently surveyed plantations in Australia, New Zealand, China, Chile, and South Africa, among others.)

Unfortunately, the net estimate of plantation area does not distinguish between failed plantations on the one hand, and harvested or double-counted plantations on the other. It therefore obscures insight into the sustainability of current management techniques. Some countries report low national planting success rates, including the Philippines (26 percent), Laos (47 percent), and Colombia (57 percent). In some cases, poor management or other technical factors appear responsible; in others, environmental factors, including poor site selection and nutrient management, may be to blame. Whatever the cause, a recent survey refers to only two significant examples of productivity decline over successive rotations of trees (*Pinus radiata* in South Africa and *Cunninghamia lanceolata* in China) (Evans, 1997). Other scattered evidence indicates that intensive plantation forestry can maintain productivity, given careful management of organic matter.

According to many forestry experts, the need for further exploitation of natural forests could be greatly reduced by expanding production from industrial wood plantations. The FAO estimates that current plantation area in the Southern Hemisphere has a potential annual growth of 1.1 billion m^3 (FAO, 1998). Another estimate is that, assuming average annual growth rates of 10 cubic meters per hectare, the world's current demand for industrial roundwood could be met from plantations on 1.5 million km^2 of land, equivalent to just over 4 percent of global forest area (Sedjo and Botkin, 1997:15-21). However, the extent to which plantations displace — rather than simply complement — harvesting from natural forests will depend on relative production costs under each system, the degree of legal forest protection, adoption of policy incentives, public acceptance, and the biological sustainability of plantations. Plantation forestry has expanded in response to favorable economic signals, but shifting wood production from natural forests to plantations is not a matter of straightforward substitution, nor is it simple. (*See Box* 2.)

Ecological Externalities of Industrial Roundwood Production

Many local-level studies document the impacts of timber management regimes and logging on forest structure, flora and fauna, and soil and water quality. Fiber production clearly involves some trade-offs in the availability of other goods and services. However, the nature and severity of impacts on the wider forest environment are highly site-specific, depending on local physical conditions and the forest management practices in use. The worldwide trend in forest harvesting over the past three decades

Box 2

Substituting Forests with Plantations: the Experience of New Zealand

New Zealand provides a rare example of a country that consciously developed plantation forestry, to protect its fast diminishing natural forests. Today, New Zealand's plantations cover an area equivalent to 19 percent of total forest cover and provide 99 percent of industrial roundwood production. Analysis of the transition by the New Zealand Ministry of Forestry points to the following key lessons: substitution takes time —harvesting in New Zealand's natural forests continued for some 70 years while plantations came on stream. Technical research and market development are required to assist product change-over and overcome industry and consumer resistance. Harvesting restrictions in natural forests are much easier to impose in state-owned natural forest land, and private landowners tend to demand compensation for implementing new forest management practices. Plantations are controversial, unpopular with both forest industries still using natural forest wood and with environmental groups and local communities. The success of a plantation strategy depends heavily on the end-product required. Tree species providing sawlogs or veneer logs are generally slower growing and more difficult to raise in plantations, while utility species, such as pine, generally yield more acceptable rates of return.

Source: FAO, 1999:22

has been toward increased mechanization to improve economic efficiency. The introduction of heavy machinery is often associated with careless felling, tree damage, and soil compaction. Economic considerations may also encourage less damaging and wasteful practices, where forestry is practiced as a long-term form of land use. In the absence of global data, this section presents (1) a case study of the effects of prolonged timber harvest regimes on trees in mature production forests (United States), and (2) a literature review of studies on the environmental impacts of logging activities in the Tropics.

PROLONGED TIMBER HARVESTS IN MATURE PRODUCTION FORESTS

Effective forest management practices in the United States have helped maintain forest cover at roughly stable levels since 1920, despite rising production. However, a study of U.S. forest resources shows that after a steady increase in growth for 40 years, the estimated rate of growth slowed in the late 1980s, and even declined in absolute terms in 1991 (Powell et al., 1994). (*See Figure 10, Chart A.)* While increment growth is projected to continue increasing for the next 40 years, the rate of annual growth is projected to be slower than the growth rate for timber removals. This could lead to the end of sustained-yield management in U.S. production forests within a few decades.

A WRI study of the U.S. forestry sector has concluded that, if current trends in wood harvest rates and net annual timber growth continue, sustained yield conditions will end as early as 2010 (Johnson and Ditz, 1997:191-280). This does not mean that the United States will exhaust its wood supplies; it does mean that the average size of harvested trees and the average age of timberlands will decline. Production forests in the United States will consist of young stands of more uniform age and size structure, a scenario already evident in recent trends.

The U.S. Forest Service surveys tree diameter-class data, which can be used as a proxy for age-class data, to give a good approximation of forest structure. Chart B gives the diameter-class distribution changes over time for U.S. softwood production forests, showing an overall trend toward smaller trees and more simplified stand structure. The standing volume of the largest diameter class (>29.0 inches) has declined almost by half over the last 40 years, from 120 billion cubic feet (ft^3) in 1952 to 64 billion ft^3 in 1992.

There are significant regional differences in forest sector trends within the United States. Charts C and D compare changes in the two most important regions for softwood production, the Pacific Northwest and the South. On the Pacific Coast, especially in the Pacific Northwest, the volume of larger softwood trees has diminished significantly. Chart C shows the dramatic decline in the >29.0 inch diameter class in this region, accounting for almost two thirds of the national decline in the largest diameter class since 1952. It should also be noted that, in the Pacific Northwest, softwood trees grow much larger than 29 inches; the loss of very large trees therefore does not fully show up in data for the largest diameter class. In the southern states, Chart D shows the significant increase in smaller diameter classes over the last 50 years. As a result of these trends, standing softwood volume in the southern United States has risen from 60 billion ft^3 to over 100 billion ft^3, while in the Pacific Northwest it has fallen from 150 billion ft^3 to about 113 billion ft^3. Overall, the average diameter of harvested trees from all timberlands declined by over 20 percent between 1976 and 1991 (Haynes et al., 1995, cited in Dower et al., 1997).

These data alone do not tell us exactly how much standing timber has been lost from the largest diameter class because of harvesting and how much has been withdrawn from harvesting records because the trees have been given protected status. In the 1960s and 1970s, large amounts of federal land in the Pacific Northwest and elsewhere were removed from production status and converted into forest reserves. Because diameter-class statistics are given only for U.S. production forests, such changes in status mean that protected forests are no longer included in USFS assessments of standing timber.

Nevertheless, U.S. forestry experts confirm that the steep reduction, both in the volume of the largest trees and the vol-

Figure 10

Timber Harvests and Tree Size in the United States

Chart B
Softwood Growing Stock Volume in the United States by Diameter Class, 1952-1992

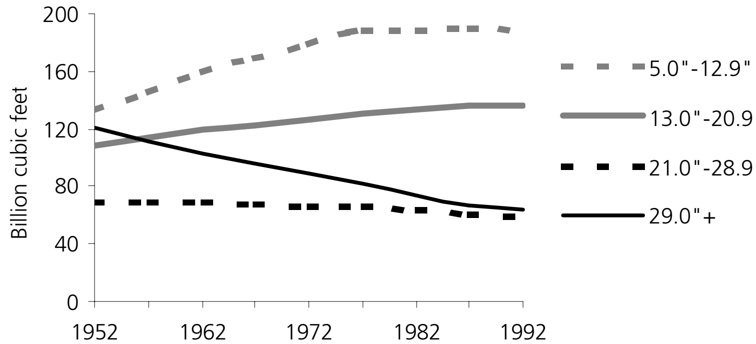


Chart A
Net Annual Growth and Removals, all U.S. Production Forests, 1950-2040

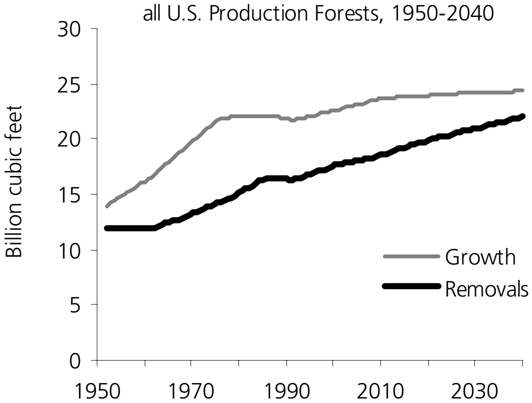
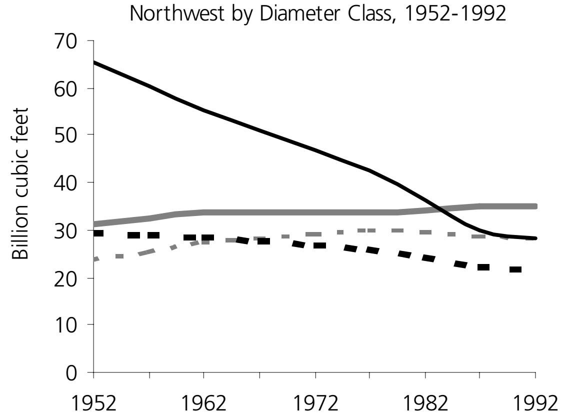


Chart C
Softwood Growing Stock Volume in the Pacific Northwest by Diameter Class, 1952-1992



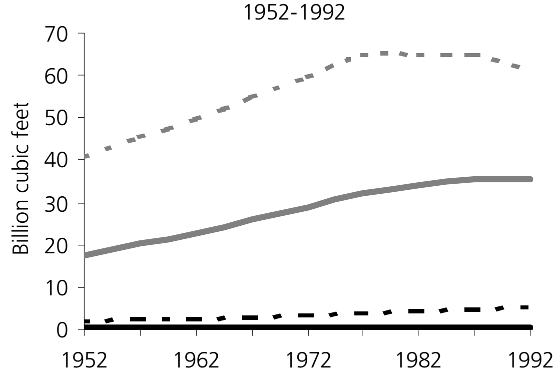
Notes:
Data on the net annual growth and volume of removals from production forests in the United States are collected by the U.S. Forest Service (USFS). The increment data for existing assessments are calculated from the sum of measurements made by USFS on 220,000 plots across the United States; projections are then made for different forest types for the whole country from these measurements. In most cases, direct harvest data have not been collected in the past, so estimates of harvest volumes have been made regionally from records of timber product outputs and other sources. Future projections are based on a number of assumptions about socioeconomic and demographic trends, including future timber demands and output. The projections assume a fixed policy environment, with no major changes in laws and regulations governing forestry. Diameter class data from USFS are given in 10 diameter classes: 5.0 to 6.9 inches (in).; 7.0 to 8.9 in.; 9.0 to 10.9 in.; 11.0 to 12.9 in.; 13.0 to 14.9 in.; 15.0 to 16.9 in.; 17.0 to 18.9 in.; 19.0 to 20.9 in.; 21.0 to 28.9 in.; and >29.0 in. For all charts in this case study, the first four and second four age classes were combined to form the two smaller age classes.

Sources:

Chart A: Haynes et al., 1995.

Charts B, C, D: Powell et al., 1992.

Chart D
Softwood Growing Stock Volume: Diameter Class Change in the Southern United States, 1952-1992



ume of standing timber in the Pacific Northwest, is reducing average tree size and simplifying forest structure. Older forest stands on private timberlands in the Pacific Northwest and the South have been completely lost. By 2010, almost no forest stands older than 60 years are predicted to remain on forest industry lands in the Pacific Northwest, and none older than 35 years in the South (Haynes et al., 1995, cited in Dower et al., 1997). Such habitat simplification has adverse impacts on biodiversity, as species whose evolutionary histories have led them to be dependent on older, larger forests — such as the marbled murrelet and the spotted owl — are put at risk of extinction.

ENVIRONMENTAL IMPACTS OF LOGGING

Impacts on Biodiversity

Conservationists and others often claim that timber extraction, particularly in the tropics, will have "devastating impacts" on species diversity, doing irreparable harm at local and regional scales (Bowles et al., 1998:1899; Bawa and Seidler, 1998:46-55). These arguments are based in a paradigm, dating back to the early 1970s, that depicts tropical forests as inherently fragile ecosystems (e.g., Gomez-Pompa et al., 1972: 762-765). This study reviews the literature, much of it cited by those working within this paradigm, assesses the available evidence, and comes to somewhat different conclusions. (*See Table 7.*) As one group of taxa rarely serves as an adequate indicator for the effects of ecosystem disturbance on any other group of taxa (Lawton et al., 1998:72-75), this study concentrates on the response of birds and moths/butterflies to selective logging in tropical countries.

A system of forest management in any type of ecosystem will have some simplifying and homogenizing effects on species structure and composition. The immediate local level effects of tropical forestry on biodiversity are often quite severe, as the papers reviewed in Table 7 attest. It is still not well understood to what degree, and over which spatial scales, these effects occur.

To address these questions, we reviewed studies comparing species diversity in logged and adjacent primary tropical forests. Two distinct observations can be made from this literature. The first is that, at least for birds, observable trends can help predict which species are more likely to be affected, but overall changes in species diversity, abundance, and composition are proportional both to the intensity of disturbance and the habitat recovery time. While some groups are significantly affected immediately after logging, most groups of species surveyed in the literature appear to recover with time. The second observation is a methodological one: many of the most devastating effects of logging on biodiversity can have as much to do with sampling design as with actual species losses (Whitman et al., 1998:449-457). The most serious impacts on moth diversity in Malaysia were found in a study with a mere three sample plots, each sampled for a period of two hours. Other studies of forestry impacts on moths, sampled over longer periods of time and wider geographical areas, show much smaller differences in moth species diversity in logged and unlogged forests. Concerning the evidence for birds, the studies reviewed here indicate that while some groups will need reserves of intact primary forest for continued survival, others may not.

Impacts on other forest taxa, particularly invertebrates, remain far less well studied. Fragmentation and the edge effects induced by logging, including reduced soil and atmospheric moisture, can adversely affect plant and animal species in ways that are far from fully understood (Laurance and Bierregaard, 1997). In addition, selective logging practices reduce the survival rate and abundance of specific tree species.

Impacts on Soils and Water

Studies in North America indicate that logging-related road construction greatly increases compaction in a variety of soil types, leading to waterlogging, increased run-off and sediment loading, and reduced plant growth (NRDC, 1999:67-98). A major inventory of logging roads in California concluded that their development was responsible for nearly 90 percent of major erosional events recorded and that these events accounted for more than 60 percent of total soil erosion (McCashion and Rice, 1983:23-26). This suggests that erosion from logging-related road construction may far exceed erosion associated with removal of forest cover. A study of Palawan, in the Philippines, found that logging an area increased erosion rates fourfold but converting uncut forest to road surface increased erosion by a factor of 260. Roads accounted for only 3 percent of the area studied but for an estimated 84 percent of surface erosion (Hodgson and Dixon, 1988, cited in Chomitz and Kumari, 1998:13-35).

Information Status and Needs

Data on industrial roundwood production are generally good, though inconsistencies exist at the national level in some developing regions. More detailed information on forest inventories, including data on annual growth and harvest rates, tree mortality, species and age-class distribution, and forest land ownership, is available for the industrialized countries. The same information is still needed for many developing countries. Major questions remain on the proportion of industrial roundwood obtained from primary and secondary-growth forests, and on the extent and legality of logging concessions in many countries.

Information on the biological condition of forests under timber management regimes is generally of poor quality. Currently available data do not allow experts to draw firm conclusions

Table 7

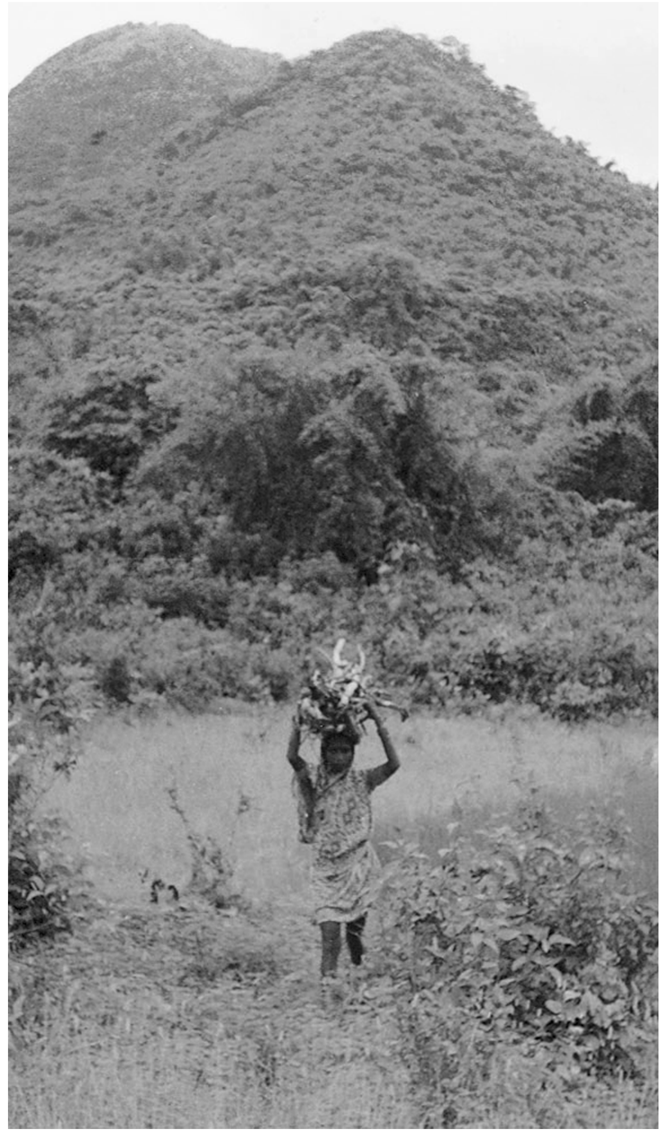
Review of the Effects of Logging on Different Taxa in the Tropics.

Fauna and Study Location/Methodology	Citation	Harvesting Intensity	Effects on Fauna	Comments
Transect census study of large birds and mammals in primary and 3–5-year-old logged forest in East Kalimantan, Indonesia.	Wilson and Johns, 1982	8 trees/ha (40 cubic meters/ha)	Four species of hornbill and one pheasant species were found in logged forest; one of the hornbill species was not observed in primary forest. Most primates not seriously affected by logging.	Most species in primary forest were found in higher densities than in 3–5-year-old logged forest. Hornbill densities higher for a few species in logged forest.
Mist net and transect census of understory birds in primary and 25-year- old logged forest in Malaysia.	Wong, 1985	Not given	Found 81 understory species in primary forest versus 73 species in secondary forest; logged forest able to sustain "a majority of understory bird species" after 25 years.	Recommends that logging be planned on a landscape level to reduce impacts on biodiversity.
Comparison of forest structure between primary and 1–6-year-old logged forest in Malaysia.	Johns, 1988	18–25 trees/ha (~100 cubic meters/ha)	Not a direct study of the effects on wildlife, but theorizes that most frugivorous and folivorous birds are unlikely to be affected by logging; insectivorous birds more likely to be affected.	Despite extensive structural damage, author states: "Animals that survive the critical period immediately following logging appear able to persist in logged forest."
Point counts of canopy birds in primary and 5-year-old logged forest in Papua New Guinea.	Driscoll and Kikkawa, 1989	Not given, described as 'intensively logged'.	86 canopy birds found in primary forest vs. 77 found in secondary growth, with 75% overlap of species.	
Transect census of birds in primary and 11-year-old logged forest in the Amazon.	Johns, 1991	3–5 trees (20 cubic meters)/ha	Found relatively small differences in species richness between logged and primary forest, with the largest number of species found in regenerating scrub on abandoned agricultural lands.	Logged forest had a decrease in terrestrial and bark- and foliage-gleaning insectivores. Understory insectivores with specialized foraging strategies were the most severely affected by disturbance.
Mist net and transect census of birds in primary and 10-year-old logged forest in Sabah, Malaysia.	Lambert, 1992	90 cubic meters/ha	Found 195 species in primary forest versus 177 species in logged forest, with an increase in relative abundance of nectarivores and opportunistic frugivores, and a relative decrease of trogons, woodpeckers, wren-babblers, and flycatchers in logged forest.	Author cites this and other studies to state that "most forest bird species use logged forest…Present evidence indicates that time elapsed since logging is an important determinant of species composition.
Point counts of birds in primary and in 1- and 10- year old logged forest in Guyana.	Thiollay, 1992	7–15 cubic meters/ha	Significant decrease in both logged plots of mixed species flocks, understory insectivores, large flycatchers and game birds, raptors, and woodcreepers. Terrestrial insectivores showed the greatest decline.	Increase in hunting pressure after logging. Nonrandomized sampling in logged forest was only conducted in logging gaps where forest damage is most severe and localized.
Mist net study of understory birds in primary and 1- and 6-year-old logged forest in Venezuela.	Mason, 1996	7 cubic meters/ha	Nectarivores were significantly more common in logged forests than in primary forest. Frugivores showed mixed responses to logging. Most woodcreepers declined with logging, and terrestrial understory insectivores were the most affected by logging. Bird diversity was the highest in managed logged plots.	Sampling in logged forest included unlogged patches (contra Thiollay, 1992). "This study confirms earlier observations (e.g., Lambert, 1992) that most forest species persist in logged forest, although often in very reduced numbers."
Mist net and point count census of birds in primary and 5-year-old logged forest in Belize.	Whitman et al., 1998	1.8 cubic meters/ha	Found no statistically significant effects of selective logging on any bird species.	Lower densities of larger species could be due to hunting pressure.
Survey of moths in primary and 7-year-old logged forest in Sabah, Malaysia.	Holloway et al., 1992	Not given	Significantly higher diversity of moths in primary forest than in logged forest samples.	Very small number of sampling points, and short duration of sampling times mean that results should be interpreted with caution.
Survey of butterflies in primary and 5-year-old logged forest in Indonesia.	Hill et al., 1995	Not given	37 species found in primary forest versus 29 found in logged forest, with 25 species found in both.	Unlogged forest had significantly higher species richness, abundance, and evenness than logged forest.
Survey of moths in primary and logged sites at 6 different locations in Malaysia.	Intachat et al., 1999	Not given	Species diversity did not differ significantly between logged and unlogged forests, but unlogged forests did contain a higher number of rare species.	

about soil nutrient balance, soil microorganisms, water use, water quality, or biodiversity under various forest management regimes. More systematic collection of data, including fertilizer and pesticide/herbicide application rates, harvesting methods, incidence and extent of pest attacks, and the development of agreed indicators of biodiversity in managed forests in different ecofloristic zones, would begin to address this deficit.

Given the growth of intensive plantation forestry, the assessment of forest condition requires better information and indicators to distinguish classes of plantation. Such indicators would include data on soil nutrient balance, runoff, and biological diversity over time. Management parameters, such as mixed-species planting, use of buffer zones around watercourses, balance of native and non-native species, and preservation of natural forest enclaves are other vital elements yet to be systematically recorded.

WOODFUELS



Global Production of Woodfuels

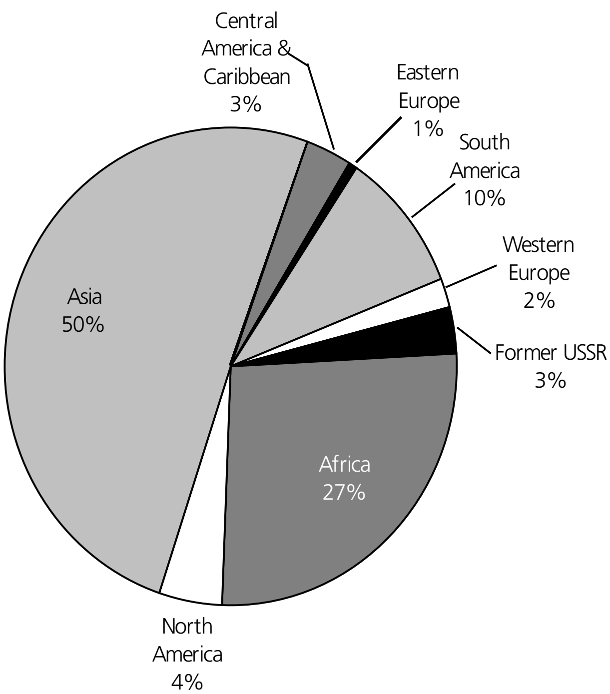
Fuelwood, charcoal, and other wood-derived fuels (collectively known as woodfuels) are the world's most important form of nonfossil energy. According to the FAO, fuelwood and charcoal production in 1998 equaled 1.8 billion cubic meters (m^3) of fiber. Production and consumption are concentrated in low-income countries, with five countries — Brazil, China, India, Indonesia, and Nigeria — accounting for about 50 percent of the total (FAO, 1997a:55). (*See Figure 11.*) In addition to direct sources, wood residues from the forest products industry are also commonly burned as fuel. The FAO has estimated that, of the 3.4 billion m^3 of wood harvested in 1995, about 63 percent was ultimately used as woodfuel (FAO, 1999:37). However, woodfuel data published by FAO are based largely on estimates derived from scattered 1960s household consumption surveys, which are updated annually in line with population and income growth. These estimates substitute for information on actual woodfuel consumption in most developing countries.

Statistics from the International Energy Agency (IEA) show the importance of wood energy in the lives of hundreds of millions of people. Biomass energy, which includes woodfuels, crop residues, and animal wastes, provides on average nearly 30 per cent of total primary energy supply in developing countries. Over 2 billion people depend directly on biomass fuels as their primary or sole source of energy. Although woodfuels are the dominant form of biomass energy, the current state of global data does not allow analysts to distinguish wood from other forms of biomass in many countries. The available data suggest that woodfuels account for more than half of biomass energy consumed in developing countries, or 15 percent of their total energy supply. If China is excluded (where agricultural residues are an important fuel), woodfuels provide about 20 percent of total energy supply in the developing world (IEA, 1996: II.289-308, III.31-187). In some countries, for example, Nepal in Asia, and Uganda, Rwanda, and Tanzania in sub-Saharan Africa, woodfuels provide 80 percent or more of total energy requirements. (*See Map 8.*) Most of this fuel is obtained directly from trees and shrubs, not necessarily from areas defined as forests (*see below*).

In most industrialized countries, wood energy contributes only about 3 percent of total energy supply. There are some exceptions: wood energy accounts for more than 16 percent of total energy supply in Sweden and Finland, and between 12 and 18 percent in some Central and East European countries (FAO, 1997b:7,11). Wood contributes 3 percent of U.S. energy supply but, in absolute terms, U.S. wood energy consumption is almost double the wood energy consumption of the entire European Union (FAO, 1997b:11-12). The United States is also unusual in that almost 60 percent of wood used for energy is directly harvested from forests: fuelwood accounts for about 18 percent of the country's total roundwood harvest (Nilsson et al., 1999:8-9). In other industrialized countries, most wood energy is derived from black liquor and other wood industry residues

Figure 11

Global Woodfuel Production, 1998



Source: FAOSTAT.
Note: Woodfuel production in 1998 totaled 1.8 billion m^3.

(FAO, 1997b:12-13). Perhaps surprisingly, in the Organisation for Economic Cooperation and Development (OECD) region as a whole, about 30 to 50 percent of all wood removed from forests is ultimately used for energy purposes. The average for the 15 countries of the European Union is 50 percent (FAO, 1997b:3).

Trends in Woodfuel Production

The FAO estimates that woodfuel consumption rose by nearly 80 percent between 1961 and 1998, slightly trailing world population growth of 92 percent over the period. The largest increases in woodfuel consumption were reported in Asia and Africa. The IEA has only recently begun to publish disaggregated data on biomass consumption, and time series data are not available.

Demand for fuelwood and charcoal is driven primarily by rising numbers of rural poor, who depend on wood for their cooking and heating needs. Charcoal, often consumed in the form of briquettes, is also an important fuel among the urban poor, whose numbers are expanding rapidly. Charcoal is also an industrial energy source in some Latin American countries; the steel industry in Brazil, for example, depends heavily on charcoal. Economic growth might be expected to reduce demand for biomass fuels in coming years. The conventional view is that, as incomes rise, countries shift toward the use of commercial fuels and reduce their dependence on biomass. In fact, it appears that, even with economic development, woodfuel use will not necessarily decline significantly.

In recent decades, economic growth in the developing world has indeed caused fossil fuel use to increase, and the relative share of energy consumption accounted for by biomass has declined. But absolute biomass energy consumption has continued to rise. Recent research shows that biomass consumption in Indonesia, Malaysia, Philippines, Thailand, and Vietnam grew by nearly 2 percent annually between 1985 and 1994, when these countries' economies were growing strongly. In these cases, there was no inverse correlation between per capita GDP and biomass consumption levels (RWEDP, 1997b:20). Rather, in many developing countries, fossil fuels are simply added to the energy mix, not substituted for woodfuels. Unequal distribution of wealth is also a factor in persistent use of biofuels despite rising national GDP. If increasing income is concentrated in the top percentiles of the population, large numbers of poor people continue to depend on biomass fuels.

Relatively little analytical work has examined future demand for woodfuels at the global level. FAO production trend estimates provide too little information to assess the current situation accurately, still less to produce reliable forecasts. Some projections of future demand are simple extrapolations of FAO production trend data. Still others are based on estimates of how much woodfuel will actually be available for consumption or how much woodfuel people *would* consume if all their needs were fully met. As a result, projections of global woodfuel consumption in 2010 range from 1.5 billion m^3 (a decrease of 16 percent on 1998 levels) to 4.25 billion m^3 (an increase of 136 percent) (cited in Brooks et al., 1996:45-74). Forecasts for 2020 are broadly similar.

Forest Modification to Increase Woodfuel Production

Most woodfuel comes from sources other than closed canopy forest so attributing forest modification to woodfuel collection is difficult. Insofar as forests are managed for fuelwood supply, practices are local and documentation is scattered. Trees are rarely felled; rather, branches and twigs are cut as needed. Plantations are estimated to provide less than 5 percent of global woodfuel supplies (Brown, 1999:41), though they assume greater importance in parts of China, India and South America. Fuelwood plantations are less extensive than those for industrial roundwood, and the degree to which they have replaced natural forest is not known. Numerous plantations and community woodlots exist that are too small in area to be included in national inventories, so their real extent is unknown.

Much evidence suggests that local communities can be a positive force in forest management, as they seek to protect vital woodfuel supplies from state-sponsored clearance and logging schemes. For example, some 4,000 km^2 of forest in Orissa State, India, have been restored by village communities, after commercial logging and unregulated grazing had removed almost all tree cover. The forests are currently protected and managed by villagers, who are trying to win legal control over the forest lands from the State government (WRI, forthcoming 2000).

Forest Capacity to Sustain Woodfuel Production

Lack of data makes any assessment of the long-term sustainability of woodfuel supply problematic. This section presents evidence which suggests that: (1) woodfuel supply does not depend wholly on forests, (2) woodfuel scarcity does exist at the local and regional level, and (3) interest in modern, renewable energy sources is likely to encourage afforestation.

SOURCES OF WOODFUEL

Twenty years ago, many observers assumed that all woodfuels came from forests. Woodfuel collection was blamed for deforestation and some analysts predicted that forests would be depleted to the point where a critical fuelwood gap would open between supply and demand within a few decades (RWEDP, 1997a:19-20). Today, systematic data on the sources of woodfuel are still lacking, but regional studies indicate that as much as two thirds of woodfuel worldwide probably comes from nonforest sources. (See Figure 12.) Woodlands, roadside verges, and backyards are alternative sources for collecting fuelwood; residues from logging, wood industries and agroindustry plantations, wood recovered from construction waste, and waste packaging supplement other nonforest sources (RWEDP, 1997a:21). Closed canopy forests appear not to be a prime source of woodfuels and, at the global level, wood collection for fuel is not regarded by the FAO as an important cause of deforestation. This knowledge should be tempered by recognition that woodfuel collection causes severe localized deforestation in some areas.

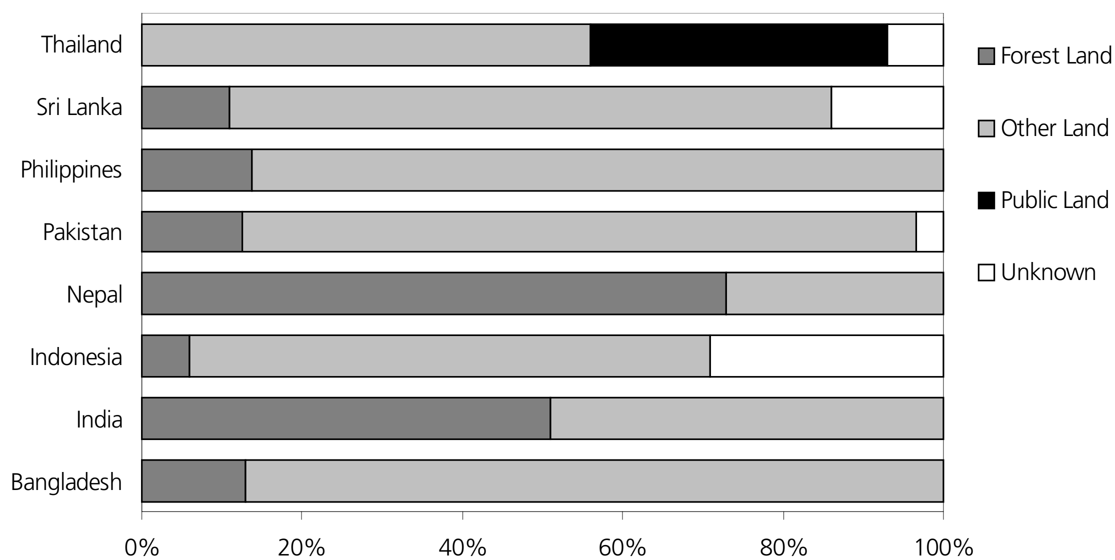
WOODFUEL SCARCITY

Supply shortfalls and social hardship undoubtedly exist at the local and regional level in many parts of Africa, Asia, and Latin America. Numerous studies document instances of villagers traversing ever longer distances to gather daily wood supplies. For example, a study of rural Botswana found that distance increased from an average of 1.3 km in 1969 to 3.6 km in 1979, as woodlands were cleared for commercial agriculture (Opschoor, 1994). The areas at greatest risk of woodfuel scarcity are developing regions with high or growing population density, low tree cover, and low per capita incomes.

In order to highlight these regions, this pilot assessment has developed a simplified version of such an indicator. Map 9 overlays areas of moderate population density (>250 people per 1000 hectares [people/1000 ha]) and tree cover (whether defined for-

Figure 12

Indicative Sources of Woodfuel



Source: RWEDP, 1997a:29

Notes: Forest land includes plantations. Other land is mainly private land, neighbours' land, and common land. Public land may include forest. Data are from different years, ranging from the early 1980s to the mid-1990s.

mally as forest land or not). A density of 250 people/1000 ha is roughly the average population density found in Africa; it is much higher than that of North America or Russia. Map 9 shows that relatively high population densities occur in closed forests (>60 percent tree cover) in Central America and the Caribbean, sub-Saharan Africa, and developing Asia. However, the greatest pressure on woodfuel supply is likely to occur in forest transition zones, which may be equated with the 10-30 percent and 30-60 percent tree cover classes (*See pp. 19-20: Forest/Cropland Transition Zones*). Extensive areas with population densities between 300 and 660 people/1000 ha are found in forest transition zones in Central America, coastal South America, sub-Saharan Africa and developing Asia.

Woodfuel shortages are especially likely to occur near cities. Poor, urban populations gather fuelwood and also rely heavily on charcoal, which, though it burns more efficiently than wood, is inefficient in terms of the conversion process from wood. Rising demand for fuelwood and charcoal is causing a halo of deforestation around many cities, towns, and roads. Anecdotal evidence exists of closed forests being affected, notably in Sri Lanka, India, and Thailand, but systematic data are lacking. A survey undertaken for the government of Ivory Coast, during preparation of a national energy strategy, assessed demand for biomass energy and supply, that is, the annual growth in biomass. In 1988, five urban zones proved to have demand in excess of natural supply, meaning that trees, as opposed to twigs and residues, were being cut and charcoal imported from other regions (Garnier, 1997:49-56).

Despite such evidence, generally poor data mean that the possibility of a future woodfuel crisis cannot be accurately assessed. There is a tendency to use consumption estimates, modeled from household survey data, as production estimates. This approach probably underestimates both real production levels — one study claims that fuelwood collection in India is 10 times greater than officially reported (Jones, 1995) — and real future needs. At the global level, forecasts of scarcity have probably been exaggerated. "Doom scenarios" under which biomass-dependent countries would lose all their forests to fuelwood collection have not come to pass. For example, a 1979 Nepalese forecast predicted that all accessible forest in the country would disappear by 1990. Actual forest loss has been about one half the predicted amount, and there is no suggestion that it results from fuelwood collection. The error was caused by the mistaken assumption that forests were the sole source of fuelwood (RWEDP, 1997a:20).

Contrary to predictions of wholesale deforestation, there is good evidence that woodfuel supply can be sustainable even in densely populated areas, where government planting programs, community woodlots, and plantations are adequately managed. Studies in Africa indicate that institutional factors, such as insecure property rights, not scarcity of trees, are often to blame for woodfuel shortages.

WOODFUELS AS A MODERN, RENEWABLE ENERGY SOURCE

Woodfuels are a carbon-neutral energy source, as long as the rate of harvest equals the rate of regrowth. (*See p. 59.*) Woodfuels currently provide only a small share of energy in most industrialized countries, but their potential to reduce fossil-fuel related carbon emissions is attracting interest from policymakers and the fossil energy industry. The use of wood energy is encouraged under the U.N. Framework Convention on Climate Change (UNFCCC), and a number of countries, including Austria, Denmark, Finland, and the Netherlands have launched programs to promote afforestation and bioenergy schemes. A number of developing countries have also established successful wood energy initiatives as part of economic cooperation programs (FAO, 1999:37-39). Wood energy is likely to become more competitive with fossil fuels as more countries introduce tax differentials, and as new technologies raise combustion efficiency and improve the transport, handling, and storage of woodfuels. Increased demand for wood energy will be met in part through afforestation; however, the availability of suitable land, and economic competition from alternative land uses, may constrain major expansion of this energy source.

Ecological Externalities of Woodfuel Production

The effects of woodfuel production on forest condition are not well documented. Local examples of deforestation were noted previously. Short of deforestation, fuelwood collection is also known to contribute to significant reductions in biomass in parts of tropical Asia and tropical Africa. (*See p. 59.*) Woodfuel collection and charcoal production in Brazil are known to be responsible for damaging habitat for birds and small mammals. (*See p. 50.*) Examples of such damage are common in the Brazilian cerrado, which produces charcoal for the steel industry, and in northern Thailand, which exports charcoal to Bangladesh.

Information Status and Needs

Information on the production and consumption of woodfuels is limited and unreliable. Despite the importance of wood energy, it is generally accorded low priority by policymakers in developing countries, who tend to undervalue its role. Relatively little effort has gone into collecting and analyzing statistics. At present, most experts would agree that, "information on biomass production and use patterns is grossly inadequate even as a basis for informed guesses, let alone the making of policy and the implementation of plans" (Hall, 1997:57-58). Two global datasets are currently available.

THE FAO WOOD ENERGY DATABASE

The FAO's stated aim is to refine the presentation of wood energy in FAO statistics and take account of other bioenergy database methodologies. To accomplish this task, FAO is working with a variety of institutions, including the International Energy Agency (IEA), and individual experts. The database will group all kinds of energy material from wood in one class called "woodfuel", include new types of wood energy products, and better disaggregate supply and demand. This aim cannot be realized given the current state of data. FAO acknowledges that, at present, its dataset does not adequately cover black liquor (derived from by-products of the pulp industry, and a major source of energy in some countries), nor does it include wood energy from nonforest sources such as community woodlots or wood industry residues. These are major omissions: the FAO's reliance on forestry data results in a lower estimate of global wood energy consumption than that produced by IEA.

The FAO dataset is intended, in time, to cover production data for wood energy derived from direct sources (wood removed from natural forests, plantations, other wooded lands, and other lands, such as homesteads and roadsides); indirect sources (industrial by-products derived from primary and secondary wood industries); and recovered sources (wood from construction and demolition wastes, packaging, and other wastes). Demand is broken down by major economic sectors (e.g., households, industry) and major products (e.g., fuelwood, charcoal, black liquor). An energy balance, accounting for imports, exports, and transformation losses is also included for each country. Many data, as noted above, are currently missing.

THE IEA COMBUSTIBLE RENEWABLES AND WASTE DATABASE

IEA collects information from OECD countries via annual questionnaires. The product categories listed are solid biomass and animal products, gases derived from biomass and wastes, industrial waste and municipal solid waste. Energy data are expressed in thousand tonnes of oil equivalent. The questionnaire requests data on individual fuels such as wood, vegetal wastes, black liquor, and landfill gas. For non-OECD countries, IEA follows the same classification, but relies on a variety of information sources. Sources include national publications or statistics, regional organizations, and specific studies or surveys. Where other sources are unavailable, IEA data draws on UN information. A recent two-year IEA project sought to expand coverage of biomass data to the global level and to provide a more detailed breakdown of energy commodities. Though IEA notes many data gaps, the study has provided a clearer picture of what is missing. Published IEA energy data since 1994-95 have included combustible renewables and waste in national energy balances, disaggregated into separate categories for wood, charcoal, black liquor, and other biomass. These data are currently being used by the organization for more detailed modeling and analysis. The IEA's rationale is that energy balances and carbon flows would be inaccurate for the majority of countries if biomass energy were not included.

Information is urgently needed (1) to provide more accurate data on woodfuels as a component of the world's energy supply, and (2) to improve understanding of how forests and woodlands can be sustainably managed for woodfuel production over the longterm. Priority questions concern production data and sources of woodfuel supply, at the national level, and actual consumption requirements at the household level. Biomass data are difficult to gather and surveys can be costly and time consuming. Cost-effective sampling and analysis techniques must be developed to reduce the current range of uncertainty regarding consumption and future demand.

BIODIVERSITY

The Diversity of Forests

Forests contain the greatest assemblages of species found in any terrestrial ecosystem, and the status of biodiversity is, in itself, an indicator of forest condition. Forests encompass biodiversity at the ecosystem level, the species level, and the genetic level. Numerous distinct types of forest ecosystem have been identified, occurring in fresh and saltwater environments, moist lowlands and arid highlands, low and high latitudes. Plant, animal, and insect species in these forests directly supply the needs of forest-dwelling peoples. Wood products from thousands of tree species are used domestically and traded internationally. Nonwood forest products, including fruits, nuts, mushrooms, Christmas boughs, and floral decorations, are collected by individuals, traded in local markets and, in some cases, exported worldwide. The genetic diversity of forest flora and fauna is a resource of great potential value to the agricultural and pharmaceutical biotechnology industries, though the process of winnowing valuable genes from millions of unrewarding species is proving time-consuming and expensive.

Use values aside, the biological richness and beauty of forest ecosystems are at the core of their appeal to environmentalists and the wider public today. Saving the rainforest is a passionate cause for many individuals who have no direct connection with, or use for, tropical forests. The rise of ecotourism testifies to the need felt by (largely) urban-dwelling people to witness natural, as opposed to human-made, wonders. Forest-dwelling indigenous peoples are seen, by some, as safeguarding the cultural diversity and intimate knowledge of nature that are likely to be lost in an industrializing and homogenizing world.

Forest biodiversity is perceived as a good in itself, but perhaps no other ecosystem good is subject to so many different interpretations. The conservation, and exploitation, of biodiversity are variously supported on scientific, economic, spiritual, aesthetic, cultural, religious, and moral grounds.

Measuring forest biodiversity is beset by problems. Indicators of biodiversity status, at any level, are still controversial, and the data needed to support their development are incomplete. Genetic diversity is still largely unmapped. Many species remain unknown to science, baseline and trend data are largely lacking, and detailed systematic monitoring is beyond the resources of even the high-income countries. Nevertheless, much work has been carried out in recent years, in particular by international NGOs. Their efforts have improved our understanding of some aspects of forest biodiversity. The importance of forests to global biodiversity is demonstrated here by three indicators: the Global 200 Distinctive Ecoregions, developed by WWF-U.S.; Endemic Bird Areas, identified by BirdLife International; and Centers of Plant Biodiversity, identified by the World Conservation Union (IUCN), the Worldwide Fund for Nature (WWF), and WCMC.

GLOBAL 200 ECOREGIONS

In an attempt to identify priority areas for conservation, WWF-U.S. has conducted an analysis of ecoregions representing the world's 19 terrestrial, freshwater, and marine major habitat types (MHTs). (Olson and Dinerstein, 1998.) MHTs are geographic areas sharing environmental conditions, habitat structure, and patterns of biological complexity, and containing species with similar guild structures and adaptations. WWF-U.S. also developed the "Global 200" categorization for ecoregions that are outstanding representatives of the world's diverse ecosystems. At the time of writing, 232 ecoregions were identified, comprising 136 terrestrial, 35 freshwater, and 61 marine ecoregions (Olson and Dinerstein, 1998: 509).

At the global level, and within each biogeographic realm, ecoregions were chosen based on the following set of parameters: species richness; species endemism; higher taxonomic uniqueness; unusual ecological or evolutionary phenomena (such as migrations); global rarity of MHT; keystone habitats.

The importance of forests for global biodiversity conservation is clear. Forest ecosystems account for 6 of the 12 terrestrial MHTs, and these 6 forest MHTs contain nearly two thirds of all terrestrial ecoregions. The distribution of ecoregions is shown in Map 10.

ENDEMIC BIRD AREAS

More than one quarter of all birds of the world have restricted breeding ranges, that is, they are confined to areas of less than 50,000 km^2 (the size of Costa Rica). Restricted-range birds include 816 species currently classified as threatened; this number represents more than one half of all restricted-range birds, and 74 percent of all threatened bird species. In an attempt to prioritize areas of particular conservation importance to these birds, BirdLife International has identified 218 endemic bird areas (EBAs) worldwide. An EBA is defined as:

> "An area which encompasses the overlapping breeding ranges of restricted-range bird species, such that the complete ranges of two or more restricted-range species are entirely included within the boundary of the EBA. This does not necessarily mean that the complete ranges of *all* of an EBA's restricted-range species are entirely included within the boundary of that single EBA, as some species may be shared between EBAs." (Stattersfield et al., 1998:24.)

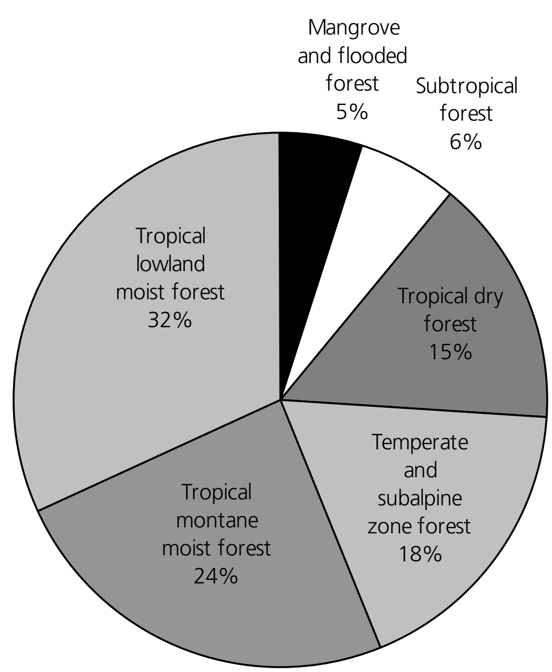
Forests provide the habitat for 83 percent of all EBAs. The distribution of EBAs, and the various forest ecosystems in which they are found, are shown in Map 11 and Figure 13.

Map 11 shows that over half (53 percent) of restricted-range birds are found on islands; the other 47 percent on continents. The size of EBAs varies widely, from tiny islands of a few square kilometers to the southeastern mountains of China, which cover over 600,000 km^2. Most are under 30,000 km^2. The majority support between 2 and 10 restricted-range species, but a few outstanding EBAs support 50 species or more. Nearly half of all EBAs are estimated to have lost more than 50 percent of their key habitats, and more than 10 percent have lost over 90 percent. Partly as a result, most EBAs support one or more threatened restricted-range species and in 23 of them, all are threatened. According to BirdLife International, the Atlantic slope and forest lowlands of Brazil are particularly at risk, with many species threatened with extinction.

The relevance of EBAs to conservation goes beyond restricted-range bird species. Analysis by BirdLife International has established that EBAs partially encompass the ranges of many widespread threatened bird species and that they include the key habitats and sites for many more widespread species, including some important migrant species. However, many habitats important to widespread bird species fall outside EBAs and conservation action centered on EBAs alone would not be sufficient to protect them. Temperate and arid or semiarid habitats are poorly represented because restricted endemism is not characteristic of these regions. However, EBAs appear to include many areas of importance for other fauna and flora, although the degree of overlap is hard to establish, given poor data for other species. Restricted range birds are a reasonable indicator

Figure 13

Key habitats of endemic bird areas.



Source: Stattersfield et al., 1998

of the presence of some other plants and invertebrates that show similar dispersal abilities.

CENTERS OF PLANT DIVERSITY

Diversity of plant life is an essential attribute of most terrestrial ecosystems. Like birds, plants influence decisions regarding conservation priorities, because they have dispersed to, and diversified in, all regions of the world, and they occur in virtually all habitat types and altitudinal zones. Identifying sites of high plant diversity is an approach to determining which areas should receive priority conservation action.

WWF and IUCN have identified 234 priority centers of plant diversity (CPDs) worldwide (WWF and IUCN, 1994). About 80 percent of all centers of plant diversity are found in forests. In order to qualify, the sites had to be either particularly species-rich or contain a large number of endemic species. The mainland centers must contain at least 1,000 vascular plant species (estimated), with 100 or more endemics; the island centers must contain at least 50 endemics or at least 10 percent of the flora must be endemic. Additional characteristics considered in selecting the centers included: an important gene-pool of plants having value, or potential value, to humans; a diverse range of habitat types; a significant proportion of species adapted to special soil conditions; and under threat of large-scale devastation. Because the centers designate sites that are of global botanical importance, some sites were omitted that would have qualified if assessed from a national perspective.

A comparison of CPDs and EBAs, provided in Map 11, shows a strong spatial association between the two, which reinforces the validity of mapping biodiversity hotspots, at least with respect to endemism. According to BirdLife International, 70 percent of CPDs overlap in some way with EBAs, and 60 percent of EBAs overlap with CPDs. However, some significant sites do not show any overlap, and both studies stress the limitations of using selected species, or collections of species, as proxy indicators of overall biodiversity.

Trends in Forest Biodiversity

Extinction rates in the past few centuries indisputably have been far higher than background extinction rates — those expected based on evidence from the fossil record. Extinction rates rose with the spread of human populations to previously isolated continents and islands, and rose again with European expansion in the 15th and 16th Centuries. Most information from this period relates to birds and mammals, though it is still far from complete, while knowledge of lower vertebrate and invertebrate extinction rates remains scanty. Analysis of the available data shows that the most important reason for population extinctions, especially on small spatial scales, is habitat destruction. At larger spatial scales, populations may go extinct when the density of habitat patches falls below a critical threshold. Interactions with introduced organisms (predators and competitors), hunting, and deliberate extermination are also important causes of human-related extinctions (Heywood, 1995: 240).

Actual extinctions of known forest species to date are very hard to document. Many forests are surveyed only rarely, and baseline data are lacking. In addition, many species are widely dispersed and may survive incremental habitat loss. However, there is widespread evidence of extinctions of distinct populations of species. In several parts of Europe, for example, fungal species diversity in forests has dropped by 50 percent or more in the past 60 years (WRI, IUCN, UNEP, 1994:7-8). Ecologists believe that the fastest rates of extinction in the world are occurring in the tropical forests, where deforestation rates and genetic and species diversity are highest. However, most species in these regions remain undocumented, and actual rates of extinction are unknown. Estimates of current extinction rates are believed to be highly conservative, because species are generally not declared to be extinct until years after their last sighting. Other species whose populations have fallen below the threshold for long-term survival may struggle on for decades while their populations dwindle without hope of recovery.

Measures to Protect Forest Biodiversity

PROTECTED AREAS

Direct efforts to conserve forest biodiversity focus on legal protection of forested land. IUCN defines 5 categories of protected area, using the management objective as the basis of classification. Categories range from *Category I* (Strict Nature Reserve, managed mainly for scientific research and environmental monitoring) to *Category V* (Protected Landscape/Seascape, managed mainly for landscape/seascape conservation and recreation). A recent WCMC study shows that just over 3 million km^2 of forest were protected under all 5 IUCN categories in 1996 (WCMC, 1999). It should be noted that WCMC estimates global forest cover at nearly 40 million km^2, about 11 percent greater than the FAO estimate, and more than 30 percent greater than forest area according to the IGBP classification scheme. (*See Table 8.*)

Of 25 forest types defined by WCMC, those with the highest degree of protection (expressed as a percentage of total area of that forest type) were nontropical evergreen broadleaf forests (22.6 percent), and tropical lowland rainforests (13.1 percent). Among forest types with the lowest degree of protection were nontropical deciduous needleleaf forests (0.9 percent), and tropical mixed needleleaf/broadleaf forests (2.5 percent). These data must be interpreted with caution. Many protected areas have been established primarily for recreation, and have little sig-

Table 8

Protected Forest Area, 1996

Region	Forest Area (km^2)	Protected Forest Area (km^2)	Percentage of Forest Protected
Africa	5,683,130	496,927	8.7
Australasia	1,493,234	125,819	8.4
Caribbean	53,847	7,899	14.7
Central America	901,984	88,096	9.8
Continental S and SE Asia	1,707,679	192,461	11.3
Europe	1,815,396	144,832	8.0
Far East	1,456,027	77,401	5.3
Insular SE Asia	1,468,360	247,497	16.9
Middle East	1,676,661	6,386	3.8
North America	8,453,988	699,956	8.3
Russian Federation	8,257,159	150,637	1.8
South America	8,429,459	874,924	10.4
World	**39,887,924**	**3,112,835**	**7.8**

Source: World Conservation Monitoring Centre. National Protection Systems: Protected Areas Database. Unpublished data (Cambridge, UK: WCMC, May/August 1999).
Data on-line at: http://www.wcmc.org.uk/forest/data/cdrom2/gtabs.htm Accessed March 10, 2000.

nificance for the conservation of biodiversity. In addition, protected areas are often selected on pragmatic, rather than scientific grounds. Finally, protected area status is no guarantee of enforcement on the ground. The countries of Central America — excluding Mexico and El Salvador — have designated between 19 and 43 percent of their forests as protected, yet the FAO's annual forest change rate for Central America (excluding Mexico and El Salvador) is -2 percent, a figure exceeding the global average of -0.3 percent.

The Capacity of Forests to Sustain Biodiversity

HABITAT LOSS AND DEGRADATION

Habitat loss and degradation is regarded by ecologists as a prime cause of recent extinctions, and the leading threat to biodiversity in the future. The pace and scale of deforestation were discussed on pp. 15-19 of this report. Forest modification by road construction and shifting cultivation, and estimates of forest naturalness, were discussed on pp. 19-24. Some of the documented impacts of logging on biodiversity were reviewed on pp. 35-36.

The nature of threats to forest habitats vary among major forest types. The temperate forests of the United States and Europe are stable in area, but appear to have undergone the greatest modification by humans. Forests are either heavily managed, or are in a seminatural state of secondary or tertiary regrowth. According to the FAO's forthcoming TBFRA 2000, 90 percent of forest area in Europe (excluding Russia) consists of even-aged stands; just over 20 percent by area of these stands are under 20 years old, nearly 40 percent are between 20 and 60 years old, and just over 20 percent are between 60 and 100 years old. Only 12 percent of forests are in stands of more than 100 years old. The high-latitude boreal forests of the Russian Federation are reported to be in a largely undisturbed condition, but there is growing evidence of illegal or unreported logging activity, and serious fire damage. Over one third of the world's boreal forest is found in Canada, and nearly 50 percent of the Canadian Boreal Forest Region is under tenure for wood production (Smith et al., 2000:12).

Moist and dry tropical forests tend to be less altered by intensive management regimes, but are the most likely to be converted to other land uses. They also appear to be increasingly vulnerable to human-set fires and to logging, development, and settlement following road construction. Tropical montane forests are undergoing the fastest clearance rates of any major forest type, and these forests rank among the richest in rare and endangered species. Subtropical forests, particularly in South America and Australia, have been extensively converted to industrial wood and cash crop plantations.

FOREST SPECIES AT RISK

Quantitative information at global or continental level is available for only a limited number of species in forests; the following sections summarize recent research on endangered tree species, endangered forest-dwelling birds, and non-native species in forests.

Threatened Tree Species

The world's tree flora are estimated at about 100,000 species, of which some 21,000 species are found in the temperate regions. The full diversity of trees in the tropics is still incompletely known, and the total number of species is only an informed guess. Information on the threat status of trees is essential for conservation planning and sustainable management of individual species, and for use as an indicator of ecosystem status. Tree species diversity is recognized as a surrogate for overall species diversity in forest ecosystems.

WCMC has compiled a worldwide list of threatened trees, assessed according to the revised threat categories and criteria published by IUCN in 1994 (Oldfield et al., 1998). (*See Figure 14.*)

The new IUCN guidelines were intended to make threat categories more quantitative, objective, and equally applicable to all higher taxa of plants and animals. Threat categories can only be assigned to species if one or more of five criteria apply; the criteria involve size of populations; degree of fragmentation; population structure; and expected, defined rates of decline. The assessment process involved considerable subjectivity, given imperfect information and reliance on many assessors. The outcome was the assignment of threat categories without using fully quantifiable information. Nevertheless, the Global List of Threatened Trees represents many years of effort, and is the first internationally comparable database on the status of tree species.

WCMC reports that over 7,300 trees are now threatened globally. Additional threatened tree species have been documented in Australia and Japan that were not included in the main report. Altogether, more than 8,700 tree species, or nearly 9 percent of the total, are now at some risk of extinction.

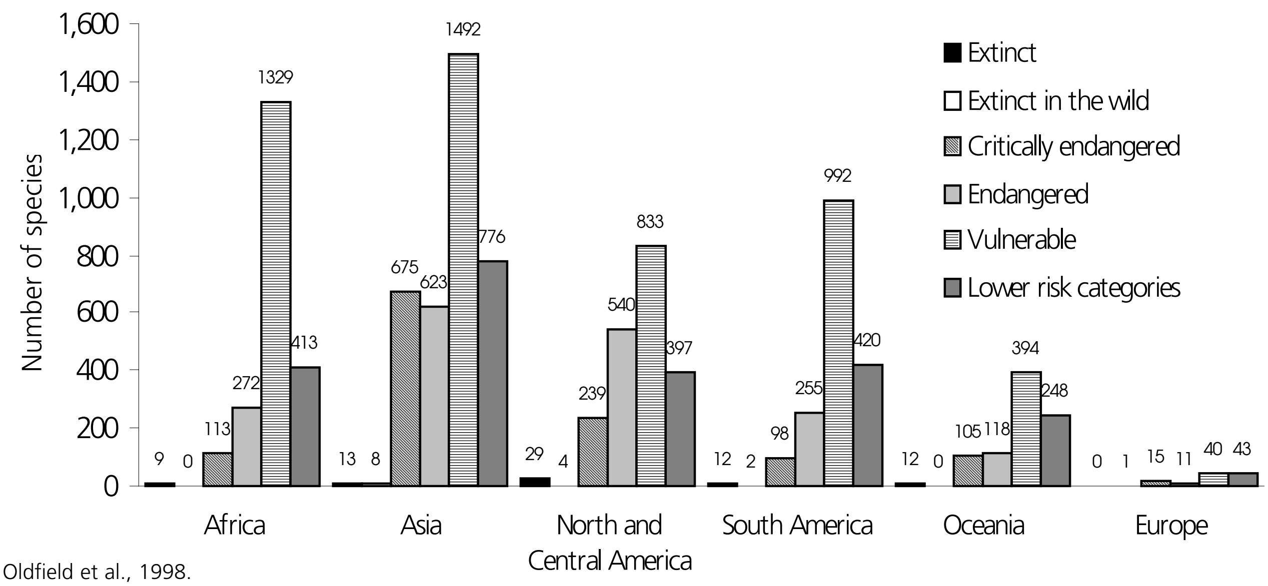
According to WCMC, habitat modification and destruction are the general cause of tree species being assigned threatened status. Specific threats also result from direct exploitation of a species for timber or other products. The leading threats to trees globally are identified, in order of importance, as logging (1,290 species), agriculture (919 species), expansion of settlement (751), grazing (417), burning (285), invasive plants (245), forest management (220), local use (173), mining/exploration (151), and tourism/leisure (134). In practice, these threats are often closely linked and cannot readily be prioritized in this way. Nevertheless, the fact that nearly 1,300 tree species — 15 percent of all threatened trees — are estimated to be at risk of extinction because of logging, including both clear-cutting and selective felling, adds weight to the findings of the Forest Frontiers study (Bryant et al., 1997). That study identified logging roads, because of the access they provide, as the principal threat to intact, primary forest.

Key Areas for Threatened Bird Species

The forest ecosystems of the non-Caribbean Neotropics provide exceptionally rich habitat for birds. Approximately 3,600 species inhabit the region, of which 290 (8 percent) are listed

Figure 14

Global List of Threatened Trees



Source: Oldfield et al., 1998.

as threatened in *Threatened Birds of the Americas* (Collar et al., 1992). These 290 species represent 25 percent of all threatened bird species in the world. BirdLife International has documented nearly 600 Key Areas which are the most important areas currently known for the conservation of these threatened birds (Wege and Long, 1995). (A recent revision to the list has increased the number of threatened birds to 326, but the additional species have not been included in the Key Area analysis).

BirdLife International mapped the location of about 7,000 sites where threatened bird species are known to occur and, using a set of criteria, reduced these sites to a smaller list of 596 Key Areas for these species. (*See Map 12.*) The criteria for identifying Key Areas included documented evidence for, or strong likelihood of, an extant population of the species in question. Preference was given to sites that were larger, more intact, already protected, or that would ensure representation of the entire range of a species. If the Key Areas identified by BirdLife International were to be adequately protected, the conservation of 280 (97 percent) of threatened species in the Neotropics would be greatly advanced.

The study documents both the importance of forest habitats to threatened birds in the Neotropical region, and the severity of the threats these birds face. The three main habitat types that support the threatened birds in the region are wet forest, dry forest, and grassland areas. Of the 596 Key Areas, more than 70 percent are in forests. Wet forests support nearly 55 percent of the threatened birds (180 species), while dry forests support more than 17 percent (57 species). (Wege and Long, 1995:15-16.)

As Map 12 illustrates, the Atlantic coastal forests of Brazil are of critical importance; the majority of Key Areas in the country support populations of 10 or more endangered species. The northern Andes and adjacent lowlands, particularly in western Colombia, are also highlighted. Wet forests support two to four times as many threatened bird species as other habitat types. Dry forests, which include deciduous forest and dry scrub, are of most importance in southwest Ecuador and northwest Peru. Another important cluster of dry forests is found in the states of Central Brazil; many of these forests have been badly damaged by clearance for agriculture and charcoal production (Wege and Long, 1995:16).

Throughout the Neotropics, according to BirdLife International, the primary threat to birds is habitat loss or alteration. Almost 75 percent of the threatened species are regarded as threatened in part because of habitat loss, while 48 percent are regarded as threatened solely because of habitat loss. In addition, hunting is an important component of the threat profile for 15 percent of species, and trade is a threat to 11 percent. Neither of these factors is believed to be the sole threat facing any species.

Non-Native (Exotic) Species

Humans are responsible for introducing, whether deliberately or accidently, thousands of non-native plants and animals to new habitats. Many of them — food crops, livestock, ornamental plants, pets — are beneficial. A relatively small number have attacked or overwhelmed native species, or so altered the composition of native habitats that they can no longer support some species of native flora or fauna. Aggressive invasions by exotic species rank, by many estimates, as the leading cause of historically recorded extinctions, and second only to habitat conversion as a threat to future global biodiversity.

Although comprehensive global data on non-native species are not available, numerous databases have been developed for specific geographic regions (for example, Invasive Species of Indian Ocean Islands, Invasive Species of Pacific Islands, America's Least Wanted), or major threats (The World's 100 Worst Invasive Species), or specific invasives (Slow-the-Spread Gypsy Moth, Witchweed Management). It is not always easy to distinguish between good and bad non-native species because some species have both beneficial and harmful consequences. According to the U.S. Congress's Office of Technology Assessment (OTA), approximately 15 percent of non-native species in the United States cause severe harm, affecting agriculture, industry, human health, or natural areas (U.S. Congress, 1993:5). However, OTA believes that, where damage is done to ecosystems, rather than to human health or the economy, the number and impact of harmful invasives is chronically underestimated. The number, however, is far less important than the scale of their effects; a single aggressive species can invade extensive areas, resulting in wholesale ecosystem changes and extinction of indigenous species. Less visible, but potentially damaging, long-term impacts can include subtle ecological changes and increased biological homogeneity.

In North America, 40 percent of the insect pests that attack trees are of foreign origin, although these exotic insects compose only about 2 percent of the total insect fauna (Niemela and Mattson, 1996:741-753). WWF-U.S. has mapped the distribution of non-native plant species in North America (Ricketts et al., 1997). (*See Map 13.*) Data were compiled from county-level lists, documented as native or non-native plant species, and aggregated to the ecoregion level. However, the data do not distinguish between benign non-native species and aggressive species harmful to native flora and fauna. This seriously limits the usefulness of the data as an indicator of forest condition. Box 3 documents two cases of non-native species in North American forests that have proved destructive in the environment.

Map 13 shows that the highest concentrations of non-native species, relative to native species, are found in and around coastal cities, which have served historically as ports of entry for commercial goods, travelers and exotic species. High concentration rates are also found along major transportation routes

Box 3

Harmful Invasive Species in North American Forests

In the eastern United States, native fir and hemlock forests are threatened by several species of adelgid, a tiny aphid-like insect. The balsam wooly adelgid (*Adelges piceae*) has affected fir forests of the southern United States, killing large stands of this tree in the Appalachian Mountains. A related insect, the hemlock wooly adelgid, is killing hemlocks in the South and is moving north into New England. The destruction of fir and hemlock forests in the Great Smoky Mountains National Park and elsewhere is dramatically changing forest ecosystems: as firs in the canopy die, they are being replaced by hardwoods because of increased light and temperatures on the forest floor. These microclimatic changes are also affecting animal and plant communities on the forest floor, threatening spiders, salamanders, and the Carolina flying squirrel, all of which are adapted to the cooler fir and hemlock forests (Stein and Flack, 1996).

Another recent insect pest is the Asian long-horned beetle (*Anoplophora glabripennis*), which feeds on and destroys a wide variety of trees, including maples, birches, poplars, willows, horsechestnuts, and elms. This beetle is also a serious pest in its native range of China, and has no natural predators in the United States. The insect, which is introduced on untreated wood product imports from China, was first discovered in New York City in 1996 and has since been found in Chicago and other cities. To contain the beetle in New York, city and state agencies had to undertake a costly campaign in which all potential host trees in infected areas were cut down, chipped, and burned. This effort to eliminate the beetle appears to have been successful (Haack et al., 1997). However, with increased international trade, the introduction of this beetle and other exotic pests is a trend that is likely to continue in the future, unless stricter preventive measures are implemented.

Sources:

Haack, R.A., K.R. Law, V.C. Mastro, H.S. Ossenbruggen, and B.J. Raimo. 1997. "New York's Battle with the Asian Long-Horned Beetle." Journal of Forestry 95 (12):11–15.

Stein, B.A. and S.R. Flack, eds. 1996. America's Least Wanted: Alien Species Invasions of U.S. Ecosystems (Arlington, Virginia: The Nature Conservancy).

and in fertile agricultural regions that proved hospitable to both introduced crops and their pests. In the northeastern coastal forests, up to 32 percent of total vascular plant species are non-native. In the northern Californian coastal forests, the eastern U.S. forest/boreal transition and the eastern Canadian forests, up to 28 percent of plant species are non-native. Densely forested tundra regions, away from major human settlements, appear to be little affected, while the southeastern conifer forests have proved relatively resistant to invasion by exotic species. This pattern is in line with other evidence that suggests that human disturbance increases the susceptibility of ecosystems to invasions, although successful invasions of undisturbed ecosystems are also common (Heywood, 1995: 758-759).

PROJECTED EXTINCTION RATES

Despite improving knowledge of the extent and nature of forest change, it remains extremely difficult to link this information to possible species declines or extinction rates. Existing knowledge of geographical and other variation in species richness is incomplete and heavily biased in favor of a few taxonomic groups and parts of the world. Estimates of present and projected global extinction rates have been based, not on observed extinctions, but on extrapolations from estimates of habitat loss coupled with assumptions derived from biogeography, which relate numbers of species to area of habitat. The most widely quoted species-area curve generalization is that a 90 percent loss of habitat results in the loss of half the species.

Over the past two decades, ecologists have made various estimates of future biodiversity losses in forests. Most loss estimates are based on extrapolations of deforestation rates in the tropics, since that is where the greatest biodiversity occurs. The more moderate estimates forecast rainforest species losses of between 2 and 5 percent per decade (Ehrlich and Wilson, 1991; Reid and Miller, 1989, cited in WCMC, 1992:202-203). A finer analysis, which distinguished among deforestation rates in different tropical areas, estimated that global losses of closed forest species will be around 1 to 5 percent per decade, resulting in a total loss of 2 to 8 percent of species by 2015 (Reid, 1992:55-73). These projections represent the number of species committed to eventual extinction, not the number which will become extinct by 2015.

Such estimates have high and largely unknown levels of uncertainty, because of the uncertainty of the underlying data and the assumptions on which they are based. Species richness and endemism vary widely among different areas, habitat loss rates are approximate, and the nature of habitat loss varies from total conversion to selective change. In addition, the effects of fragmentation are often discounted. A number of studies have sought to compare predicted with actual extinction rates, with mixed results. (S*ee Box 4*.) The many uncertainties in predicting extinction rates (not least, the uncertainties surrounding the willingness and ability of humans to take steps to slow those extinction rates), mean that estimates are best viewed as indicators of threat in a particular region, not as actual forecasts of species loss.

Box 4

Species Area Curves as a Predictor of the Biodiversity Impacts of Forest Loss

The Atlantic Coast rainforests of Brazil once covered over 1,200,000 km^2, but have been reduced to 12 percent of their original extent. Fragments vary in extent from 1 percent to 29 percent of original forest cover, in different regions (Brown and Brown, 1992). Much of this fragmentation was initiated over a century ago, yet there have been no recorded extinctions of birds in these forests. In an attempt to explain this discrepancy, one study examined endemic bird species in four Atlantic Coast forest types, comparing species losses predicted under the species-area relationship to the number of currently threatened endemic birds (Brooks and Balmford, 1996). In forest types where only 2 to 6 percent of cover remained, 11 out of 13 endemic species were threatened. Where 12 to 20 percent of the forest area remained, 29 of 61 endemic species were threatened with extinction. These figures compare well with predicted extinction rates using species-area equations for endemic birds of these forests.

Another study applied the species-area equation to the Philippines and Indonesia, a region of high avian endemism and diversity, and significant deforestation. This analysis found that, for birds endemic to a single island, species-area equations predicted fewer numbers of species than were actually threatened in roughly 60 percent of the cases examined, and overestimated the numbers of threatened species roughly 40 percent of the time. For endemic birds found on more than one island, and for wide-ranging species, the same equations consistently overestimated the number of threatened species (Pimm et al., 1995).

A historical analysis of deforestation in Puerto Rico found that, by 1900, clearance for agriculture had left less than 1 percent of primary tropical forest standing. An additional 9 percent of the land area was under shaded coffee plantations. Subsequently, forest cover was re-established and secondary-growth forest now covers a significant portion of the island. In this case, several birds have been recorded as becoming extinct; the recorded avian extinction rate was less than 12 percent, with several of these extinctions attributed to hunting pressure rather than habitat loss per se (Brash, 1987).

These examples clearly offer mixed results. Using birds as a test case, species-area equations appear to work well in predicting the number of threatened restricted-range endemic species. It is possible that these threatened species are committed to extinction, with a time-lag existing between fragmentation and eventual extinction (Pimm et al., 1995; Brooks and Balmford, 1996). But in the Puerto Rico case, where actual extinctions were reported, the equations greatly overestimated the extinction rate. In a majority of cases, species-area equations also overestimated the number of threatened birds endemic to several islands in Indonesia and the Philippines.

A shortcoming of the species-area curve as it was applied in all of these case studies is that predictions about species numbers were made only on the basis of area. For area alone to be an adequate predictor of species number, it must be highly correlated with other important variables, such as habitat diversity or resource availability (Boecklen and Gotelli, 1984). As a study of frog species in the Amazon demonstrated, different frog species have specific breeding habitat requirements. A larger area with no essential breeding habitat would contain fewer frogs than a smaller one that contained the necessary habitat. Area in this case acts only as a surrogate for habitat diversity. The larger the area surveyed, the greater the chance of encountering the necessary habitat (Zimmerman and Bierregaard, 1986). This is borne out in a study of the effects of habitat heterogeneity and area on species diversity for eastern U.S. forest birds (Boecklen, 1986). This analysis of habitat heterogeneity was carried out using 10 measured variables to determine vegetation structure. The structural heterogeneity of forests was found to be a better predictor of species number than forest patch size alone. The results of this research demonstrated that habitat heterogeneity is an important predictor of species richness, and should be factored into species-area curves to improve their predictive power (Boecklen, 1986). With recent improvements in remote-sensing technology, measurements of habitat heterogeneity can be made more easily, and species-area equations can be adjusted to incorporate this information. A potentially larger problem is that species-area equations are not dynamic. If habitat is lost gradually over time, species have a greater chance of relocating and adjusting than if habitat is destroyed suddenly.

Sources:

Boecklen, W.J. 1986. “Effects of Habitat Heterogeneity on the Species-Area Relationships of Forest Birds.” *Journal of Biogeography* 13: 59-68.

Boecklen, W.J. and N.J. Gotelli. 1984. “Island Biogeographic Theory and Conservation Practice: Species-Area or Specious-Area Relationships?” *Biological Conservation* 29: 63-80.

Brash, A.R. 1987. “The History of Avian Extinction and Forest Conservation in Puerto Rico.” *Biological Conservation* 39: 97-111.

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Pimm, S.L. et al. 1995. “The Future of Biodiversity.” *Science* 269: 347-350.

Zimmerman, B.L. and R.O. Bierregaard. 1986. “Relevance of the Equilibrium Theory of Island Biogeography and Species-Area Relations to Conservation with a Case from Amazonia.” *Journal of Biogeography* 13: 133-143.

Trade-Offs Involved in Protecting Forest Biodiversity

This report has focused on the negative impacts on biodiversity caused by human-induced forest loss and modification. Managing forests for greater biodiversity conservation also has implications for other goods. Production forests increasingly are being brought under modified management regimes that reduce harvest intensity, alter logging practices, reduce road building, and otherwise allow more space for biodiversity, and social functions, such as recreation. More than 150 countries are participating in processes to establish criteria and indicators for sustainable forest management. Others have instituted temporary bans on the export of logs.

The spread of protected areas and sustainable forest management practices is expected to reduce fiber yields, at least in the short term. Quantifying the impacts of environmental and social considerations on future fiber supplies is difficult, but they could be considerable. As one example, the adoption of ecosystem management and application of the Endangered Species Act in the United States have reduced annual timber harvests from federal lands from about 50 million m^3 to less than 20 million m^3 (FAO, 1997a:81). The FAO has estimated that implementing sustainable forest management worldwide would reduce harvest volume over the short term and increase management costs by between 5 and 25 percent. Offsetting this, improved harvesting techniques could reduce waste and improve forest productivity in the longer term (FAO, 1999:14-15). These scenarios may be slow to materialize, given that the FAO's Forest Resources Assessment 1990 found less than 5 percent of tropical production forests meeting sustainable forest management standards (FAO, 1997a:24).

Information Status and Needs

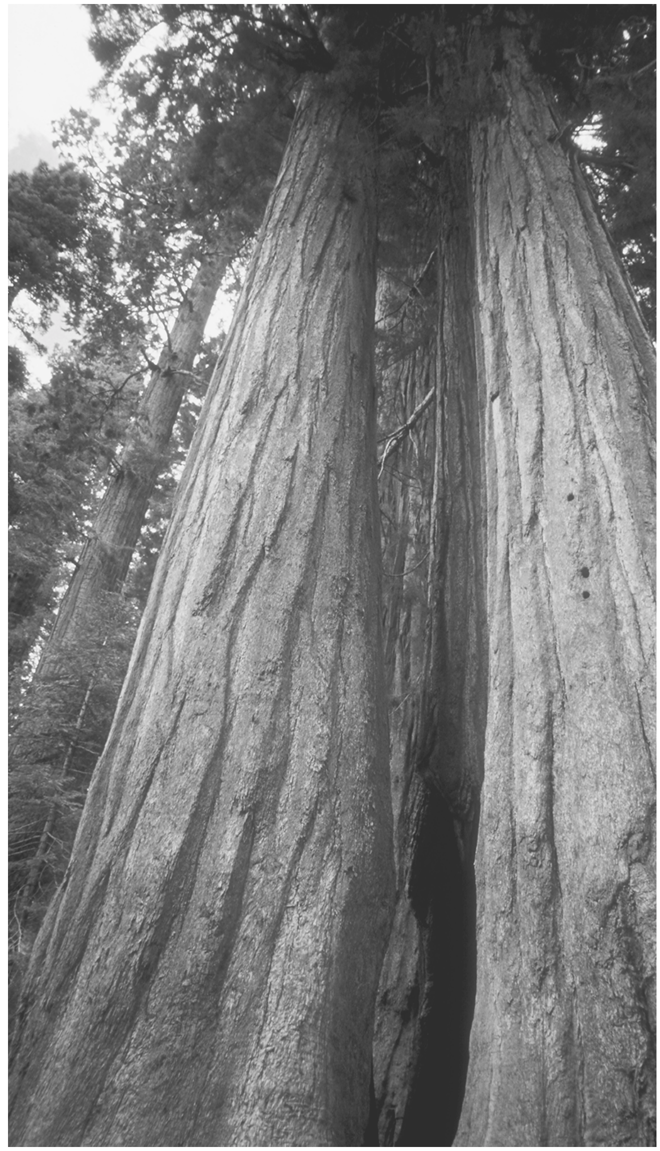
Better baseline information on forest biodiversity must be assembled to undergird sound conservation policies. Information is needed at the levels of ecosystems, species, and genetic resources. We still lack agreed-upon indicators of biodiversity, monitored over time. With these measures, experts can assess the impact of habitat alterations, such as fragmentation by agriculture and settlement, road building, mining, and logging. For example, how does species richness in one taxonomic group correlate with richness in another?

More information is required on the importance of habitat heterogeneity, minimum species composition, and various thresholds in maintaining population viability. Information of great importance in the design of conservation areas relates to size of forest reserves, keystone species in different kinds of forests, minimum viable population of these keystone species, and size of forest needed (block size) to maintain natural disturbance regime in different types of disturbed and undisturbed forest.

Despite well-documented examples of specific harmful invasives, datasets often lack baseline assessments and standardized criteria that would improve international data compatibility and sharing. According to experts in the field, critical information needs include the following: characterizing patterns of invasion in space and time by species and transport mechanism; identifying ecological and economic impacts; predicting invasive species pathways and patterns; establishing best management practices for prevention, eradication, and control; and assessing effectiveness by monitoring the effectiveness of control techniques (Ridgway et al., 1999:1). The Global Invasive Species Programme, a component of DIVERSITAS (an international program on the science of biodiversity), is assessing the current status of the science, as well as management practices for dealing with harmful alien species.

Accurate predictive information is a prerequisite for forest management planning. Detailed biodiversity surveys over more than a fraction of a forest management unit is impractical. A cost-effective substitute would be the ability to predict species occurrence and habitat type using simple environmental information easily obtained from GIS and remote sensing. In addition, such predictions would assist in survey design for further biodiversity studies. Elevation is known to be an important factor in determining species composition; topography may also have significant influence on the ecological resources and biodiversity of an area. Incorporating these parameters in biodiversity research would increase the relevance and applicability of results.

CARBON STORAGE AND SEQUESTRATION



Each year, as forests grow and increase their biomass, they absorb carbon from the atmosphere and store it in plant tissue. This process is known as carbon sequestration. Despite constant exchanges of carbon between forest biomass, soils, and the atmosphere (*see below*), a large amount is always present in leaves and woody tissue, roots, and soil nutrients. This quantity of carbon is known as the carbon store. Carbon sequestration and storage slow the rate at which carbon dioxide accumulates in the atmosphere and mitigate global warming. Forests sequester and store more carbon than any other terrestrial ecosystem, and constitute an important natural defense against climate change.

How Forests Sequester and Store Carbon

The earth's vegetation absorbs carbon dioxide from the atmosphere through photosynthesis, and releases it again through respiration. The total amount of carbon dioxide (CO_2) absorbed annually —about 120 billion (giga) tons of carbon, or 120 GtC—is known as gross primary productivity. Carbon losses from respiration halve the gross carbon uptake; the net primary productivity of the earth's plant matter is thus about 60 GtC. This giant breathing process can be observed in the atmosphere, where concentrations of carbon dioxide fall during the growing season (i.e., spring and summer) and rise again during the colder months when plant growth largely ceases. At the same time, carbon losses from ecosystems occur continuously due to the decomposition of organic matter by soil biota. These losses further reduce the productivity of ecosystems to about 10 GtC globally. Finally, additional carbon losses occur as a result of various disturbances, including storms, fire, harvest, and deforestation. The final, net production of organic matter in ecosystems is approximately 0.7 GtC annually, or less than 1 percent of net primary productivity (Steffen et al., 1998:1393-1395).

This chapter summarizes the latest scientific understanding of the global carbon cycle, and its disruption by human activities; presents an estimate of the spatial distribution of carbon stores in forests and other terrestrial ecosystems, developed for this pilot analysis; and discusses the capacity of forests to increase carbon storage, in order to slow global climate change.

The Global Carbon Cycle

In nature, carbon cycles continuously among three main global reservoirs: the atmosphere, the terrestrial biosphere, and the oceans. (Carbon is also stored in carbonate form in rocks and sediments, but this carbon cycles on a far longer time-scale if undisturbed by man.) Natural carbon exchanges between the atmosphere and the terrestrial biosphere total about 60 GtC annually (net primary productivity), while natural carbon exchanges between the atmosphere and the oceans total about 90 GtC. The oceans store by far the largest pool of carbon, about 38-40,000 GtC, predominantly in the form of dissolved inorganic carbon. The terrestrial biosphere stores the next largest pool, approximately 2,200 GtC, in vegetation and surface soils (soils to a depth of 100 cm). The atmosphere stores a relatively small amount of carbon, about 760 GtC (Schimel et al., 1996:65-131). In postglacial times, the carbon cycle is believed to have been in a state of dynamic equilibrium: despite the immense movements of carbon between atmosphere, oceans, and the terrestrial biosphere, totals in each of the three reservoirs remained roughly constant over time.

Human Modification of the Carbon Cycle: Trends in Land Use and Fossil Fuel Combustion

The store of carbon in the atmosphere, measured as the atmospheric concentration of CO_2, has risen nearly 30 percent over the past 200 years, from about 280 parts per million (ppm) to about 366 ppm. This increase is primarily as a result of land use change and combustion of fossil fuels (Keeling and Whorf, 1999).

Between 1850 and 1998, net cumulative global CO_2 emissions from land use change have been estimated at about 136 (+/- 55) GtC (Houghton, 1999:298-313; Houghton et al., 1999:574-578; Houghton et al., 2000:301-304). Of these emissions, about 87 percent resulted from deforestation and about 13 percent from cultivation of mid-latitude grasslands. Until about 1950, the rate of forest conversion was highest in the Northern Hemisphere. Since then, the situation has reversed, with forests growing back in the North (especially in the United States) and clearance rates accelerating in the Southern Hemisphere, especially in the Tropics. About 60 percent of all CO_2 emissions resulting from land use change have come from tropical countries and have been released in the past 50 years. The net annual release of carbon to the atmosphere from land use change during the 1990s is now estimated at 1.6 (+/- 0.8) GtC/year (Houghton et al., 1999:574-578; Houghton et al., 2000:301-304).

During the period 1850 to 1998, fossil fuel combustion and cement production released an estimated 270 (+/- 30) GtC to the atmosphere — about double the emissions from land use change. Fossil fuel combustion accelerated through the 20th Century and shows little signs of slowing. The most recent estimates of annual emissions of carbon from fossil fuel combustion and cement production show another sharp increase, from an estimated 5.5 GtC in the 1980s (10-year-average figure), to an estimated 6.3 GtC in the 1990s (Marland et al., 1999; British Petroleum Company, 1999).

Not all of this released carbon accumulates in the atmosphere; the oceans and the terrestrial biosphere both act as "sinks," absorbing part of the extra carbon released to the atmosphere by human activity. Cumulative uptake by the oceans since 1850 is estimated at about 120 (+/- 50) GtC (Kheshgi et al., 1999:31127-31144; Joos et al., 1999:1437-1441). Carbon accumulation in the atmosphere over the same period is estimated at 176 (+/- 10) GtC. A calculation of total carbon emissions from fossil fuel combustion and land use change, minus carbon accumulation in the oceans and the atmosphere, yields a terrestrial sink of about 110 (+/- 80) GtC. Given that carbon emissions from land use change are about 137 GtC, this means that the terrestrial biosphere has been a net *source* of carbon emissions over the period. Balancing the carbon budget for the period 1850-1998 yields a global net terrestrial source of about 26 (+/- 60) GtC.

Expressed in annual terms, fossil fuel combustion and cement-making now contribute 6.3 GtC to the atmosphere each year. Net annual uptake of carbon by the oceans is currently estimated at about 2.3 GtC/year (Jain et al., 1995:153-166; Harvey et al., 1997). About 3.3 GtC accumulates annually in the atmosphere. The balance of 0.7 GtC is believed to be the net result of terrestrial carbon sources (ca. 1.6 GtC from land use change) and terrestrial carbon uptake (ca. 2.3 GtC from ecosystem productivity). This balance indicates that, over the past few decades, the terrestrial biosphere has become a net carbon sink.

A surprising finding of recent research is that net carbon uptake by the atmosphere appears not to have increased over the past decade, despite significantly increased fossil fuel emissions. Net annual uptake by the oceans appears to have increased slightly, but increased terrestrial biological productivity accounts for the bulk of the additional carbon sequestration. There is still some uncertainty over annual carbon uptake by terrestrial ecosystems, and researchers are trying to identify more precisely the size and location of this "missing sink" (Fan et al., 1998: 442-446). Possible explanations for increasing biomass productivity include the fertilization effect of rising atmospheric concentrations of CO_2 and increased nitrogen deposition, and regrowth of forests in the Northern Hemisphere.

A human-induced net addition of 3.3 GtC annually to the store of atmospheric carbon may seem small, compared with the immense quantities of carbon cycled naturally among the major global carbon reservoirs. However, the impact is cumulative. Rising atmospheric concentrations of carbon dioxide, together with other greenhouse gases (GHGs), are believed to have contributed to an increase in the mean global temperature of about 0.7° C over the past 100 years. Continuing accumulation of GHGs will cause further changes in the global climate, leading to higher sea levels and altered precipitation patterns. Other possible consequences include prolonged drought, severe flooding, and more frequent extreme weather events.

If climate change is to be avoided, carbon accumulation in the atmosphere must be slowed, and ultimately halted. This might be achieved, in part, by diverting more anthropogenic carbon emissions into terrestrial ecosystems. Measures to encourage additional sequestration and storage of carbon in the world's vegetation and soils must be based on more accurate knowledge of the location and size of current carbon stores, the amounts of carbon released and sequestered annually (the annual carbon flux), and the potential of different vegetation types, in different sites, to increase their carbon sequestration rates and storage volumes.

Many researchers have attempted to estimate terrestrial carbon storage at a regional, national, and global level (Birdsey, 1992; Dixon et al., 1994; Houghton, 1995; Turner et al., 1995; Gaston et al., 1998). Because WRI has chosen to focus at the global level, all terrestrial ecosystems are represented in the analysis presented here.

Carbon Stores in Forests and Other Terrestrial Ecosystems

WRI has developed an estimate of the spatial distribution of global carbon stores in terrestrial ecosystems. The maps presented here are based on two global datasets, one of them modified and updated in line with best estimates of current vegetation cover.

Our estimates of carbon stored in above- and below-ground live vegetation are based on those developed by Olson et al. (1983). This study still represents "the most commonly used, spatially explicit estimates of biomass carbon densities at a global scale" (Gaston et al., 1998:97-114). However, instead of following the vegetation map used by Olson, we applied Olson's estimates to the more recent Global Land Cover Characteristics Database (GLCCD, 1998). The EROS Data Center provided WRI with a match between Olson's low and high estimates of carbon storage values for ecosystem complexes, and a vegetation map based on the GLCCD (USGS/EDC, 1999). The low and high estimates of carbon content in the main ecosystem complexes span all the vegetation types that may be found within each ecosystem. We acknowledge that Olson's estimates of carbon storage in vegetation have, in some cases, been superseded by more recent studies at the national and regional level. The advantage of the methodology adopted here is that Olson still provides the only consistent set of carbon storage estimates for vegetation types at the global level.

Our estimates of carbon stores in soils are based on those of Batjes (Batjes, 1996), who estimated the global stock of organic carbon in the upper 100cm of the soil to be between 1,462 and 1,548 GtC. The higher value corresponds to "stone-free" soil conditions. The upper 100 cm of soil is the layer believed to be most directly involved in interactions with the atmosphere, and most sensitive to land use and environmental changes. Batjes first analyzed over 4,000 individual soil profiles contained in the World Inventory of Soil Emission Potentials (WISE) database compiled by the International Soil Reference and Information Centre (ISRIC) (Batjes and Bridges, 1994). Batjes then used the soil profile data to compute the average soil organic carbon (SOC) at several depth intervals for each of the world's soil types as defined by the FAO. The global estimate was produced by summing the SOC content of the soil types found in each 30x30 minute (approximately 55 km at the equator) grid of the digitized FAO-UNESCO Soil Map of the World (FAO 1991), weighting the SOC values according to the shares of soil type area within each grid cell.

For the purposes of the PAGE study, we repeated the Batjes analysis using a more recent 5x5 minute (approximately 10 km at the equator) grid of the Soil Map of the World (FAO 1995), together with average SOC content values taken from Batjes (Batjes, 1996 and 2000). This approach yielded an estimate of global organic soil carbon of 1,555 Gt in the upper 100 cm of soil. We did not adjust for stone content, so our estimate corresponds to Batjes' estimate of 1,548 GtC.

Map 14 shows our estimate of carbon storage in the world's above- and below-ground live vegetation, mapped at a 10-km resolution. Olson's estimates of both low and high carbon storage values are expressed as a range, in metric tons of carbon per hectare; the map depicts storage values at the high end of the range. It is immediately apparent that the greatest vegetation carbon stores are found in the tropical and boreal forests. Temperate forests and tropical savannas also store significant quantities of carbon in their vegetation.

Map 15 shows our estimate of the spatial distribution of carbon storage in the world's soils. It shows that the greatest soil carbon stores are found in the high latitudes (boreal forests and tundra), with other important stores located in tropical forests, tropical savannas, and temperate grasslands.

Using GIS, the two maps were combined to produce a global map at a 10 km resolution. Map 16 represents the distribution and concentration of total global carbon stores, based on the modified high estimates of Olson et al. (above- and below-ground vegetation), overlaid with our estimates of soil carbon. The carbon stored in terrestrial ecosystems depicted in this map is 2,385 GtC. The low-end estimate is 1,752 GtC. These results are consistent with other studies (Houghton 1996; Dixon et al., 1994; IPCC, 2000). The wide gap between the low and high estimates illustrates the major uncertainties that still exist.

Our estimates of total carbon stores in terrestrial ecosystems are presented in more detail in Table 9. Differing scales of the vegetation and soil datasets, and WRI's modification of Olson's ecosystem complexes to match more recent land cover data, made it impossible to calculate a breakout of carbon storage in forest ecosystems as defined by Olson. We provide, therefore, a breakout by latitudinal belts, where low latitudes (25° S to 25° N) correspond approximately with tropical and subtropical ecosystems, mid-latitudes (25° to 50° N, and 25° to 50° S) correspond with

Table 9

Estimated Range of Total Carbon Storage Values by Ecosystem

Ecosystem Type	Total Land Area (10^6 km^2)	Global Carbon Stocks (GtC)			Carbon Stored/Area (t C /ha)
		Vegetation (Low-High)	Soils (Mean)	Total (Low-High)	Low-High
Forests					
High latitude	10.3	46-115	266	312-380	303-370
Mid latitude	5.9	37-77	84	122-161	206-273
Low latitude	12.8	48-265	131	180-396	140-310
Sub-total forests	**29.0**	**132-457**	**481**	**613-938**	**211-324**
Grasslands					
High latitude	10.9	14-48	281	295-329	271-303
Mid latitude	20.1	17-56	140	158-197	79-98
Low latitude	21.7	40-126	158	197-284	91-131
Sub-total grasslands	**52.6**	**71-231**	**579**	**650-810**	**123-154**
Agriculture					
High latitude	3.4	8-18	45	52-62	156-187
Mid latitude	12.7	21-52	134	155-186	122-147
Low latitude	9.5	20-72	85	105-157	110-164
Sub-total agriculture	**25.6**	**49-142**	**264**	**313-405**	**122-159**
Other					
High latitude	18.6	3-31	65	69-96	37-52
Mid latitude	11.1	9-25	61	70-86	64-78
Low latitude	8.8	4-16	34	38-50	43-56
Sub-total other	**38.5**	**16-72**	**160**	**177-232**	**46-60**
Total	**145.7**	**268-901**	**1,484**	**1,752-2,385**	**120-164**

Notes:

Land Area and Ecosystem Definition: Ecosystem types are based on the IGBP classification of the Global Land Cover Characteristics Database (GLCCD, 1998). Urban areas, calculated from the Nighttime Lights of the World database (NOAA-NGDC, 1998), have been subtracted from the forest, grassland and, agriculture ecosystem area totals. Grassland ecosystems are modified from the IGBP classification scheme to include tundra. The category "other" includes wetlands, human settlements, and barren land. Temperate West European countries (Ireland, United Kingdom, France, Belgium, the Netherlands, Germany, Denmark, Poland, Belarus, Lithuania, Latvia, Estonia, and Ukraine) that extend north of latitude 50° north, are included in the mid-latitude range. Total land area includes Greenland and Antarctica.

The land area of agriculture ecosystems reported here differs from that reported in the PAGE agroecosystem study (Wood et al., 2000). That report includes cropland/forest and cropland/grassland mosaics in agroecosystem extent; it therefore records both a larger land area and larger carbon storage values for agroecosystems.

Carbon Storage Values: Carbon storage values for above- and below-ground vegetation include carbon stores in Greenland and Antarctica. Soil carbon data for Greenland and Antarctica were largely incomplete and were excluded.

Our estimate of total world soil carbon stores is 1,553 GtC. The estimate of 1,484 shown here is lower because ecosystem areas were summarized within latitudinal bands using a different resolution map from that used in the FAO soil map of the world (FAO, 1991). As a result, some carbon stores in coastal areas fell outside the summary boundaries, and were missed.

Numbers may not add due to rounding.

temperate ecosystems, and high latitudes (50° to 90° N, and 50° to 90° S) correspond with boreal forests and tundra.

Our findings indicate that forest ecosystems account for about 40 percent of the total carbon stored in terrestrial ecosystems (high estimate). About 34 percent is stored in grasslands, and about 17 percent in agricultural lands. The highest quantities of stored carbon are located in the tropical and boreal forest regions. However, carbon in these two areas is concentrated in different places. In the tropics, more carbon is stored in vegetation than in soils while in the boreal region far more carbon is stored in the soils. Peatlands in the boreal region are especially important areas because of the large quantities of soil carbon stored per unit area. Grasslands generally store less carbon than forests on a carbon/unit area basis. However, their extensive area means that, in total, they are important carbon stores. Tropical (low latitude) grasslands store significantly more carbon than do temperate (mid latitude) forests, for example. These storage estimates are all critically dependent on area estimates for the ecosystems in question.

Forest Capacity to Maintain or Increase Terrestrial Carbon Stores

Current rates of deforestation and forest degradation are steadily reducing the carbon storage and sequestration potential in the tropical zone, while forest regrowth in the Northern Hemisphere is partly offsetting this trend. If the latest estimates are correct, deforestation and forest degradation account for about one fifth of anthropogenic carbon emissions. The FAO reports annual forest deforestation rates of 130,000 km^2, but this is probably an underestimate. (*See p. 17: Recent Deforestation Trends.*) In addition to forest clearance, biomass reduction is another significant source of carbon emissions: forest vegetation is thinned out wherever shifting cultivation, woodfuel collection, and logging occur. A recent study of historic carbon losses from land use change in tropical Asia estimates that forest clearance for agriculture accounted for two thirds of total carbon emissions, and forest degradation for one third. The total amount of carbon held in forest vegetation and soils in the region has been reduced by nearly 60 percent over a 145-year study period (Houghton and Hackler, 1999:481-492). Another study of forests, this time in tropical Africa, estimates that the above-ground carbon store was reduced by 6.6 GtC in the decade of the 1980s (equivalent to one year's fossil fuel emissions today). Just over one half of carbon losses were due to biomass reduction, and just under half were attributed to forest clearance (Gaston et al., 1998:97-114). Future reductions in the rate of forest clearance and improvements in fiber management (such as practicing low-impact logging, and establishing fuelwood plantations) would significantly reduce carbon emissions from these sources.

Another possible route forward is a global commitment to afforestation programs and plantation establishment. A number of studies have attempted to estimate the carbon sequestration potential of forest conservation and planting (IPCC, 1996; studies cited in Nilsson and Schopfhauser, 1995: 267-293). Plantation area is currently expanding, but remains trivial in comparison to the needs of carbon sequestration. One estimate is that, in order to offset net global carbon emissions at average 1980s emission levels, a plantation area of 19 million km^2 (slow-growing species) or 4.7 million km^2 (fast-growing species) would be required (Centeno, 1992). However, major afforestation programs must contend with political, economic, and technical issues which limit their feasibility. A study that considered these constraints calculated that about 3.5 million km^2 are realistically available for plantations and agroforestry for the sole purpose of carbon sequestration (Nilsson and Schopfhauser, 1995:267-293). Trees planted on this area could be expected to reach a maximum sequestration rate of 1.5 GtC per year, achieved only after 60 years of growth. Over a 100-year period, a total of 104 GtC would be sequestered, less than one third of net carbon released to the atmosphere, at today's emission levels. The question then arises of what to do with the fiber produced on the plantations. Short-lived products, such as fuelwood, packaging, or paper, may quickly release carbon back to the atmosphere.

Biomass energy provides a means of utilizing plantation production and avoiding greenhouse gas emissions from fossil fuel combustion. (*See p. 42: Woodfuels as a modern, renewable energy source.*) If biomass is harvested and subsequently regrows without an overall loss of carbon stocks, then there are no net CO_2 emissions over a full harvest/growth cycle. Land can then be used continuously for biomass energy production. The avoided fossil fuel CO_2 is equivalent to the fossil fuels substituted by biomass fuels, minus the fossil fuels used in the biomass energy production system. A variety of energy scenarios developed by industry, government, and independent researchers have estimated the potential benefits of a partial shift in the global fuel mix from fossils to renewable energy sources, including biomass (Williams, R.H., 1994:199-225). One study suggests that a total of 6 million km^2 of biomass plantations with an average yield of 12 dry tons per hectare could offset 50 percent of 1985 carbon emissions by the year 2050, if the biomass were used in place of fossil fuels for energy production (Hall et al., 1990). Again, such proposals must contend with competing uses of land (and water), including agriculture, settlement, recreation, and conservation.

Information Status and Needs

The state of scientific knowledge regarding the global carbon flux, and carbon stores in specific vegetation types and regions, is advancing rapidly. However, significant uncertainties remain in estimating annual carbon release and uptake rates, and all data cited here should be regarded as subject to revision. Changes in the carbon stocks of stands of forest trees over a 5-year period can now be assessed with relative precision. Changes in soil carbon stocks are more difficult to assess because of the large number of samples required. More accurate data are needed to determine the natural flows of carbon between the major carbon pools. These flows vary from one part of the globe to another, and also by timeframe, that is, between seasons, from one year to the next, and over decades and centuries. Changes caused by natural processes and human intervention remain difficult to distinguish.

Our knowledge of carbon storage values for the world's major terrestrial ecosystems is still subject to great uncertainty. The carbon storage indicator developed for this report shows that the greatest uncertainty surrounds the size of carbon stocks in tropical forest vegetation and tropical grasslands. More region-specific studies are able to narrow the range of uncertainty but, so far, different methodologies do not permit comparability among these regional studies.

More accurate information is needed on the precise quantities of carbon that can be stored in different species of tree or crop, in different sites and different soil types, under different management regimes. At present, estimated sequestration rates for given vegetation types still vary by up to a factor of 2 or more, and do not form an adequate basis for policy-making. Such information is essential, given that sequestration is emerging as an important climate change policy option, offering a complement to, or partial replacement for, the strategy of reducing carbon emissions.

WATERSHED PROTECTION

Environmental Services of Watershed Forests

Forests located in watersheds contribute in a number of ways to maintaining local and downstream environmental conditions in a state conducive to agriculture, and protective of human settlements. Forests help stabilize soil, regulate water flow rates and periodicity, maintain water quality and, in the unique case of cloud forests, capture additional water supplies from the atmosphere. These services cannot be quantified at the global level, nor would such an exercise be useful. Information on watershed conditions is most relevant at the basin, subbasin, and site-specific level but such data are currently scattered. This section draws on regional and local level studies and attempts to draw some generalized conclusions.

SOIL STABILIZATION

Forests play a major role in physically stabilizing the upper reaches of watersheds where rainfall is heavy and land steeply sloped and prone to earth movements. Tree roots "pump" water, thereby reducing soil moisture content and the likelihood of mud slides, while root structures increase the shear-strength of soil and help prevent landslips. Drier, root-bound soil is more resistant to slope failure and catastrophic downslope movements. Trees also protect against slow, persistent downslope movement (soil creep), which is equally destructive of fragile land.

These generalizations should not disguise the fact that the effects of catchment deforestation and, conversely, the benefits gained from afforestation of degraded and eroded catchments, depend on the local situation and the management methods employed. Recent research even suggests that, in certain cases, forests may be responsible for *increased* rates of soil erosion. This phenomenon can occur where tree foliage increases the size of water drops falling below the canopy, and enhances splash-induced erosion (Hall and Calder, 1993, in Calder, 1998:7). Good quality data on removal of tree cover and associated impacts on soil stability are few and far between, and knowledge of the interaction of competing factors in landslips and soil creep is still limited.

WATER FLOW REGULATION

Trees require a lot of moisture, and water yield — the amount of water that escapes plant growth and is available to replenish surface and ground water reserves — is generally lower in forests than in areas with other vegetation cover. However, forests regulate the volume and periodicity of water flow by soaking up precipitation and releasing it in a controlled, regular supply. Deforestation can cause relatively steady, year-round water flows in downstream areas to change to destructive flood and drought regimes. Forest management can also affect water flow, for example, through selection of tree species. A long-term study in the eastern United States has shown that deciduous hardwood forests yield about 20 percent more streamflow than coniferous softwood forests. This is because transpiration and evaporative losses are lower from deciduous species, which shed their leaves during the winter months (Swank and Douglas, 1974:857-859). This finding has implications for watershed management, where competing interests of timber production and water supply must be reconciled.

WATER PURIFICATION

Forests have historically been the preferred land use for drinking water supply catchment areas. Water is filtered and purified to some extent by its passage through foliage and forest soils. Perhaps more importantly, forested land is relatively free of water pollutants associated with livestock rearing, agriculture, or industrial activity. The value of forests in maintaining high-quality drinking water supplies is well documented for the United States. (*See Box 5.*) The U.S. National Forests are the largest single provider of water in the country: over 60 million people in 3,400 communities rely on these forests for their drinking water. In contrast to some other of nature's services the value of water quality protection is relatively easy to monetize, being calculated as the avoided cost of water filtration plants. The value of U.S. watershed forests in this regard has been estimated at $3.7 billion per year (Dombeck, 1999). Some would put the value much higher. In a decision already famous among environmentalists, New York City administrators decided to spend $US1.5 billion to preserve the Catskills water catchment area, which supplies much of the city's water, in order to avoid investing up to $US6 billion in a new filtration plant (Chichilnisky et al., 1998:629-630). Nevertheless, other land uses, such as housing development, might yield still greater returns, and this decision should not be regarded as final.

WATER CAPTURE

Water capture is a function carried out by cloud forests, a major forest type unique to mountain terrain. Cloud forests occur where "the atmospheric environment is characterized by persistent, frequent or seasonal cloud cover at the vegetation level" (Hamilton et al., 1993:1-16). Such conditions are found most often on tropical or subtropical mountains exposed to oceanic climates. Cloud forests are typically composed of short, gnarled, dense-canopied trees, heavily draped with epiphytes, lichens, and mosses. This densely-vegetated structure enables the forests to condense or "strip" water from the moisture-laden air and increase the normal water availability (over precipitation) between 5 and 20 per cent (Bruinjzeel and Proctor, 1993:25-46). Water stripping also occurs in the temperate rainforests of the Pacific Northwest coast of the United States. The branches of giant redwood and Sitka spruce trees are covered with fine needles, up to one inch long. As incoming fog makes contact with the needles, water accumulates and drips to the ground. A recent study estimates that a relatively small redwood can gather the equivalent of four inches of rainfall in a single evening. The additional moisture contributes to the phenomenal size of the redwood trees, supports surrounding vegetation and wildlife, and replenishes local wells and springs (Yoon, 1998:D1).

Trends in Watershed Forest Cover

A recent WRI study of 145 primary and secondary watersheds around the world estimated that 42 of these watersheds have lost more than 75 percent of their original forest cover — the closed forests that are believed to have existed in the preagricultural era. (*See Map 17.*) Fifteen of these have lost more than 95 percent of their original forest cover. Most of these basins, with the exception of the Tigris and the Euphrates, are found in Africa, Central America, and Europe. Large basins, with very extensive forest cover, have lost a relatively small fraction of their original forest, but the absolute losses are large. Nine basins, including the Amazon, Ganges, Mekong, Mississipi, Paraná, and Volga river basins, have lost more than 500,000 km^2. The Yangtze and the Congo basins have each lost more than 1 million km^2 of forest (Revenga et al., 1998:1-13).

Forest Modification to Enhance Watershed Protection

Despite the widely recognized importance of the soil and water protection functions of forests, it remains difficult to assess management responses. According to the FAO's forthcoming Temperate and Boreal Forest Resources Assessment (TBFRA 2000), most European countries manage some proportion of their forests primarily for soil protection. The proportions range from under 10 percent in lowland countries (Netherlands, Denmark), to 42 percent (Switzerland), 78 percent (Spain), and even 100 percent (Greece). However, countries differ in their interpretation of "managed primarily." While some forests may be designated specifically or even exclusively for the protection of soil and water resources, others are probably managed for multiple purposes.

Many countries with mountainous and upland areas have established protection forests not only to protect soil and water, but to help control the incidence and severity of hazardous events. For example, up to 11 percent of the annual budgets of mountain prefectures in Japan are allocated to restoration or maintenance of forests on landslip-prone soils (Hamilton et al., 1997:281-311).

Box 5

Forests and Drinking Water Quality in the United States

The city of Portland, Oregon obtains all of its drinking water from a watershed in Mt. Hood National Forest. This water is so pure that Portland is one of the few cities in the country not required by law to filter its drinking water supply, saving the city more than $200 million in building costs alone for a water filtration plant. The Mount Hood National Forest was declared off limits to logging by Congress in 1996, ensuring that fresh water will continue to flow. In contrast, logging in the watershed that supplies the city of Salem, Oregon, with its drinking water has caused mudslides and sediment runoff that has overwhelmed the city's filtration system, disrupting water services for weeks at a time (Sierra Club, 1999).

Private and state-owned forests also provide drinking water to large cities. In Seattle, the 38,000 hectare Cedar River Watershed provides 1.25 million people with drinking water. When logging in the watershed threatened the quality of the water, a logging moratorium was declared in 1999. The Commonwealth of Massachusetts also relies on private forests to clean drinking water for much of the state. Over four million Massachusetts residents get their water in part from one of these forested surface water protection zones. In some cases, the water provided from these forests still needs to be filtered, but many watersheds have been granted exemptions from filtration requirements. The savings in construction costs of filtration plants for these watersheds is estimated at $31 million, not counting the costs of ongoing operation and maintenance (Terry, personal communication).

Sources:

Sierra Club. 1999. "Salem and Portland depend on clean water from Oregon's Cascade Range." Online at: http://www.sc.org/forests/report/tale.html. (Accessed August 1, 1999).

David Terry, Program Director, Massachusetts Drinking Water Program, personal communication, August 3, 1999.

There are some scientific questions concerning the importance of forests' role in preventing floods (*see below*). An equally important factor in some areas may be drainage of wetlands, which act as natural sponges for excess river flow. Nevertheless, many governments have taken steps to slow deforestation in major water catchment areas. The Chinese Government banned further logging in the upper reaches of the Yangtze and other major rivers, following the devastating floods of 1998, and is planning massive tree-planting programs. The mountainous western parts of Sichuan, Yunnan, and Gansu Provinces were about 20 percent forested in 1950; logging and agricultural expansion have since reduced forest cover by half. Much of what remains is slowly recovering secondary-growth forests or plantations, which the Chinese Government believes to be less effective in conserving soil and water (New York Times, 1998).

Capacity of Forests to Sustain Watershed Protection Services

In the absence of comprehensive data, it is not possible to develop specific indicators that describe forest productivity in terms of watershed protection. Removal of forest cover can threaten all watershed protection services. Useful proxy indicators, therefore, are the extent and condition of forest cover in watersheds, although tree functions can be substituted, at least in part, with alternative ground cover or careful terracing. Water purification services are especially vulnerable to contamination from air- and water-borne pollutants. Commonly used indicators of pollution are tree mortality and defoliation rates, though other factors are also involved.

FOREST COVER

Estimated forest losses in major watersheds are presented in Map 17. Montane forests are especially important in watershed protection, since they are located in the upper reaches of river systems, where water flow and quality is initially determined. Montane forests are expanding in many temperate regions, thanks to natural regeneration and reforestation for recreational and slope protection purposes. The quality of some new forests is regarded by some experts as inferior to the original forest cover, because they are less diverse in age class and species. An exception to this pattern of expansion is found in the mature coniferous forests in the Pacific Northwest of North America, Chile, Tasmania, and southern New Zealand. Highly prized as lumber, these forests may have been reduced to less than half their original extent by logging (Denniston, 1995:32). According to the FAO's 1990 Forest Resources Assessment, tropical montane forests are disappearing at an annual rate of 1.1 percent, which exceeds the loss rate for all other tropical forest types, including lowland tropical rainforest (FAO, 1993:28). According to the WCMC, just over 17 percent of upper montane forests in tropical and subtropical countries are under some degree of protection. Nevertheless, logging and clearance are believed to be widespread in some protected montane forests (WCMC, 1999).

Cloud forests are among the world's most threatened ecosystems, and appear to have been reduced to small fragments of their original extent. According to one recent estimate, about 90 percent of mountain forests have disappeared from the northern Andes, while the world's attention has been focused on the rainforests of the Amazon basin (Weutrich, 1993:23). The WCMC is compiling a global database of tropical montane cloud forests sites and their protection status. The highest remaining concentrations are found in Latin America and Southeast Asia, and to a lesser extent in Sri Lanka, the Philippines, and Papua New Guinea. Relatively isolated sites are scattered throughout Africa. Just under half the sites have some degree of protection (meeting IUCN Management Category I-IV criteria) but, according to the WCMC, continue to be fragmented or cleared at a rapid rate (WCMC, 1997:4).

FOREST CONDITION

In the tropical zone, remote montane forests are under pressure from logging, clearance for agriculture, and cultivation of illegal crops, such as opium. In some areas, population growth and an influx of tourists are leading to unsustainable rates of fuelwood collection. Poverty, resource depletion, conflict, and unstable government administrations are factors that encourage removal of rare forest species by poachers and bushmeat hunters (Hamilton et al., 1997:281-311). Air pollution is also a major factor in forest condition. Deposition of most atmospheric pollutants to forests is higher than to shorter vegetation types because forest canopies intercept more air current. Forests in upland areas, in particular, are subject to direct deposition and uptake of airborne pollutants from urban-industrial centers and traffic. Sources may be local, or many hundreds of miles away.

The long-term effects of air pollution on montane forests are uncertain, and remain a subject of controversy. Despite some dispute, evidence of forest dieback, disappearance of lichens, and loss of soil organisms and biodiversity, especially aquatic biodiversity, has been well documented in industrialized countries and attributed to air pollution. The degree of forest damage increases with altitude, especially at elevations where pollutants are concentrated in cloud, fog, or hoar frost. Spruce-fir forests in eastern North America have been intensively studied and, in at least some higher-elevation areas, deteriorating tree condition and mortality death have been attributed to soil chemistry changes associated with ambient acidic deposition (Eagar and Adams, 1992). More extreme examples are found in Central and Eastern Europe. The most recent survey of forest condition in Europe indicates that 26 percent of trees were damaged (i.e., suffered defoliation rates of more than 25 percent). Many countries listed air pollution as an important contributing factor. Most of the degradation was concentrated in montane forests, especially those in the "black triangle" of mountain ranges along the border of the Czech Republic, southeast Germany, and southwest Poland (UN-ECE, 1998:24). Such pollution leads to both long-term acidification of catchment vegetation and acidification of run-off.

Air pollution is a growing problem in parts of Asia and Latin America, as industrialization leads to higher levels of acid deposition. A World Bank study shows that parts of eastern and southern China, northeast India, Bangladesh, and northern Thailand already experience high levels of sulfur deposition. Assuming continuation of current economic and environmental trends, total emissions are expected to triple by 2020, leading to deposition rates in excess of ecosystem critical loads in these areas (Downing et al., 1997:30, 38-39).

Externalities of Deforestation in Watersheds

SOIL EROSION

In the absence of consistent and up-to-date global data, numerous local studies serve to show that soil erosion rates increase sharply with logging. However, removal of ground cover, rather than canopy cover, appears to be the chief determinant of erosion. According to a summary of 80 erosion studies, erosion rates under slash-and-burn agriculture in the tropics are 10 times higher than in natural forest. In plantations where weeds and leaf litter have been removed, erosion is more than 100 times as great as in natural forest (Wiersum, 1984). (*See Table 10.*)

FLOODING AND SEDIMENTATION

Systematic data on the role of forests in moderating precipitation run-off, reducing sedimentation, and regulating water supply (avoiding extreme flood-drought regimes) to downstream users are not available. Despite popular perceptions that forests prevent floods, some doubt has been cast on the links between deforestation, river sedimentation rates, and major flood events (Chomitz and Kumari, 1998:13-35). Scientific evidence links extensive deforestation to annual increases in average water yield, but average rates of flow do not necessarily correspond with increases in peak flow or storm flow, which cause floods. Rather, the size of the catchment basin is an important determinant. In small drainage basins (<50,000 hectares), increases in water yield translate directly into floods. In larger basins, the limited number of studies conducted so far that use long-term time series data on floods, show no link between deforestation and flooding (Bruijnzeel, 1989:229-243; Bruinjzeel and Bremmer, 1989). Such results may be explained by the fact that large basins contain many subbasins, which tend to flood in sequence, thus dispersing even intense rainfall over both space and time.

Related research has suggested that the proportion of eroded material in a watershed that is carried by a stream declines from almost 100 percent in catchment basins of 200 km^2 to about 10 percent in basins measuring 1 million km^2 (Mahmoud, 1987). This implies that, as with flooding, smaller river basins are more vulnerable to both rapid run-off and soil transport into the river system. Larger basins simply have more places for sediment to be trapped before it reaches a water course. Lower sediment ratios are also associated with longer sediment trans-

Table 10

Relation Between Land Cover and Erosion

Type of Land Cover	Surface Erosion (metric tons/hectare/year)		
	Minimum	Median	Maximum
Natural forests	0.03	0.3	6.2
Shifting cultivation, fallow period	0.05	0.2	7.4
Forest plantations, undisturbed[1]	0.02	0.6	6.2
Multistoried tree gardens[2]	0.01	0.1	0.15
Tree crops with cover crop/mulch	0.1	0.8	5.6
Shifting cultivation, cropping	0.4	2.8	70
Agricultural intercropping in young forest plantations	0.6	5.2	17.4
Tree crops, clean-weeded	1.2	48	183
Forest plantations, litter removed or burned	5.9	53	105

[1] Refers to forests for timber production, as opposed to tree crops.

[2] A system in which various perennial and sometimes annual crops are cultivated simultaneously with trees.

Source: Wiersum,1984.

portation times in larger basins, causing a lag between changes in land cover and downstream impacts.

Information Status and Needs

Although experts recognize that the role of watershed forests in protecting soil and water resources is important, underlying mechanisms are still poorly understood. Information on deforestation in major watersheds is too coarse to be linked to water flow regimes and soil erosion at the subbasin level. The 1990 Global Assessment of Soil Degradation (GLASOD) remains the most up-to-date dataset on soil erosion at the global level. While it provides a useful overview of the causes, extent, and severity of erosion worldwide, it cannot be used to analyze specific cause and effect linkages between deforestation, soil erosion, and river sediment levels.

Global datasets are of relatively little value in assessing forest watershed services. The most urgent need is for information and analysis at the river basin and subbasin level. More information is needed on land use patterns, management practices, river flow regimes and sediment loads, if linkages among them are to be understood. Currently, it is not possible to estimate the human and economic costs which may be imposed on human settlements and agriculture downstream when making decisions on upstream land use. The hydrological regimes of many major river systems are still unknown, and land use cover changes and related hydrological impacts in large catchment areas (as opposed to small sample plots) have been little studied. At the subbasin level, the complexity of competing factors affecting seasonal water flows indicates that detailed, site-specific models will be required to predict the impacts of deforestation or afforestation in catchment areas. Information is needed on the evaporative characteristics of different tree species and soil type combinations, if evaporation and run-off estimates are to become more reliable. The erosive potential of water drops falling from tree canopies needs to be better understood in developing soil erosion control measures in watersheds. It is not yet possible to distinguish accurately between natural, or background, rates of soil erosion, and erosion caused by human activities. More studies are required to determine the relations between air-borne pollutants, and downstream water contamination, and to develop appropriate mitigation measures.

GLOSSARY

AVHRR	Advanced Very-High-Resolution Radiometer
CARPE	Central Africa Regional Program on the Environment
CDIAC	Carbon Dioxide Information and Analysis Center
CIAT	International Center for Tropical Agriculture
CIESIN	Center for International Earth Science Information Network
CPD	Center of Plant Diversity
DCW	Digital Chart of the World
EBA	Endemic Bird Area
EC	European Commission
EDC	EROS Data Center
EFI	European Forest Institute
EROS	Earth Resources Observation System
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization of the United Nations
FRA	Forest Resources Assessment
GFW	Global Forest Watch
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GISP	Global Invasive Species Programme
GLASOD	Global Assessment of Soil Degradation
GLCCD	Global Land Cover Characteristics Database
GOFC	Global Observation of Forest Cover
ICBP	International Council for Bird Preservation
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
IGBP	International Geosphere-Biosphere Programme
IIASA	International Institute for Advanced Systems Analysis
IIED	International Institute for Environment and Development
INPA	National Institute of Amazonas Research (Brazil)
INPE	National Institute of Space Research (Brazil).
IPCC	Intergovernmental Panel on Climate Change
ISRIC	International Soil Reference and Information Centre
IUCN	World Conservation Union
IUFRO	International Union of Forestry Research Organizations
JRC	Joint Research Centre (European Commission)
MHT	Major Habitat Type
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NGDC	National Geophysical Data Center
NGO	Nongovernmental Organization
NOAA	National Oceanic and Atmospheric Administration
NRDC	Natural Resources Defense Council
OECD	Organisation for Economic Cooperation and Development
ORNL	Oak Ridge National Laboratory
OTA	Office of Technology Assessment
PAGE	Pilot Analysis of Global Ecosystems
RWEDP	Regional Wood Energy Development Programme
SFM	Sustainable Forest Management
TBFRA	Temperate and Boreal Forest Resource Assessment (FAO)
TREES	Tropical Ecosystem Environment observation by Satellite
UMD	University of Maryland
UNDP	United Nations Development Programme
UN-ECE	United Nations-Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USFS	United States Department of Agriculture, Forest Service
USGS	United States Geological Survey
WCMC	World Conservation Monitoring Centre
WISE	World Inventory of Soil Emission Potentials
WRI	World Resources Institute
WWF	Worldwide Fund for Nature (International)
WWF-U.S.	World Wildlife Fund (United States)

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